MM17: Reducing Soil Compaction

Measure category

Cropland management: water and soil management

Overview

Excessive compaction of soil is likely to contribute to greater net N_2O emissions, and to reduce the capacity of soil to be a net CH_4 sink (Eory et al., 2015). Reduced root penetration and primary productivity (Hallett et al., 2012; Chamen et al., 2015) is also likely to reduce soil C inputs, which may reduce CO_2 sequestration in soil. Preventing soil compaction on arable land involves ensuring minimal traffic, especially when the soil is wet, and reducing tillage of wet soils (Frelih-Larsen et al., 2014). On grassland, soil compaction typically results from excessive stocking density, particularly during wetter periods.

Mitigation summary

Effect on GHG categories*	**Rating**	**Notes**
Enteric CH_4		
Manure CH_4		
Manure N_2O	-	
Soil N_2O: residue N		
Soil N_2O: applied N	-	
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	High	
Cost-effectiveness**	Low to moderate	
Confidence in cost-effectiveness	High	

*   ”-“ 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
16. Improving/renovating drainage on mineral soils	Reduction of soil waterlogging will reduce costs associated with this measure. Reduction of soil compaction will reduce surface runoff intensity.
10. Precision farming	Will increase the efficacy of elements of this measure, especially tramline management, reducing the requirement for remediation and hence reducing costs.
18. Move stock off wet land	Will reduce soil compaction and hence reduce requirements for remediation
19. Sustainable increase stocking density & grazing management	Will impact soil compaction and hence impact requirements for/effectiveness of remediation
14. Low emissions slurry spreading	Will reduce nutrient runoff, potentially reducing the additional abatement effect of this measure.
11. Avoiding N excess	Will reduce nutrient runoff, potentially reducing the additional abatement effect of this measure.
12. Nitrification inhibitors	Will reduce nutrient runoff, potentially reducing the additional abatement effect of this measure.

Inclusion in other marginal abatement cost curves

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

*Preventing soil compaction/loosening compacted soil was considered for these MACCs, but excluded due to small abatement potential.

For loosening compacted soils and preventing soil compaction, Eory et al. (2015) estimated a total abatement potential of 225 kt CO_2-eq at a cost of £1 tonne CO_2-eq^{-1}.

What does the measure entail?

Compaction is caused when pressure from traffic or livestock causes damage to soil pores (Chamen et al., 2015). When considering soil compaction, it is useful to classify the soil into three layers of increasing depth (Alakukku et al., 2003; Chamen et al., 2015);

1. The **annually cultivated layer** which is loosened annually by typical cultivation instruments in tilled soil.
2. The **pan layer**, directly below the cultivated layer, which may become compacted during normal cultivation.
3. The **unloosened subsoil layer**, which exists below the pan layer. It is typically unaffected by compaction, and loosening it is undesirable, as this may make the soil more vulnerable to future compaction.

Graves et al. (2011) identify three key areas where soil compaction may occur in agricultural land; these are:

1. The **headland**. This is the turning area for machinery at either end of a field, and is typically not cultivated or planted.
2. The **tramline** area. These are the ‘tracks’ utilised by agricultural machinery in the field area during the cultivation and harvest of crops.
3. The **general field area**. This is the remainder of the field not specified as headland or tramlines.

This measure can be divided into two categories; a) remediating soils which have become compacted, and b) avoiding soil compaction on vulnerable soils. The following options are considered by Chamen et al. (2015) as pathways to these goals:

Remediation of compacted soils

- **Subsoiling**. This involves cultivation of the soil to a depth greater than that typically reached by typical implements e.g. mouldboard ploughs. The aim of this measure is to loosen the pan layer, i.e. below that reached by typical tillage instruments.
- **Targeted subsoiling.** Subsoiling focused specifically on affected areas.
- **Ploughing**. Ploughing with typical tillage instruments, aiming to alleviate compaction in the upper soil layers. Effective only where compaction exists in the upper layer.

Prevention of compaction of vulnerable soils

- **Low ground pressure tyres.** Tyres with a wide profile and low inflation pressure, increasing the vehicle footprint and reducing ground pressure.
- **Tracked tractors.** Tractors with rubber ‘caterpillar’ tracks rather than tyres, which increase the vehicle footprint and reduce ground pressure.
- **Controlled traffic farming**. Confinement of all agricultural traffic to the smallest possible area of permanent traffic lanes.

Soil compaction is long-lasting and difficult to correct (Alakukku et al., 2003); it is therefore desirable to prevent, rather than remediate, soil compaction wherever possible. Fig. 1 summarises the causes of soil compaction together with the pathways to its remediation and prevention.

