**MM03 Optimisation of soil pH**

**Category**
Cropland management: Agronomy

**Overview**
Calcium carbonate rich soils provide free calcium, which binds with OM to form complex aggregates, providing soil carbon with physical protection from microbial decomposition (Tu et al., 2018). Soil pH is therefore highly important in the spatial distribution of SOC (Tu et al., 2018), with alkaline soils capable of supporting greater concentrations. Optimising soil pH generally consists, therefore, of reducing soil acidity through application of alkaline calcium or magnesium carbonates or oxides, known as lime, or reducing sodicity via gypsum applications (Hamilton et al., 2007).

Amendments (i.e. lime or gypsum) must be purchased on an ongoing basis to implement liming, and increased complexity of system management will also incur time costs. However, crop or grass yield improvements are likely to go some way towards offsetting this cost (Li et al., 2018). Dependent on baseline application rates, this measure may also reduce requirements for agrochemical nutrient inputs (Fornara et al., 2011).

Liming agricultural land may precipitate a number of GHG impacts. Pre-farm emissions are associated with the extraction and transportation of lime, and direct $CO_2$ emissions from fieldwork are likely to increase to facilitate application. In some circumstances, the inorganic C in lime ($CaCO_3$) may remain in long-term storage (Hamilton et al., 2007; Fornara et al., 2011), though lime application is typically considered a direct net source of C (de Klein et al., 2006). Lime application may, however, modify soil microbial communities (Goulding, 2016) and increase organic matter (OM) inputs (Fornara et al., 2011; Jokubauskaite et al., 2016) with the effect of increasing soil carbon stocks (Fornara et al., 2011). The change in microbial community may also alter the $N_2/N_2O$ ratio during denitrification, thereby affecting $N_2O$ emissions (Goulding, 2016).

**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 | - | Main effect in cropland is yield gap closure. |
| | | |
| **Confidence in mitigation effect**<br>Cropland<br>Grassland | <br>Low<br>High | <br>Unlikely to be net sink<br>Likely to be net sink |
| **Cost-effectiveness****<br>Cropland<br>Grassland | <br>NA<br>Moderate | |
| **Confidence in cost-effectiveness**<br>Cropland<br>Grassland | <br>NA<br>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 |
|---|---|
| Biological N fixation (legumes in rotations) | Increased viability of this measure where pH is optimised. Growth of legumes may acidify soils. |
| Catch/cover crops | Increased viability of this measure where pH is optimised |
| Agroforestry | Optimisation of pH may offset yield losses from this measure |
| Precision farming | This measure is likely to increase the AR and CE and reduce likelihood of high MAC for pH optimisation |
| Avoiding N excess | Optimisation of pH may change optimal implementation of this measure. Reduced application of ammonium based fertilisers may reduce soil acidity |
| Biological N fixation (grass-legume mixtures) | Optimisation of pH may increase legume viability |
| Sustainable increase stocking density & grazing management | Optimisation of pH may increase optimal stocking density |

**Inclusion in other marginal abatement cost curves**

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

*Restoration of degraded soils (including acidified soils) was considered, but rejected owing to limited applicability.

**What does the measure entail?**

Optimisation of soil pH typically involves the application of lime on land which is below the optimal pH for crop or grass growth. Optimal pH varies depending on the land use, type of crop grown, and soil type. Required lime application rates to optimise pH vary depending on soil type and on the difference between the existing soil pH and the target pH.

