MM02: Catch/cover crops

Overview

Cover crops are non-cash crops integrated into the main crop rotation. They are typically grown either to maintain soil cover during fallow periods (Ruis & Blanco-Canqui, 2017), or are planted alongside main crops to reduce bare soil area and reduce erosion. The former is either ploughed under as green manure, or killed with herbicides under no-till regimes. Cover cropping practices are also viable in perennial systems such as orchards and vineyards (Pellerin et al., 2013; Frelih-Larsen et al., 2014). Cover crops can be divided into catch crops, grown to prevent N leaching (Cicek et al., 2015), and green manure, grown to improve soil physical conditions (Alliaume et al., 2014) and main crop nutrition (Dabney et al., 2010). Cover cropping serves to maintain SOC input to soil (Rutledge et al., 2017), prevent erosion (De Baets et al., 2011), decrease N leaching (Blombäck et al., 2003), and increase main crop productivity (Lal, 2004). Poeplau & Don (2015) show that cover cropping can also minimise SOC loss between rotations; systems avoiding or reducing fallow have been demonstrated to increase soil C stocks independently of other factors (Gentile et al., 2005; Goglio et al., 2012; Goglio et al., 2018).

Mitigation summary

Effect on GHG categories*	Rating	Notes
Enteric CH_4		
Manure CH_4		
Manure N_2O		
Soil N_2O: residue N	+	Increased residue input to soil
Soil N_2O: applied N	-	Reduced N requirement or increased N use efficiency
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground	-	
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect Companion-type cover cropping Fallow-type cover cropping (spring crops) Cover cropping in orchards	 high high high	
Cost-effectiveness** Companion-type cover cropping Fallow-type cover cropping (spring crops) Cover cropping in orchards	 high high low	
Confidence in cost-effectiveness Companion-type cover cropping Fallow-type cover cropping (spring crops) Cover cropping in orchards	 low moderate low	

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Related measures and potential interaction

Measure	Impact on other measures
8. Integration of grass/herbal leys into rotations	Potential implementation overlap.
10. Precision farming	N_2O AR and CE reduced (Eory et al., 2015)
11. Avoiding N excess	N_2O AR and CE reduced (Eory et al., 2015)
12. Nitrification inhibitors	N_2O AR and CE reduced (Eory et al., 2015)
13. Biological N fixation (legumes in rotations)	Potential definitional overlap for companion-type cover cropping.
15. Analysis manure prior to application	N_2O AR and CE reduced (Eory

	et al., 2015)

Inclusion in other marginal abatement cost curves

UK 2008	UK 2010	UK 2015	Ireland 2012	France 2013	France 2019
No*	No*	Yes	Yes	Yes	?

*Measure was considered for assessment in the MACC but rejected on the grounds of low abatement rate.

Baseline and uptake

There are no clear statistics for uptake of cover crops in European cropping systems (Poeplau & Don, 2015). Eory et al. (2015) assumed a current United Kingdom uptake of 30%, but stated this assumption was made in the absence of information from the literature; a more recent assessment (Martineau et al., 2017) also gave no clear indication of baseline uptake. Based on a consolidation of smaller-scale surveys, Poeplau & Don (2015) estimate that between 1 and 10% of cropland globally is already under cover crops.

Around 50% of European cropland is covered each winter, which forms a baseline for the implementation of fallow cover cropping in Europe; around half of the remaining land (25% total area) is ‘conservatively’ assumed to be suitable for cover cropping (Poeplau & Don, 2015). Inherent in this assumption is that cover cropping may not be possible in late harvest cropping systems e.g. potatoes or beets (Poeplau & Don, 2015), in soils with high clay content (e.g. > 60%, Pellerin et al., 2017) or where soils are poorly drained (Martineau et al., 2017) or have temperature constraints (Poeplau & Don, 2015).

Types of cover cropping system

Typology. Based on systems commonly found in the literature (Pellerin et al., 2013; Frelih-Larsen et al., 2014), cover cropping systems may be broadly divided into three groups:

a) Cover crops grown as temporary monoculture within an arable rotation to cover periods which would otherwise be **bare fallow**.
b) Cover crops grown as part of an arable rotation **together with the main crop**. This may also referred to as **companion cropping** (e.g. Lanini et al., 1991; Hellin, 2013).
c) Cover crops grown on otherwise bare soil in **perennial systems** such as orchards or vineyards (e.g. Garcia et al., 2018).

Cover crops are known as such in reference to the covering of bare ground or fallow; in reference to broader ecosystem services provided by such systems, the crop may also be referred to as a **service crop** (e.g. Garcia et al., 2018). Where the primary role of the cover crop is to prevent losses of applied nitrogen, such crops may be referred to as **catch crops** (e.g. Aertsens et al., 2013)**.** Peripherally planted biomass (e.g. a grass buffer strip) is not usually referred to as a cover, catch, or service crop, though such measures are often assessed in tandem (e.g. Pellerin et al., 2013). One approach to fallow cover cropping involves allowing vegetation to develop naturally in fallow periods; whilst simple and inexpensive, this approach is not often seen, probably because it tends to encourage the presence of weeds in subsequent arable treatments (Baggs et al., 2000).