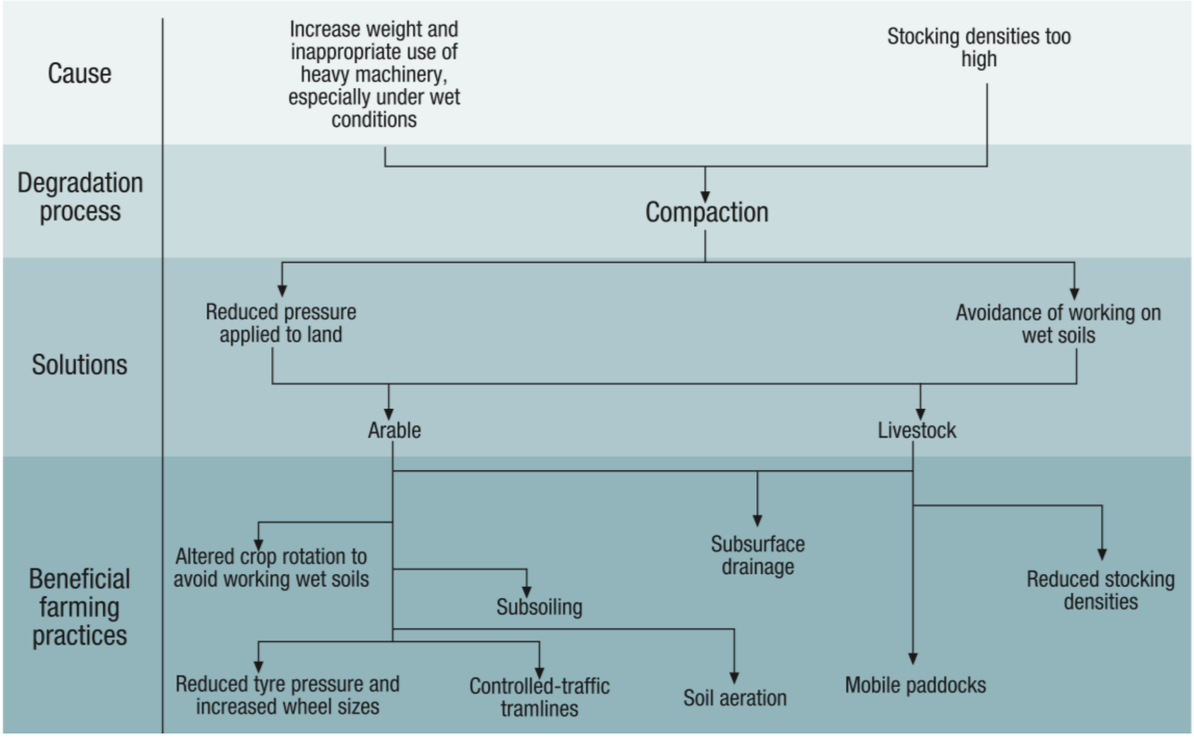

Fig.1. Concept diagram of causes, pathways and solutions for soil compaction. Source: Gay et al. (2009).

Abatement potential

Impacts on N_2O emissions
Previous MACC assessments (Moran et al., 2008; Eory et al., 2015) assume a reduction in direct N_2O emissions in the form of a reduction in the EF_1 emission factor (de Klein et al., 2006), relating to direct emissions of N_2O from applied nitrogen. The magnitude of this reduction varies, and estimates from the literature (as reported by Eory et al., 2015) vary from around 6% (Moran et al., 2008) up to 65% (Ball et al., 2000). Based on a presumed EF_1 reduction of 40%, Eory et al. (2015) calculated an abatement rate of 0.44 and 0.32 tonnes CO_2-eq ha^{-1} year^{-1} for arable an grazing land respectively. The Farmscoper tool (Gooday et al., 2014, 2015) assumes a reduction of 0—10% (typically 2%) for direct N_2O emissions, and 10—50% (typically 25%) reductions in leached N resulting in indirect N_2O emissions where soil compaction is alleviated, and 2—25% (typically 10%) reductions in all N_2O emissions resulting from use of correctly inflated (low ground pressure) tyres.

Impacts on diesel CO_2 and embedded emissions
Soil compaction in tillage land increases the fuel usage required to perform cultivation operations (e.g. ploughing) (Graves et al., 2011; Eory et al., 2015; Chamen et al., 2015). The extent of this increase varies depending on the operation and soil type, though compacted clay soils have the greatest detrimental impact on fuel efficiency. Based on estimates of required field operations, fuel usage and compaction impact, Graves et al. (2011) estimate fuel use increases of 87%, 60%, 29% and 29% for tillage operations on compacted clay, silt, sand and peat soils respectively.

Compaction of soils also increases nutrient runoff, reducing the amount available to the crop. Literature estimates (Graves et al., 2011; Chamen et al., 2015) suggest that increases in leaching where soils are compacted are around 20% for N, and 4% for P_2O_5 and K_2O. Alleviation of soil compaction reduces this runoff; as well as positive environmental impacts (e.g. reduced eutrophication), this reduces the overall application rate required, reducing emissions burdens associated with a) direct and indirect N_2O emissions stemming from applied N, and b) 'embedded' production emission associated with the industrial production of synthetic fertilisers.

Active alleviation of compacted soil (see section #RSC.7 for detail) is likely to involve operations which require additional diesel usage; the emission impacts of this should also be accounted for and balanced against emissions abatement resulting from reduced compaction.

Impacts on CH_4 emissions and removals
Whilst soil compaction limits the potential of soils to act as a net CH_4 sink, this is difficult to quantify accurately. All compiled relevant assessments (Graves et al., 2011; Gooday et al., 2015; Eory et al., 2015; Chamen et al., 2015) assume no or CH_4 impacts for either cultivation of compacted tillage soils, or loosening of compacted grassland; mitigation potential is derived solely from reduction of N_2O emissions.