**Abatement**

Soil OC is likely to increase where pH is raised, though this response is complex and context specific (Li et al., 2018). In grassland, Fornara et al. (2011) report substantial increases in grassland soil C for limed treatments, both in fertilised and unfertilised swards. For cropland, Tu et al. (2018) report a positive correlation between pH and SOC ($r^2$ = 0.43); the model reported in this assessment suggests a non-linear relationship between pH and SOC, with an increase of 1 pH unit in the range pH 4—7 corresponding to an increase in SOC concentration of 0.82—1.97 g $kg^{-1}$. At a typical soil bulk density of 1.1 g $cm^{-3}$, and assuming pH impact to 20cm (Goulding, 2016) this roughly equates to an increase of 1.8—4.3 tonnes C $ha^{-1}$. Assuming a 20-year stabilisation period (de Klein et al., 2006), this equates to a sequestration rate of 330—788 kg $CO_2$-eq $ha^{-1}$ $year^{-1}$. Data reported by Kemmitt et al. (2006) also suggests a non-linear interaction between pH and SOC stocks in cropland, with maximum stocks occurring around pH 5.5—6 and reducing at both higher and lower pH values.

Direct $CO_2$ emissions from lime application means that lime can be (though is not necessarily) a net source of $CO_2$ (Hamilton et al., 2007). The relevant IPCC Guidelines for National GHG Reporting (de Klein et al., 2006) assume lime to be a $CO_2$ source, with an estimate of 0.0625—0.125 kg $CO_2$ kg $lime^{-1}$. This emission factor is directly related to the mass fraction of C in lime ($CaCO_3$), with the maximum emission assuming release of all molecular C to the atmosphere as $CO_2$ (de Klein et al., 2006; Fornara et al., 2011). This contrasts with the findings of Hamilton et al. (2007), who show that whilst lime can be a source of $CO_2$, it is more often a net sink. Fornara et al. (2011) also show that lime can be a C sink; the authors identify two pathways by which this can be the case. Lime may either a) increase carbonic acid ($HCO_3^-$) concentrations in soil water, sequestering 25-50% of lime C, or b) contribute to the movement of existing soil C from labile to humified pools, increasing its net storage time in the soil.

Changes in $N_2O$ emissions following lime application result from changes to the nitrification and denitrification processes. These effects are context-specific, with variable relationships between pH and the proportion of applied N emitted as $N_2O$ (Skiba et al., 1998; Russenes et al., 2016). However, since liming increases soil nutrient availability (ALA, 2011; Goulding, 2016), requirement for N application may decrease, which would result in a net reduction in $N_2O$. Lime application is not currently assessed in the existing methodology for GHG reporting (de Klein et al., 2006) as a net source of $N_2O$ emissions; for this reason, can be assumed to have a net neutral effect on $N_2O$ emissions.

Emissions associated with lime extraction (embedded emissions) have been estimated at 0.074 kg $CO_2$-eq kg lime$^{-1}$ (range 0.054—0.089 kg $CO_2$-eq kg lime$^{-1}$) (Kool et al., 2012).

**Cost-effectiveness**

Where pH is suboptimal, liming increases crop yield (Li et al., 2018; Holland et al., 2019). This effect is consistent regardless of other variables (e.g. lime material, rate, crop species, fertilisation practices), though the effect size may be mediated by these. Based on UK data, Holland et al. (2017) show that yield response to liming is roughly linear below 90% maximum yield. Field trials in the United Kingdom (ALA, 2011) reported yield increases of 3.6—9.2 tonnes ha$^{-1}$ for sugar beet and 0.2—0.7 tonnes ha$^{-1}$ for barley.

All variables which contribute to the cost-effectiveness of liming are highly dependent on baseline pH and lime application rates. Much less lime is applied in the UK than is required, and many soils are below optimum pH (Goulding, 2016). Combing agricultural soil pH data from PAAG (2016) with pH recommendations from Defra (2017) shows that around 39% of arable land and 52% of grazing land is below the recommended pH (Table 2). It is important to note that many upland organic (peaty) soils are naturally acidic. C turnover in these soils is typically limited by their acidity; increasing the pH of such soils increases productivity, but also increases microbial decomposition of existing stocks. Addition of lime to peaty soils may therefore result in a net loss of soil C (Bhogal et al., 2009; Moxley et al., 2014).