Implementation. For integration of companion-type cover crops into arable systems, Pellerin et al. (2017) proposed cover cropping comprising leguminous crops on 15% of cropped area. Cover crops on fallow land are typically introduced over winter (Baggs et al., 2000), and may require a switch to spring cereals if this system is not already in place. Cover crops in orchards or vineyards will typically cover already bare ground (Pellerin et al., 2013; Garcia et al., 2018), though may be implemented only over the winter period. The majority of cover cropping systems present in the literature appear in the arable/fallow cover category; table #CC.1 summarises a sample of specific pairings.

Table 1. Pairings of cash and cover crops for fallow cover present in the primary literature.

Cover crop	**Leguminous?**	**Integrated with**	**Source(s)**
White mustard (*Sinapis alba*)	N	Wheat/maize rotation, spring oats	Baggs et al. (2000); Wittwer et al. (2017)
Common vetch (*Vicia sativa*)	Y	Wheat/maize rotation	Wittwer et al. (2017)
Mix: Phacelia (*Phacelia tanacetifolia*), Persian clover (*Trifolium resupinatum*) and berseem clover (Trifolium alexandrinum)	M	Wheat/maize rotation	Wittwer et al. (2017)
Grazing rye (Secale cereale)	N	Spring oats	Baggs et al. (2000)
FForage rape (Brassica napus)	N	Spring oats	Baggs et al. (2000)
Winter peas (*Pisum sativum*)	Y	Spring oats	Baggs et al. (2000)
Italian ryegrass (*Lolium multiflorum*)	N	Spring oats	Baggs et al. (2000)
Winter barley (*Hordeum sativum*)	N	Spring oats	Baggs et al. (2000)
Winter wheat (Triticum aestivum)	N	Spring oats	Baggs et al. (2000)
White mustard (*Sinapis alba*)	N	Spring oats	Baggs et al. (2000)
Fodder radish (*Raphanus sativus*)	N	Spring oats	Baggs et al. (2000)
Red clover (*Trifolium pratense*)	Y	Spring oats	Baggs et al. (2000)
White clover (*Trifolium repens*)	Y	Spring oats	Baggs et al. (2000)
Birdsfoot trefoil (*Lotus corniculatus*)	Y	Spring oats	Baggs et al. (2000)
Black medick (*Medicago lupulina*)	Y	Spring oats	Baggs et al. (2000)
Forage peas (*Pisum sativum*)	Y	Spring oats	Baggs et al. (2000)
Oats (Avena sativa)	N	Spring oats, alfalfa	Baggs et al. (2000); Lanini et al. (1991)
Mix: White clover (*Trifolium repens*) and wild flower mix	M	Spring oats	Baggs et al. (2000)

Abatement potential and cost effectiveness

Carbon sequestration effects. Pellerin et al. (2013) and Pellerin et al. (2017) estimated soil carbon sequestration potential of 240 kg C ha^{-1} $year^{-1}$ (0.88 tonnes CO_2-eq ha^{-1} $year^{-1}$) for arable cover cropping (both companion-type cover cropping, and fallow cover. The authors also estimated potentials of 490 kg C ha^{-1} $year^{-1}$ (1.80 tonnes CO_2-eq ha^{-1} $year^{-1}$) and 320 kg C ha^{-1} $year^{-1}$ (1.17 tonnes CO_2-eq ha^{-1} $year^{-1}$) for cover cropping in orchards and vineyards respectively. Aertsens et al. (2013) estimated sequestration of 160 kg C ha^{-1} $year^{-1}$ (0.59 tonnes CO_2-eq ha^{-1} $year^{-1}$ based on rates reported in French systems. Poeplau & Don (2015), based on a global meta-analysis of the primary literature, estimated an annual sequestration potential of 320 $\pm$ 80 kg C ha^{-1} $year^{-1}$ (1.17 $\pm$ 0.29 tonnes CO_2-eq ha^{-1} $year^{-1}$) for arable cover crops. The authors also estimated a saturation point of 16.7 tonnes C ha^{-1} (61.2 tonnes CO_2-eq ha^{-1}) for land under cover crops. This annual sequestration potential was adopted by Martineau et al. (2017) in the form of an upper and lower bound of 0.88 – 1.47 tonnes CO_2-eq ha^{-1} $year^{-1}$. Posthumus et al. (2015) estimated a carbon sequestration potential of 479 kg C ha^{-1} $year^{-1}$ (1.76 tonnes CO_2-eq ha^{-1} $year^{-1}$) for arable cover cropping in the United Kingdom.

N_2O mitigation effects. Basche et al. (2014) found that cover cropping is likely to increase direct N_2O emissions from land, especially where leguminous cover crops are used and residues are incorporated. Cover crops increased direct N_2O emissions in 60% of cases, though the authors found that in the long term, the net N_2O impact may be closer to zero. Cover crops may also reduce N_2O emissions by extracting unused N from the soil following the main crop harvest (Aertsens et al., 2013). Pellerin et al. (2017) also estimated a reduction in N requirements of 11 kg ha^{-1} where leguminous crops are integrated into an arable system, though assumed no effect of cover crop residues on N_2O emissions. For an assessment in the UK, Eory et al. (2015) accounted for reduced N_2O emissions by assuming a 45% reduction in the leached N fraction ($Frac_{Leach}$) in the IPCC guidelines (de Klein et al., 2006).