Impacts on CO_2 sequestration by soil
Previous assessments of the abatement potential of soil compaction remediation and prevention have assumed a net neutral impact on soil carbon stocks (Moran et al., 2008; Graves et al., 2011; Gooday et al., 2015; Eory et al., 2015). The key pathway by which soil compaction is likely to influence soil organic carbon stocks is via reduction in primary productivity, particularly below ground; as a reduction in C input, this is likely to reduce soil C stocks. Remediation or prevention of soil compaction is therefore likely to have either a net neutral or positive effect on carbon stocks. An exploratory analysis based on literature data (McSherry & Ritchie, 2013; Abdalla et al., 2018) found a weak negative correlation between soil bulk density change (in response to grazing pressure) and soil organic carbon stocks (Fig. #RSC.2).

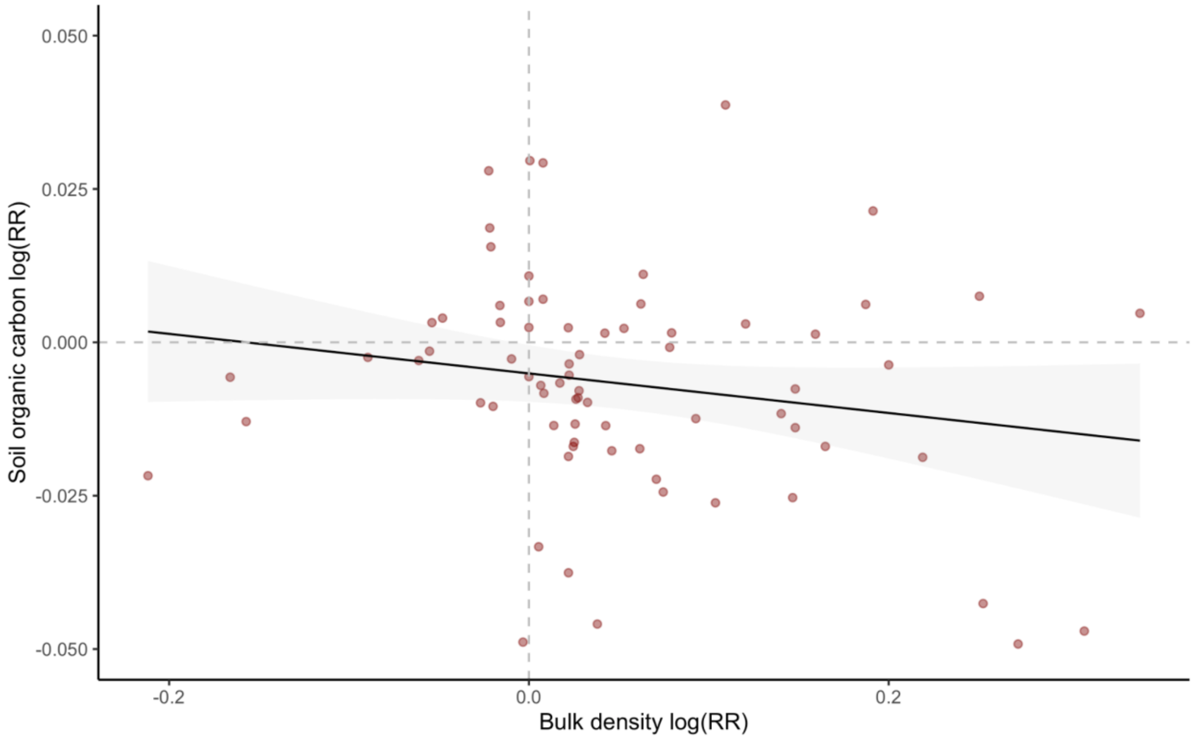

Fig. 2. Relationship between bulk density change (log response ratio) and soil organic carbon stock change (log annual response ratio) in response to different stocking densities on global grasslands. Linear model fit is not significant (p > 0.05, R^2 = 0.036). Data sourced from literature cited in the meta-analyses of McSherry & Ritchie (2013) and Abdalla et al. (2018).

The relationship showed in Fig.2 is consistent with the majority of literature accounts in that there is a tentative indication of a link between bulk density increase and soil carbon increase, but this is largely overshadowed by other more influential variables.

Implementation costs

Costs of remediating and avoiding soil compaction

Chamen et al. (2015) identify subsoiling, targeted subsoiling and ploughing as remediation strategies for soil compaction, and low tyre pressures, tracked tractors and controlled traffic systems for avoidance of compaction (see #RSC.5). Each of these measures has an associated cost of implementation.

Posthumus et al. (2015) estimate costs of £15—25 ha^{-1} $year^{-1}$ to prevent soil compaction in field cultivation tramlines (i.e. vehicle wheelings through the planted area of the field). Post-harvest cultivation of compacted soils with discs or tines is estimated to cost £4 ha^{-1} $year^{-1}$ (Cuttle et al., 2007). Eory et al. (2015) report costs of £60 ha^{-1} $year^{-1}$ for alleviating deep compaction on tilled land, £4—25 ha^{-1} $year^{-1}$ for alleviating topsoil compaction on tilled land, and £11—40 ha^{-1} $year^{-1}$ for alleviating compacted grassland. Chamen et al. (2015) estimate costs of £20—56 ha^{-1} $year^{-1}$ for compaction remediation strategies, and £0—21 ha^{-1} $year^{-1}$ for avoidance strategies; variation in this estimate stems from technology type and soil type. Controlled traffic tramlines (estimated at £0 ha^{-1} $year^{-1}$ by Chamen et al., 2015) may be implemented without the integration of precision farming technologies, though their precision and effectiveness is likely to be lower than were this technology to be utilised (Gay et al., 2009); it can be assumed that this would increase the cost of their implementation.

Benefits of remediating and avoiding soil compaction

Direct farm costs stem from yield losses, reduced nutrient use efficiency, and restricted land access (Chamen et al., 2015). These costs therefore take the form of both impacts to revenue (lower yields), and increases in production costs (higher fertiliser use and difficult land access).

Yield losses resulting from soil compaction stem from a) increased penetration difficulty for roots, b) reduced soil water, and c) decreased aeration (Chamen et al., 2015). Losses to arable crops measured by Håkansson & Reeder (1994) averaged 3.7% over a 12-year recovery period[1]; at the end of this period, in the absence of further compaction, yields had recovered to c. 99% of non-compacted controls. Graves et al. (2011) estimated overall yield losses on UK farmland of 3—6%, 3—5% and 1—3% on compacted horticultural, arable and grassland respectively. For compacted land, this translates to crop yield impacts of 17% in clay soils, 25% in sandy soils, and 4% in medium, shallow and peaty soils.

Nutrient losses result in higher required rates of fertiliser application for the same yield response. Graves et al. (2011) estimate costs of £1.12—3.51 ha^{-1} $year^{-1}$ stemming from nutrient losses resulting from compaction.

Diesel usage reductions for tillage operations (reported in #RSC.6) will also contribute to reduced production costs for crops. Chamen et al. (2015) report diesel reductions equivalent to £3.29—11.21 ha^{-1} $year^{-1}$ (assuming the authors reported diesel price estimate of £0.70 $litre^{-1}$) resulting from complete alleviation of soil compaction.

Applicability, current uptake and potential additional maximum uptake
Eory et al. (2015) assessed the published literature which could provide an indication as to the baseline levels of soil compaction and uptake of compaction mitigation strategies. The authors comment that there is no definitive source from which estimates of compaction or mitigation can be drawn; this does not appear to have changed in the time since publication of this report.

The 2012 Farm Practices Survey (DEFRA, 2013) reported soil compaction rates 51%, 43% and 12% for the top 12", plough depth and the whole soil profile respectively. These percentages relate to surveyed land; soil compaction surveys were typically conducted only where compaction was obvious in the majority of cases, meaning these values are not representative of farming land as a whole. Eory et al. (2015) interpreted this to suggest that for the area affected by compaction, 45% was topsoil compaction only, and 55% was deep compaction. There has been no update to the Farm Practices Survey since 2012 which included assessment of soil compaction rates.

Graves et al. (2011) assume that 38—42% of agricultural and horticultural land in England and Wales is 'at risk of compaction'; this estimate is subsequently used by the authors to scale a national-level calculation of soil compaction costs, with the associated implication that this value can be interpreted as unalleviated compaction. Eory et al. (2015) interpreted this slightly differently, to suggest that 20% of agricultural land (i.e. arable and grassland) was susceptible to compaction but already undergoing good practice to alleviate this, and 20% was in need of compaction remediation (i.e. additional uptake is 20%).

Assumptions used in MAC
The following assumptions were employed in the marginal abatement cost assessment of remediating and preventing soil compaction.

1. **Scenario delimitation.** Based on the main data sources for this synthesis (Graves et al., 2011; Chamen et al., 2015), the scenarios assessed were defined based on soil

[1] Data extracted from graphic using the *digitize* R package (Poisot, 2011).

type (clay, sand, silt or peat) and land use (horticulture, arable intensive, arable extensive, improved grassland, unimproved grassland). Relative land areas belonging to these categories were taken from Graves et al. (2011) and scaled to totals based on more recent UK-wide data from Defra (2018a).