Costs. Implementation of cover cropping is not expected to incur any substantial one-off costs (Frelih-Larsen et al., 2014; Posthumus et al., 2015). Annual maintenance costs are expected to stem from seed purchase, and cover crop planting and destruction, with savings resulting from reduced crop N requirements. Posthumus et al. (2015) estimated per-hectare annual costs of £50 – 55, £25 – 60 and £25 for seed purchase, cultivation and residue incorporation respectively. The scenarios considered were companion-type cover cropping (grass under sown maize) and barley sown as a winter cover. The authors also noted that a switch from winter to spring production (necessary, depending on baseline practice, to implement winter fallow cover cropping) could incur a substantial yield penalty equivalent to £175 ha^{-1}. The FarmScoper tool, developed by ADAS (Gooday et al., 2014), estimated costs of £63 ha^{-1} for implementation of autumn (fallow) cover cropping. The tool also estimated costs of £263 ha^{-1} if winter crop production was switched to spring to allow implementation of cover cropping.

***Benefits*. ** Posthumus et al. (2015) assumed no benefits other than soil carbon accumulation from cover cropping. Pellerin et al. (2013) assume benefits arising from fertiliser application reduction, but do not quantify this independently of the estimated net cost. Frelih-Larsen et al. (2014) assume savings of €41 ha^{-1} $year^{-1}$ arising from fertiliser reduction.

Cost effectiveness. The range of cost-effectiveness estimates present for cover cropping in the literature is highly variable depending upon system, region, and underlying assumptions. Table #CC.2 summarises the available data.

Table 2. Summary of extant cost-effectiveness estimates from the literature for cover cropping in agricultural systems. Cost-effectiveness measure is either GHG (total greenhouse gas mitigation) or SCS (abatement only from soil carbon sequestration.

System type	Cover cropping type	Region	Cost-effectiveness (currency units tonne CO_2-eq^{-1})	Cost-effectiveness measure	Source	Currency
Arable	Companion (15% area)	France	347	N_2O + CO_2	Pellerin et al. (2013); Pellerin et al. (2017)	EUR 2013
Arable	Fallow cover	France	31 — 79	N_2O + CO_2		EUR 2013
Vineyard	NA	France	9 — 17	N_2O + CO_2		EUR 2013
Orchard	NA	France	4 — 12	N_2O + CO_2		EUR 2013
Arable	Fallow cover	United Kingdom	80 — 179	CO_2 only	Posthumus et al. (2015)	GBP 2012
Arable	Companion	United Kingdom	57	CO_2 only		GBP 2012
Arable (spring cereals)	Fallow cover	Ireland	48	N_2O + CO_2	Schulte et al. (2012)	EUR 2012
Arable	Fallow cover	Europe	-19 — 307	N_2O + CO_2	Martineau et al. (2017)	EUR 2017
Arable	Fallow cover	United Kingdom	1,226	N_2O only	Eory et al. (2015)	GBP 2015

A variety of cost effectiveness estimates for cover cropping in European systems were compiled by McVittie et al. (2014). Given their range and specificity, these estimates are difficult to condense and so are excluded from table #CC.1. The range of estimates by McVittie et al. (2014) is summarised in fig. #CC.1a, with fig. #CC.1b showing a subset of these estimates specific to Scotland (Scotland is the nearest proxy to the United Kingdom presented by McVittie et al. (2014). This data was also used to inform estimates made in the mitigation summary (#CC.2).

Cover cropping with legumes appears to be the most cost-effective implementation (fig. #CC.1a), though this has yet to be specifically assessed in UK systems. This increase in cost-effectiveness stems from offset of synthetic N requirements. In many cases winter cropped areas are less cost-effective options for implementation of cover cropping, as this implies shifting production from winter to spring, with associated costs.