2. **Baseline compaction and uptake**. Baseline compaction was defined by land use type using data extracted from Graves et al. (2011). Existing uptake was nominally set at 20% (Eory et al., 2015). These authors also assumed an uptake rate of zero at time of publishing, indicating no directional trend in uptake.
3. **Mitigation strategies.** The three remediation strategies (subsoiling, targeted subsoiling and ploughing) and three prevention strategies (low ground pressure tyres, tracked tractors and controlled traffic farming) defined by Chamen et al. (2015) were included in the assessment. Based on Eory et al. (2015), it was assumed that alleviating soil compaction required (for soils at risk of compaction) the implementation of a remediation strategy every 10 years, and the implementation of a prevention strategy annually. Based on the interpretation by Eory et al. (2015) of data published by the Farm Practices Survey (DEFRA, 2013), it was determined that 45% of compacted land was compacted in the top layer, while 55% was compacted in deeper layers. The former could be remediated by ploughing, while the latter required subsoiling.
4. **Emissions abatement.** The following emissions categories were assumed to be associated with alleviation of soil compaction:
    a. **Direct N_2O emissions (EF_1).** For applied N, the direct emission factor (EF) was deemed to be increased by values summarised by Eory et al. (2015). Emissions were calculated based on 5-year-average fertiliser and manure application rates from the British Survey of Fertiliser Practice (Defra, 2018b) and methodology from the IPCC Guidelines (de Klein et al., 2006). Uncertainty in application rates and emission factors was accounted for in the model.
    b. **Nutrient losses (direct and indirect N_2O, and CO_2-eq).** Soil compaction was deemed to increase the leached fraction of nutrients by 2—20%, depending on soil type (Graves et al., 2011). Baseline N losses from leaching were calculated according to de Klein et al. (2006), while baseline losses of P_2O_5 and K_2O were assumed to be 4% (Graves et al., 2011). For the lost fractions, embedded emissions from fertiliser production were calculated according to EFs from Kool et al. (2012), and direct and indirect N_2O emissions from N according to de Klein et al. (2006). Uncertainties in these emissions were accounted for in the model.
    c. **Diesel usage (CO_2).** Additional diesel usage caused by soil compaction was calculated based on estimates by Graves et al. (2011). Diesel required to implement the mitigation strategies (subsoiling and ploughing) was calculated based on reported fuel consumption figures from SAC (2017). The emissions associated with both diesel usage categories were calculated using a UK-specific EF (DEFRA/DECC, 2015).
5. **Financial costs.** The following costs associated with implementation of the mitigation strategies were accounted for:
    a. **Remediation operations cost.** Cost for contractors to perform subsoiling and ploughing operations were sourced from SAC (2017), along with associated uncertainties. Although some farmers may perform these operations themselves, the cost for DIY remediation is likely to have parity with contractor

costs. Diesel costs (not included in contracting) were also estimated based on data from SAC (2017). These were scaled to the area of compacted land, and annualised using an annuity factor with a discount rate of 3.5%.

   b. **Prevention operations cost**. The cost of implementing compaction prevention strategies was sourced from Chamen et al. (2015). The difference between cost estimates for different strategies was characterised as an uncertainty in the model.

6. **Financial savings.** Costs associated with nutrient losses and additional diesel usage were based on the estimates derived for emissions estimation in (4b) and (4c). The prices of nutrients and diesel were based on data from SAC (2017).
7. **Abatement effectiveness**. The effectiveness of the suggested mitigation actions in reducing soil compaction is one of the most uncertain elements of this calculation. Chamen et al. (2015) consider effectiveness estimates of 25—100% for each remediation/alleviation strategy. Actual effectiveness is likely to vary between scenarios, soil types and mitigation strategies, and is not necessarily 100%; for example, Hallett et al. (2012) estimate that controlled traffic farming may only reduce compaction by 5—10%. For combined remediation and prevention measures, we assume (based on Chamen et al., 2015) an effectiveness of *BE* = 75%, *Min* = 25%, *Max* = 100%. As both financial and emissions impact categories scaled linearly with compaction reduction, this parameter acted as a scaling factor for the overall cost savings and abatement of the measure.

The GHG abatement potential of combined soil compaction alleviation strategies varied from 12—64 kg CO_2-eq ha^{-1} annually for total agricultural area (i.e. not only on compacted land) (Table #RSC.5). Considering only compacted land, this abatement rate rises to 68—236 kg CO_2-eq ha^{-1} year^{-1}. In both cases, the highest rates per hectare were seen on intensive arable land (referring to land used to grow potatoes, sugar beets and other root crops; see Graves et al., 2011 for derivation). Lowest abatement rates were seen on grassland, especially unimproved grassland. These differences are largely due to the presence of tillage operations, the fuel efficiency of which is negatively impacted by compaction, on arable land. The rates of nutrient application, especially N fertiliser, also influences abatement rates. Considerable uncertainty was also present within categories, though abatement was always positive (i.e. a net GHG reduction).

Table 5. Greenhouse gas abatement rates for combined soil compaction alleviation strategies.

Land use	**Abatement rate(kg CO_2-eq ha^{-1} year^{-1})**			
	Mean	**Std. Dev.**	**2.5% C. I.**	**97.5% C. I.**
Arable extensive	52	39	11	150
Arable intensive	64	36	20	152
Grassland improved	28	24	1	90
Grassland unimproved	12	13	-2	46
Horticulture	30	22	5	86

Summarising the results of Table 5 yields an overall average abatement rate of 36.7 kg CO_2-eq ha^{-1} year^{-1} for total agricultural area, and 176.5 kg CO_2-eq ha^{-1} year^{-1} for compacted soil only.

Measure costs varied by land use and soil type (Table 6, Fig.3). This factor strongly influenced yield and diesel impacts, which were the main revenue streams following implementation. Costs indicate that it is typically cost-effective to implement compaction alleviation on most agricultural and horticultural land, especially on clay soils. The very low costs for horticulture stem from the high value and fieldwork requirements of this crop category; these may be somewhat overestimated and are subject to high uncertainty, but reflect conclusions of Graves et al. (2011).

Table 6. Costs of implementing combined soil compaction alleviation measures. Costs are presented as mean ± 1 std. dev. and are based on the entire agricultural area (rather than just compacted area).

Land use	**Measure implementation cost (2017£ ha^{-1} year^{-1})**			
	Clay	**Silt**	**Sand**	**Peat**
Arable extensive	-4 ± 7	3 ± 6	3 ± 6	3 ± 6
Arable intensive	-54 ± 17	-35 ± 12	-46 ± 15	-59 ± 18
Grassland improved	5 ± 6	12 ± 6	11 ± 6	11 ± 6
Grassland unimproved	8 ± 6	12 ± 6	11 ± 6	12 ± 6
Horticulture	-283 ± 70	-134 ± 35	-209 ± 52	-134 ± 35

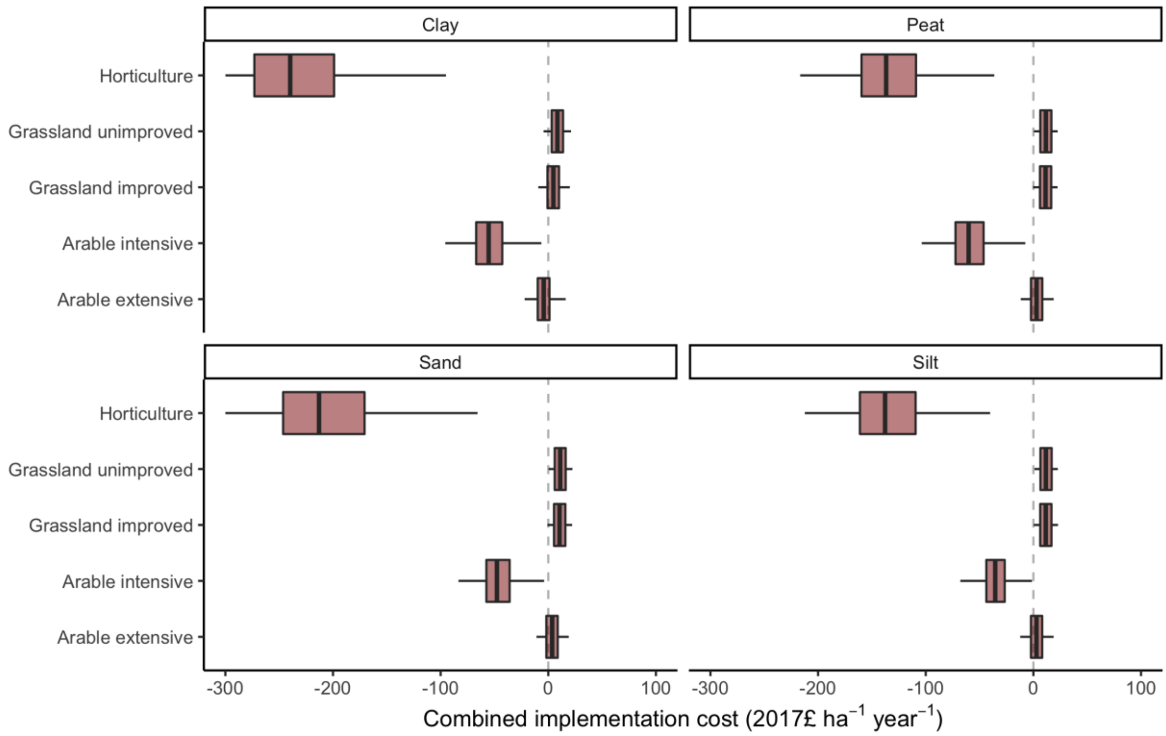

Fig.3. Estimated implementation cost for combined soil compaction alleviation strategies.

The marginal abatement cost (MAC) of GHG mitigation via soil compaction was variable depending on land use and soil type (Fig.4, Table.7). The MAC was consistently below zero for horticulture and intensive arable production; inflated negative values for horticulture stemmed from a combination of low abatement rates and negative abatement costs. Extensive arable (which includes cereal and oilseed production) is variable, with the greatest efficacy being shown on clay soils, but consistently with around half or more of scenarios showing abatement at less than the social cost of carbon (SCC).