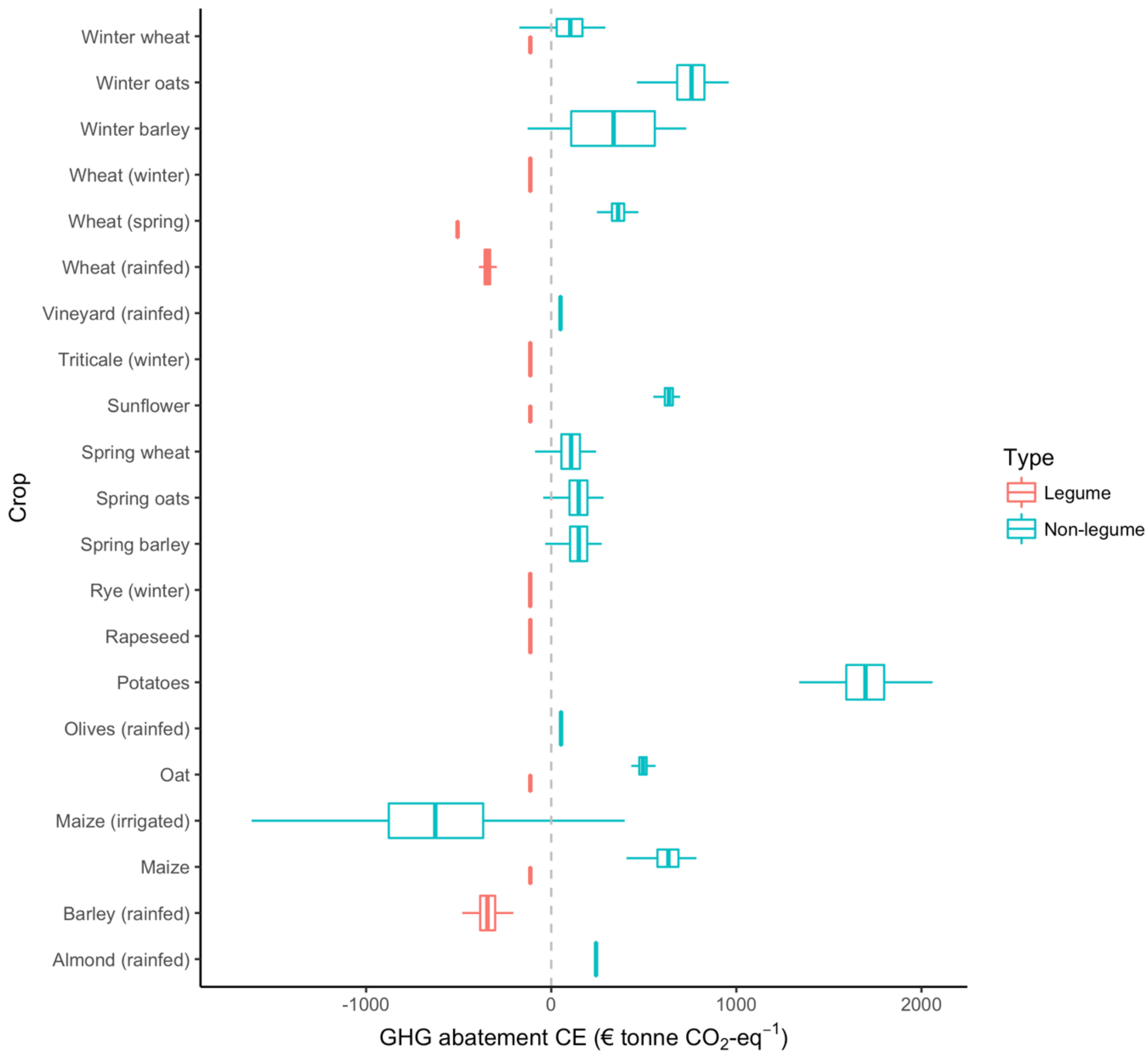

Fig.1a. Greenhouse gas abatement potential cost effectiveness estimation by cropping system, adapted from McVittie et al. (2014). Estimates are split into legume and non-legume cover crop types. The data was collected from a range of European countries.

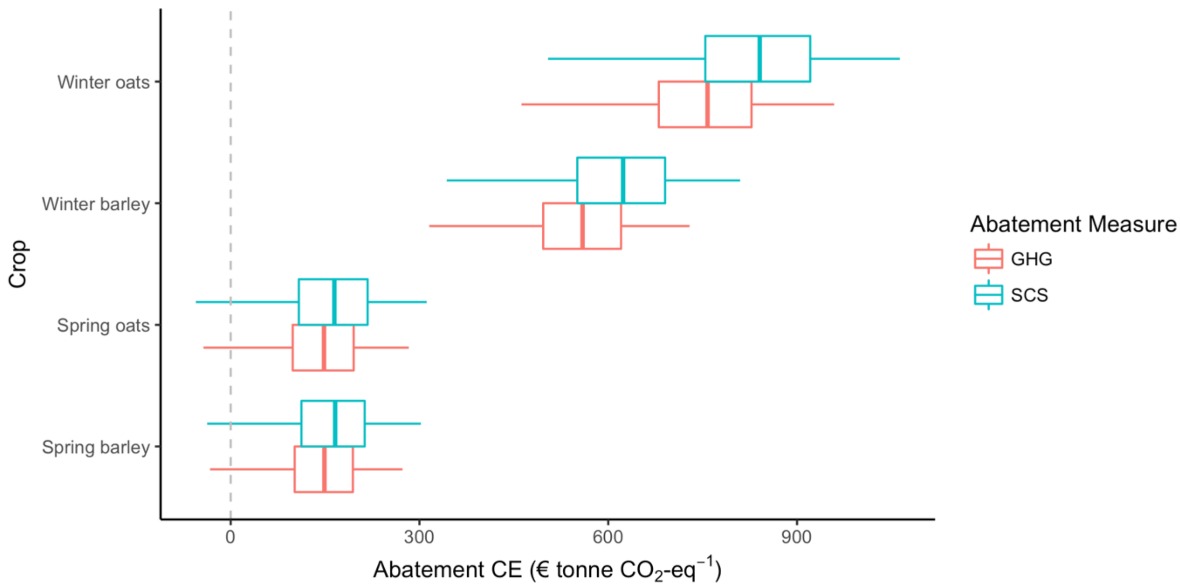

Fig. 1b. Scotland-specific abatement potential cost effectiveness for GHG mitigation and SCS sequestration by cropping system, adapted from estimates by McVittie et al. (2014).