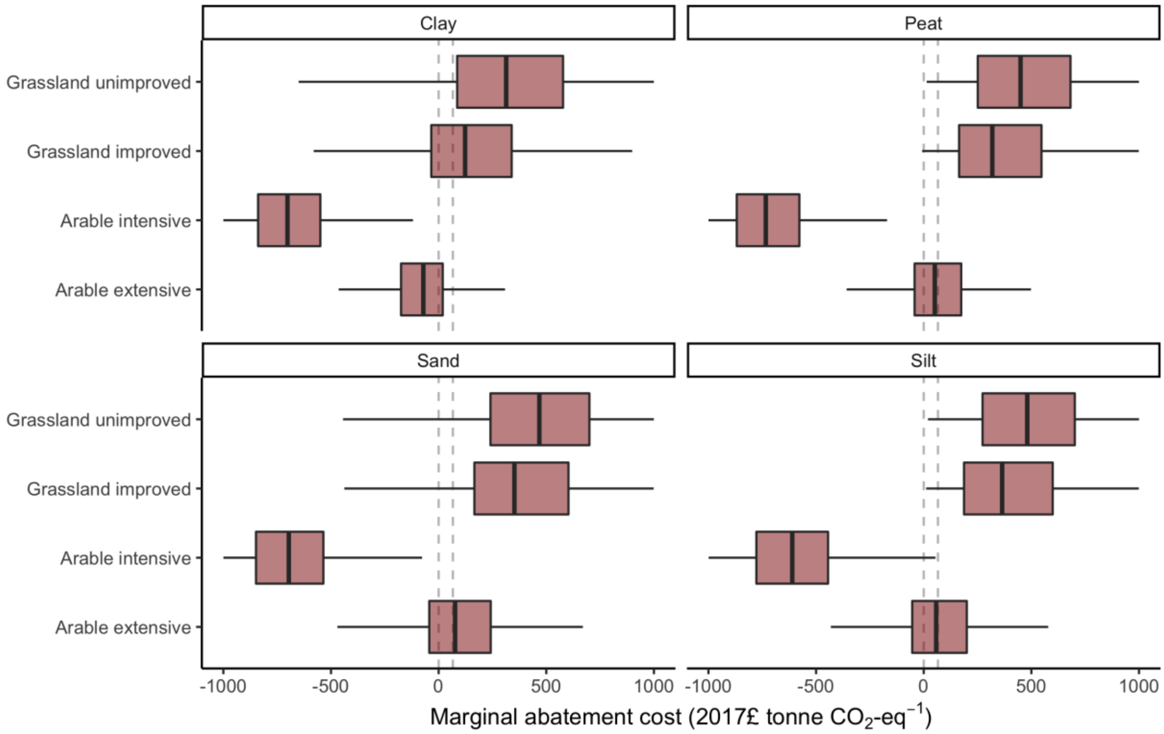

Fig. 4. Marginal abatement cost of combined soil compaction alleviation strategies (*x*-axis truncated at -£1000; the horticulture LU category is removed due to an inflated negative MAC).

Table 7. Marginal abatement cost for soil compaction alleviation. Data is presented in the form *Mean* [*Fraction* < *0* | *Fraction* < *SCC*]. The SCC is set at £66.10 (Department for Business Energy & Industrial Strategy, 2018).

Land use	Clay	Silt	Sand	Peat
Arable extensive	-66 [0.71 | 0.82]	133 [0.36 | 0.51]	162 [0.33 | 0.46]	110 [0.36 | 0.53]
Arable intensive	-795 [1 | 1]	-786 [1 | 1]	-907 [1 | 1]	-1047 [1 | 1]
Grassland improved	348 [0.28 | 0.38]	1291 [0 | 0.04]	2890 [0 | 0.06]	749 [0 | 0.07]
Grassland unimproved	2640 [0.11 | 0.15]	9205 [0 | 0.01]	8380 [0 | 0.02]	2945 [0 | 0.02]
Horticulture	-10247 [1 | 1]	-8092 [1 | 1]	-13754 [1 | 1]	-6329 [1 | 1]

Scaling per-hectare abatement rates to total land area, total maximum potential abatement was calculated at 475 kt CO_2-eq. Limiting abatement to that achievable below the SCC, cost-effective abatement potential was lower at 317 kt CO_2-eq. The vast majority of this was located on clay soils used for extensive arable production, with lesser amounts on improved grassland and other soil types (Fig.5).

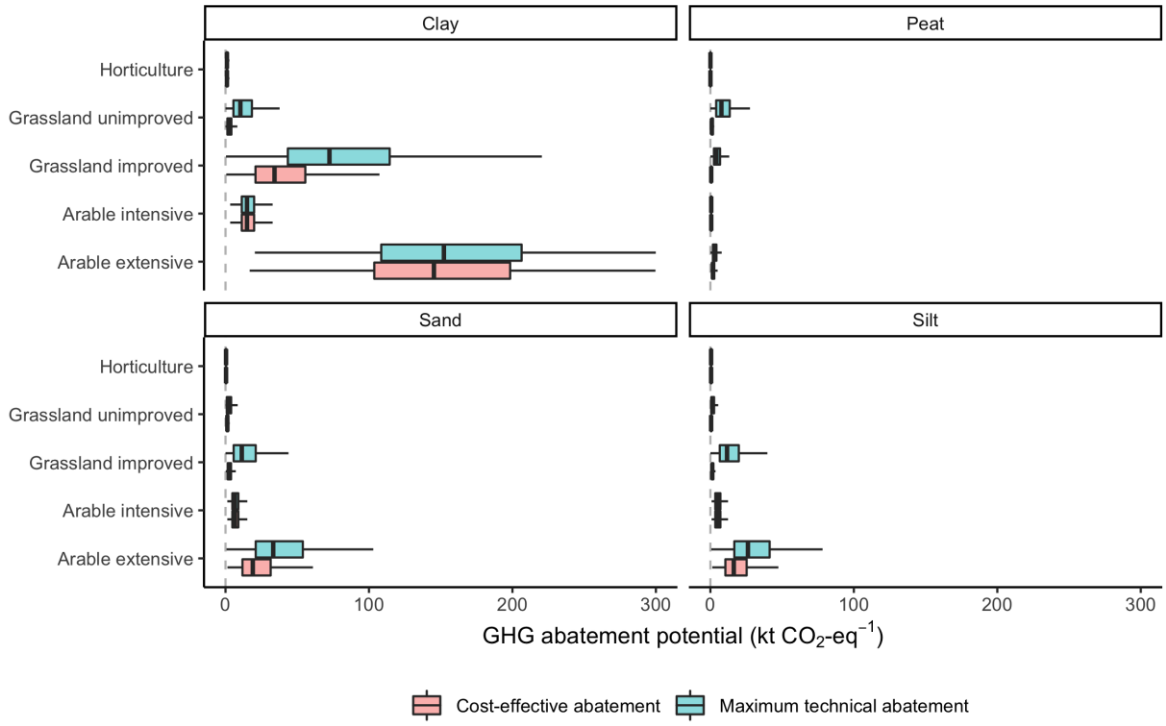

Fig.5. Maximum technical abatement potential and cost-effective abatement potential for combined soil compaction alleviation measures.