Assumptions used in MAC

Based on the literature reviewed in the previous sections, cover cropping was split into three separate actions:

1. Fallow cover cropping, where cover crops are sown on bare fallow. Given the costs associated with a move from winter to spring production (Gooday et al., 2015), it is assumed that this crop may only be applied on spring cropped systems.
2. Companion type cover cropping, where cover crops are undersown with a main crop.
3. Cover cropping in orchards, where cover crops are sown below orchard trees.

Previous UK MACCs (Moran et al., 2008; Macleod et al., 2010; Eory et al., 2015) have only accounted for the potential of cover crops to reduce N_2O emissions. The French and Irish MACCs (Pellerin et al., 2013; Schulte et al., 2012) account for N_2O, but also consider the potential of cover crops to increase CO_2 sequestration in soil. The body of literature where this effect is documented is now relatively large (see Table #CC.2), and as such, CO_2 sequestration by soil will be included in this MAC assessment.

For fallow-type cover cropping, the body of literature estimates for both costs and abatement rates is relatively large. To assess this measure, the data underlying the cost effectiveness values reported in Table #CC.2, in addition to those from McVittie et al. (2014) were aggregated via Monte Carlo simulation (samples = 10^4, Mersenne seed = 2605), and the results used to calculate an aggregate marginal abatement cost. All costs were standardised to GBP, currency year 2017, using exchange rate and CPI data from FAOstat (2017). Eory et al. (2015) suggest that cover cropping is only likely to be effective on non-clay soils; data from Graves et al. (2011) was used to adjust total cropping areas from Defra (2018) to represent non-clay soils only for the calculation of national-level abatement potential. Spring-sown crops were defined as in Eory et al. (2015), and maximum additional uptake was set at 0.6—0.8 applicable area (Eory et al., 2015).

The estimated overall implementation cost was £139 ± 56 ha^{-1} for fallow type cover cropping (Fig. #CC.2). Abatement rates per hectare were 1.14 ± 0.30 tonnes CO_2-eq ha^{-1} year^{-1}; applied on the maximum applicable area of 584 kha, this translated to 465 ± 128 kt CO_2-eq year^{-1}. Abatement was achievable at a marginal abatement cost of £130 ± 63 tonne CO_2-eq.

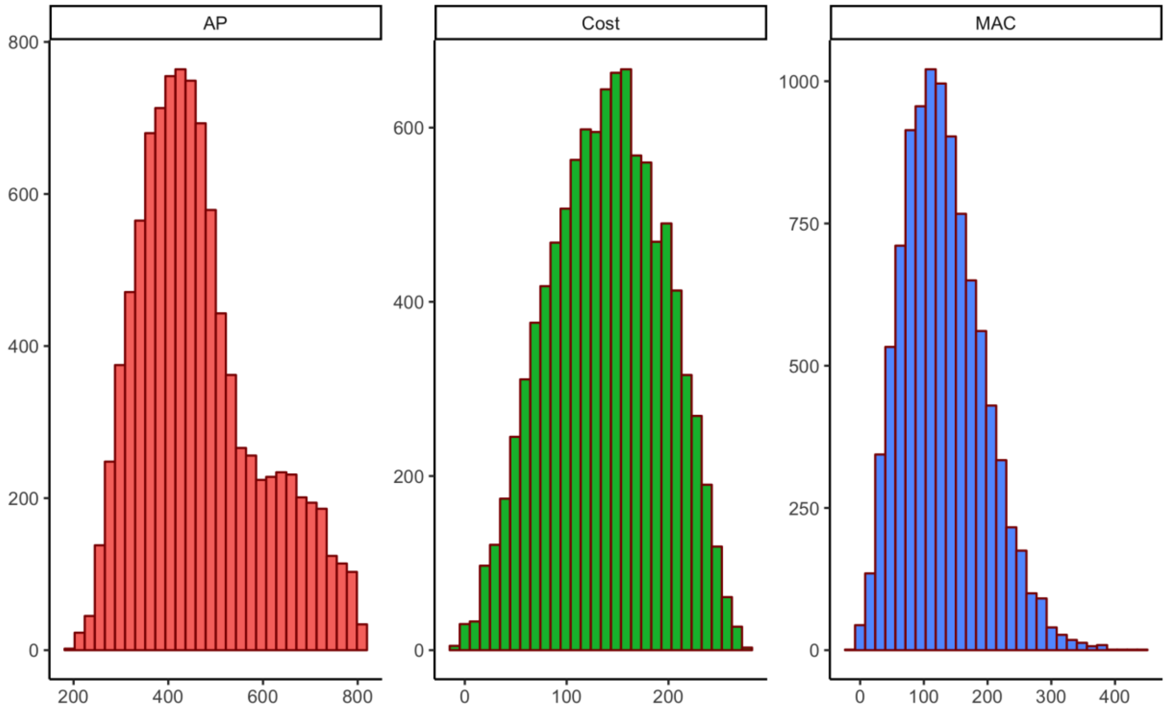

Fig.2. Combined metrics for combined estimates of fallow-type cover cropping. AP = abatement potential, kt CO_2-eq year^{-1}; Cost = implementation cost, 2017£ ha^{-1}; MAC = marginal abatement cost, 2017£ tonne CO_2-eq^{-1}.

Around 15% of the simulations shown in Fig. #CC.2 showed abatement achievable below the SCC (£66.10, Department for Business Energy & Industrial Strategy, 2018). Assuming no correlation between costs and abatement rates, this suggests that approximately 71 ± 20 kt CO_2-eq year^{-1} might be cost-effectively mitigatable via fallow-type cover cropping. In order to achieve this, areas suited to both low-cost implementation and high abatement rates (within the bounds should in Fig. #CC.2) would have to be identified; brief analysis suggests that the maximum (95% C. I.) cost permissible would be £105 ha^{-1}, and minimum (5% C. I.) abatement permissible would be 831 kg CO_2-eq ha^{-1} year^{-1} if abatement were to be achieved below the SCC. The saturation point of 16.7 tonnes C ha^{-1} (61.2 tonnes CO_2-eq ha^{-1}) estimated by Poeplau & Don (2015) should be borne in mind in this respect; such mitigation, stemming largely from CO_2 sequestration, would be finite. Depending on baseline soil carbon stocks, saturation could be reached in 20—40 years.

Fewer literature estimates are available for companion-type cover cropping. Available cost estimates (converted to GBP 2017) were £49 (Pellerin et al., 2013) and £128 (Posthumus et al., 2015). Only Pellerin et al. (2013) provided an estimate of abatement (118 kg CO_2-eq ha^{-1} year^{-1}); using these data, a cost of between £416—1084 tonne CO_2-eq^{-1} can be estimated. This type of cover cropping would not require winter fallow, so it is more difficult to estimate the cropping area upon which it could be applicable; however, given this high estimate of marginal abatement cost, it seems unlikely it would represent a cost-effective mitigation strategy.

The only literature estimate available for the implementation of cover cropping in orchards was that provided by Pellerin et al. (2013). Cost for this measure (converted to 2017 GBP) was estimated at £12 ha^{-1}, with an estimated abatement rate of 844—2753 kg CO_2-eq; this translates to a marginal abatement cost of £4—14 tonne CO_2-eq^{-1}. Based on these numbers, and an estimated orchard area (on non-clay soils only) of 13,900 ha, an abatement potential of 12—38 kt CO_2-eq could be realisable, assuming no existing uptake.

Ancillary impacts

A number of additional agroecosystem and management impacts may result from integration of cover crops into the agricultural system:

Interaction with no-till or organic systems: There may be substantial benefits where cover crops are implemented in parallel with zero- or reduced-tillage systems, or with organic agriculture; such systems are likely to see increased yields with the additional adoption of cover cropping (Wittwer et al., 2017).

Fertiliser use: Implementation of cover crops may offset synthetic N requirements, especially where leguminous cover crops are planted (Pellerin et al., 2013; Macleod et al., 2015). However, this offset may be minimal in the United Kingdom, as current guidance does not recommend a reduction in fertiliser application rates (Eory et al., 2015).

Herbicide use: Herbicides may be used to kill and remove the cover crop before planting of the cash crop, especially in no-till systems; as such, implementation of cover cropping may increase herbicide use (Macleod et al., 2015).

Microbial biodiversity: Changes to rotational management also impacts soil microbial biodiversity (Govaerts et al., 2007), with cover crops likely to positively impact this.

Residue removal mitigation: May offset soil carbon loss occurring where residues are removed (Ruis & Blanco-Canqui, 2017).

Aesthetics: Aertsens et al. (2013) observe that the introduction of certain cover crops (e.g. flowering *Phacelia* spp.) may positively impact the aesthetic qualities of an agricultural area.

Erosion: Soil erosion (from wind and water) is likely to be improved by introduction of cover crops on bare ground (Aertsens et al., 2013).

Nutrient leaching: Reduction of nitrate leaching, reduction of inorganic N levels, increased evapotranspiration, reduced drainage losses and N_2O emissions (Martineau et al., 2017).

Conclusions

1. Cover cropping in European systems has demonstrable soil carbon sequestration potential (Poeplau & Don, 2015) and is likely to prevent N leaching (Eory et al., 2015).
2. Cost effectiveness of cover cropping in the United Kingdom is generally considered to be low (e.g. Frelih-Larsen et al., 2014; Eory et al., 2015).
3. The assessment carried out in this fiche, based on an aggregation of literature estimates, reflects this sentiment and suggests that there is a low chance that mitigation will be achievable below the SCC (£66.10).
4. Previous UK MACC assessments (Moran et al., 2008; Macleod, Moran, Mcvittie, et al., 2010; Eory et al., 2015) assumed no C sequestration potential for cover crops. However, the majority of literature assessments include soil C sequestration as a result of cover crop implementation.
5. Low estimated cost effectiveness results primarily from the high cost of cultivating a non-cash crop, as well as possible loss of agricultural production (Posthumus et al., 2015).
6. Implementation cost may be reduced if the cover crop can provide additional services to the agroecosystem. Leguminous cover crops are a potentially more cost-effective option given their ability to offset synthetic N requirements, but this has yet to be explicitly assessed in UK systems (fig. #CC.1a, #CC.1b).