Ancillary effects

In addition to GHG mitigation, alleviation of soil compaction reduces nutrient leaching, with associated positive impacts for eutrophication and acidification (Williams et al., 2006). This will have associated ecosystem benefits including water quality and biodiversity (Wittwer et al., 2017). It is also likely to improve soil structure and water holding capacity (Graves et al., 2011), reducing flooding risk and providing agronomic benefits. The reduction in surface runoff is also likely to reduce erosion; (Wiltshire (2014) estimates that compaction alleviation may reduce erosion by 5% in sandy and clay soils.

Identified implementation challenges and barriers

Rainfall and drainage are significant factors in soil compaction, with waterlogged soils substantially more susceptible (Graves et al., 2011; Chamen et al., 2015). Weather is unpredictable, and the necessity of driving on or working waterlogged soils is likely to be an important but effectively uncontrollable factor in efforts to avoid or alleviate soil compaction. Controlled traffic farming is a promising measure in prevention of compaction, but may be challenging to implement. Without assistive technology, the skill of the operator is a major factor in the effectiveness of this measure (Hallett et al., 2012; Chamen et al., 2015). Use of the technology (e.g. GPS, auto-steering) required to negate this skill requirement is likely to be a skill in and of itself.

References

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M. & Smith, P. (2018) Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agriculture, Ecosystems and Environment* 253(May 2017), pp. 62–81. Available at: http://dx.doi.org/10.1016/j.agee.2017.10.023.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van Der Linden, J.P., Pires, S., Sommer, C. & Spoor, G. (2003) Prevention strategies for field traffic-induced subsoil compaction: A review Part 1. Machine/soil interactions. *Soil and Tillage Research* 73(1–2), pp. 145–160.

Ball, B.C., Horgan, G.W. & Parker, J.P. (2000) Short-range spatial variation of nitrous oxide fluxes in relation to compaction and straw residues. *European Journal of Soil Science* 51(4), pp. 607–616.

Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B. & Hallett, P.D. (2015) Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil and Tillage Research* 146(PA), pp. 10–25. Available at: http://dx.doi.org/10.1016/j.still.2014.09.011.

Cuttle, S.P., Macleod, C.J.A., Chadwick, D.R., Scholefield, D., Haygarth, P.M., Newell-Price, P., Harris, D., Shepherd, M.A., Chambers, B.J. & Humphrey, R. (2007) *An Inventory of Methods to Control Diffuse Water Pollution from Agriculture. Prepared as part of Defra Project ES0203*. IGER, ADAS.

DEFRA/DECC (2015) *GHG Conversion Factors for Company Reporting*.

Defra (2018a) 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.

Defra (2018b) *The British Survey of Fertiliser Practice: Fertiliser use on farm crops for crop year 2017*. York, England.

DEFRA (2013) Farm Practices Survey Autumn 2012 – England. (March). Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/181719/defra-stats-foodfarm-environ-fps-statsrelease-autumn2012edition-130328.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.

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*.

Gay, S.H., Louwagie, G., Sammeth, F., Ratinger, T., Maréchal, B., Prosperi, P., Rusco, E., Terres, J.-M., Velde, M. van der, Baldock, D., Bowyer, C., Cooper, T., Fenn, I., Hagemann, N., Prager, K., Heyn, N. & Schuler, J. (2009) *Final report on the project ' Sustainable Agriculture and Soil Conservation (SoCo)'*. Louwagie, G., Gay, S. H., and Burrell, A. eds. Seville, Spain: European Commission Joint Research Centre.

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.

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.

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.

Håkansson, I. & Reeder, R.C. (1994) Subsoil compaction by vehicles with high axle load-extent, persistence and crop response. *Soil and Tillage Research* 29(2–3), pp. 277–304.

Hallett, P., Balana, B., Towers, W., Moxey, A. & Chamen, T. (2012) Studies to inform policy development with regard to soil degradation. Subproject A: Cost curve for mitigation of soil compaction. 1305(Cte 1024), p. Defra SP1305 (CTE 1024), 1-97.

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*.

Kool, A., Marinussen, M. & Blonk, H. (2012) *LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: GHG Emissions of N, P and K fertilizer production*. Wageningen.

McSherry, M.E. & Ritchie, M.E. (2013) Effects of grazing on grassland soil carbon: A global review. *Global Change Biology* 19(5), pp. 1347–1357.

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.

Poisot, T. (2011) The digitize Package : Extracting Numerical Data from Scatterplots. *R Journal* 3(June), pp. 25–26.

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.

SAC (2017) *Farm Management Handbook 2017/18*. 37th ed. Craig, K. ed. SAC Consulting.

Williams, A.G., Audsley, E. & Sandars, D.. (2006) *Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities*. Main Report. Defra Research Project IS0205. Bedford: Cranfield University and Defra. Available on www.silsoe.cranfield.ac.uk, and www.defra.gov.uk.

Wiltshire, J. (2014) Assessment of the Effectiveness , Impact and Cost of Measures to Protect Soils. (1).

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.