7. The majority of cost effectiveness assessments have yet to include less tangible cover crop services to the main crop (e.g. erosion or long-term yield impacts) as a component of the estimate; this may alter the viability of cover crops as an abatement measure (Schulte et al., 2012; Pellerin et al., 2013; Frelih-Larsen et al., 2014; Eory et al., 2015).
8. The majority of cost-effectiveness assessments also focus on fallow cover-type cover cropping in arable land; companion-type cover cropping or integration of cover crops into perennial systems is less well covered in the abatement literature.
9. Expansion of abatement rates and cost effectiveness estimates to national level is hampered by lack of information on baseline uptake and potential maximum uptake of cover cropping.

References
Aertsens, J., De Nocker, L. & Gobin, A. (2013) Valuing the carbon sequestration potential for European agriculture. *Land Use Policy* 31, pp. 584–594. Available at: http://dx.doi.org/10.1016/j.landusepol.2012.09.003.

Alliaume, F., Rossing, W.A.H., Tittonell, P., Jorge, G. & Dogliotti, S. (2014) Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. *Agriculture, Ecosystems and Environment* 183, pp. 127–137.

De Baets, S., Poesen, J., Meersmans, J. & Serlet, L. (2011) Cover crops and their erosion-reducing effects during concentrated flow erosion. *Catena* 85(3), pp. 237–244.

Baggs, E.M., Watson, C. a. & Rees, R.M. (2000) The fate of nitrogen from incorporated cover crop and green manure residues. *Nutrient Cycling in Agroecosystems* 56(2), pp. 153–163.

Basche, A.D., Miguez, F.E., Kaspar, T.C. & Castellano, M.J. (2014) Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. *Journal of Soil and Water Conservation* 69(6), pp. 471–482. Available at: http://www.jswconline.org/cgi/doi/10.2489/jswc.69.6.471.

Blombäck, K., Eckersten, H., Lewan, E. & Aronsson, H. (2003) Simulations of soil carbon and nitrogen dynamics during seven years in a catch crop experiment. *Agricultural Systems* 76(1), pp. 95–114.

Cicek, H., Martens, J.R.T., Bamford, K.C. & Entz, M.H. (2015) Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand. *Agriculture, Ecosystems and Environment* 202(3), pp. 31–41.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J. & Reeves, W. (2010) Using cover crops and cropping systems for nitrogen management. In: Delgado, J. A. and Follett, R. F. eds. *Advances in Nitrogen Management for Water Quality*. Ankeny, IA, USA: SWCS, pp. 231–282.

Defra (2018) Farming Statistics: Provisional crop areas, yields and livestock populations. (October), p. 23. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/747210/structure-jun2018prov-UK-11oct18.pdf.

Department for Business Energy & Industrial Strategy (2018) *Data tables 1 to 19: supporting the toolkit and the guidance. Table 3.*

Eory, V., Macleod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Borthwick, F., Watson, C., Waterhouse, A., Wiltshire, J., Bell, H., Moran, D. & Dewhurst, R. (2015) Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget.

FAOstat (2017) Crops and livestock products [Online]. Available at: http://www.fao.org/faostat/en/#data/TP.

Frelih-Larsen, A., MacLeod, M., Osterburg, B., Eory, A. V, Dooley, E., Katsch, S., Naumann, S., Rees, B., Tarsitano, D., Topp, K., Wolff, A., Metayer, N., Molnar, A., Povellato, A., Bochu, J.L., Lasorella, M. V & Longhitano, D. (2014) *Mainstreaming climate change into rural development policy post 2013*.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H. & Metay, A. (2018) Management of service crops for the provision of ecosystem services in vineyards: A review. *Agriculture, Ecosystems and Environment* 251(October 2017), pp. 158–170. Available at: http://dx.doi.org/10.1016/j.agee.2017.09.030.

Gentile, R.M., Martino, D.L. & Entz, M.H. (2005) Influence of perennial forages on subsoil organic carbon in a long-term rotation study in Uruguay. *Agriculture, Ecosystems and Environment* 105(1–2), pp. 419–423.

Goglio, P., Bonari, E. & Mazzoncini, M. (2012) LCA of cropping systems with different external input levels for energetic purposes. *Biomass and Bioenergy* 42(6), pp. 33–42. Available at: http://dx.doi.org/10.1016/j.biombioe.2012.03.021.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., Gao, X., Hanis, K., Tenuta, M., Campbell, C.A., McConkey, B.G., Nemecek, T., Burgess, P.J. & Williams, A.G. (2018) A comparison of methods to quantify greenhouse gas emissions of cropping systems in LCA. *Journal of Cleaner Production* 172, pp. 4010–4017.

Gooday, R.D., Anthony, S.G., Chadwick, D.R., Newell-Price, P., Harris, D., Duethmann, D., Fish, R., Collins, A.L. & Winter, M. (2014) Modelling the cost-effectiveness of mitigation methods for multiple pollutants at farm scale. *Science of the Total Environment* 468–469, pp. 1198–1209. Available at: http://dx.doi.org/10.1016/j.scitotenv.2013.04.078.

Gooday, R.D., Anthony, S.G., Durrant, C., Harris, D., Lee, D., Metcalfe, P., Newell-Price, P. & Turner, A. (2015) *Farmscoper Extension: Defra Project SCF0104*. ADAS.

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K.D., Luna-Guido, M., Vanherck, K., Dendooven, L. & Deckers, J. (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. *Applied Soil Ecology* 37(1–2), pp. 18–30.

Graves, A., Morris, J., Deeks, L., Rickson, J., Kibblewhite, M., Harris, J. & Fairwell, T. (2011) *The Total Costs of Soils Degradation in England and Wales. Project Report to Defra*. Cranfield University.

Hellin, J. (2013) The Future of Mountain Agriculture. , pp. 39–50.

de Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P. & Worth, T.C. (2006) Volume 4, Chapter 11 - N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. In: *IPCC Guidelines for National Greenhouse Gas Inventories*.

Lal, R. (2004) Soil carbon sequestration to mitigate climate change. *Geoderma* 123(1–2), pp. 1–22.

Lanini, W.T., Orloff, S.B., Vargas, R.N., Orr, J.P., Marble, V.L. & Grattan, S.R. (1991) Oat Companion Crop Seeding Rate Effect on Alfalfa Establishment, Yield, and Weed Control. *Agronomy Journal* 83(2), p. 330. Available at: https://www.agronomy.org/publications/aj/abstracts/83/2/AJ0830020330.

Macleod, M., Eory, V., Gruère, G. & Lankoski, J. (2015) Cost-Effectiveness of Greenhouse Gas Mitigation Measures for Agriculture: A Literature Review. (89). Available at: http://dx.doi.org/10.1787/5jrvvkq900vj-en.

Macleod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P. & Moxey, A. (2010) Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agricultural Systems* 103(4), pp. 198–209. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0308521X1000003X [Accessed: 28 October 2014].

Macleod, M., Moran, D., Mcvittie, A., Rees, B., Jones, G., Harris, D., Antony, S., Wall, E., Eory, V., Barnes, A., Topp, K., Ball, B., Hoad, S. & Eory, L. (2010) *Review and update of UK marginal abatement cost curves for agriculture*. Edinburgh.

Martineau, H., Wiltshire, J., Webb, J., Hart, K., Keenleyside, C., Baldock, D., Bell, H. & Watterson, J. (2017) Effective performance of tools for climate action policy - meta - review of Common Agricultural Policy (CAP) mainstreaming. (340202), p. 287.

McVittie, A., Ghaley, B.B., Molnar, A., Dibari, C., Karaczun, Z. & Sanchez, B. (2014) *Report on the cost-effectiveness of SOC measures*. Edinburgh, Scotland.

Moran, D., MacLeod, M., Wall, E., Eory, V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, B., Moxey, A., Williams, A. & Smith, P. (2008) *UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050*. Edinburgh.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J., Chenu, C., Colnenne-david, C., Cara, S. De, Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-launay, F., Hassouna, M., Hénault, C., Jeu, M., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L. & Chemineau, P. (2017) Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. *Environmental Science & Policy* 77(April), pp. 130–139.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoît, M., Butault, J.P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.H., Klumpp, K., Metay, A., Moran, D. & Pardon, L. (2013) How can French agriculture contribute to reducing greenhouse gas emissions? Synopsis of the study report. (July), p. 92.

Poeplau, C. & Don, A. (2015) Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. *Agriculture, Ecosystems and Environment* 200, pp. 33–41. Available at: http://dx.doi.org/10.1016/j.agee.2014.10.024.

Posthumus, H., Deeks, L.K., Rickson, R.J. & Quinton, J.N. (2015) Costs and benefits of erosion control measures in the UK. *Soil Use and Management* 31(September), pp. 16–33.

Ruis, S.J. & Blanco-Canqui, H. (2017) Cover crops could offset crop residue removal effects on soil carbon and other properties: A review. *Agronomy Journal* 109(5), pp. 1785–1805.

Rutledge, S., Wall, A.M., Mudge, P.L., Troughton, B., Campbell, D.I., Pronger, J., Joshi, C. & Schipper, L. a. (2017) The carbon balance of temperate grasslands part I: The impact of increased species diversity. *Agriculture, Ecosystems and Environment* 239, pp. 310–323. Available at: http://dx.doi.org/10.1016/j.agee.2017.01.039.

Schulte, R., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Lalor, S., Lanigan, G., Brien, D.O., Shalloo, L. & Thorne, F. (2012) A Marginal Abatement Cost Curve for Irish Agriculture. (April), p. 32.

Wittwer, R.A., Dorn, B., Jossi, W. & Van Der Heijden, M.G.A. (2017) Cover crops support ecological intensification of arable cropping systems. *Scientific Reports* 7(January), pp. 1–12. Available at: http://dx.doi.org/10.1038/srep41911.