**Table 2.** Distribution of UK arable and grazing land in different pH ranges. Entries below recommended pH for land use (Defra, 2017) are highlighted **bold**. Data adapted from PAAG (2016).

| Soil pH range | < 5.0 | 5.00 — 5.49 | 5.50 — 5.99 | 6.00 — 6.49 | 6.50 — 6.99 | 7.00 — 7.49 | 7.50 — 7.99 | > 8.0 | Total % below threshold |
|---|---|---|---|---|---|---|---|---|---|
| % arable land in range | **1** | **4** | **12** | **22** | 24 | 16 | 14 | 8 | **39** |
| % grassland in range | **2** | **17** | **33** | 27 | 12 | 5 | 3 | 1 | **52** |

Agricultural lime is applied at a rate dependent on the pH differential (i.e. the difference between the existing pH of land and the recommended soil pH). Based on agricultural soil pH data from the PAAG (2016) (Table 2) and lime application rate recommendations from Defra (2017), the following lime application rates are estimated to be required to bring agricultural land to recommended pH (Table 3). These rates are linear, so can be used to calculate a weighted average application rate estimate across pH classes.

**Table 3.** Application rates (in tonnes $ha^{-1}$) required to bring UK crop and grazing land to recommended pH. Weighted average is calculated for all agricultural land, including that not estimated to require lime amendments. Data sources: PAAG (2016); Defra (2017).

| Soil pH range | < 5.0 | 5.00—5.49 | 5.50—5.99 | 6.00—6.49 | 6.50—6.99 | 7.00—7.49 | 7.50—7.99 | > 8.0 | Weighted average for land requiring lime | Weighted average for all land in category |
|---|---|---|---|---|---|---|---|---|---|---|
| Arable | 11.7—15.6 | 8.7—11.6 | 5.7—7.6 | 2.7—3.6 | 0 | 0 | 0 | 0 | 4.5—6 | 1.8—2.3 |
| Grassland | 5.8—8.7 | 3.8—5.7 | 1.8—2.7 | 0 | 0 | 0 | 0 | 0 | 2.6—3.9 | 1.4—2 |

The British Survey of Fertiliser Practice (Defra, 2018b) estimates that approximately 8.1% and 2.9% of arable and grazing land respectively receives lime. Based on the values reported in Table 2 (corroborated by Goulding, 2016), it can be estimated that around 31% and 49% of arable and grazing land respectively is in need of liming. In addition, comparison of estimated application rates (Table 4) with requirements (Table 3), it can be seen that even for land receiving lime, it is being underapplied.

**Table 4.** Estimated application rates of lime products for cropland and arable land in the United Kingdom. Adjusted rate incorporates an adjustment factor to convert to equivalent mass of ground lime. Data adapted from Defra (2018b).

| Land category | Product | Product application rate (kg dressed $ha^{-1}$) | Area receiving dressing (%) | Product adjustment factor* | Overall adjusted rate (kg dressed $ha^{-1}$) |
|---|---|---|---|---|---|
| Arable | Ground limestone | 4.2 | 5.5 | 1.0 | 4.2 |
| | Ground chalk | 3.7 | 0.4 | 1.1 | 4.1 |
| | Magnesian limestone | 4.9 | 0.8 | 0.5 | 2.5 |
| | Sugar beet lime | 5.7 | 0.3 | 1.0 | 5.7 |
| | Other | 0.6 | 1.0 | 1.0 | 0.6 |
| | All | 3.8 | 8.1 | NA | 3.6 |
| Grassland | Ground limestone | 3.9 | 2.1 | 1.0 | 3.9 |
| | Ground chalk | 2.9 | 0.0 | 1.1 | 3.2 |
| | Magnesian limestone | 4.6 | 0.4 | 0.5 | 2.3 |
| | Sugar beet lime | 3.8 | 0.0 | 1.0 | 3.8 |
| | Other | 1.1 | 0.3 | 1.0 | 1.1 |
| | All | 3.7 | 2.9 | NA | 3.4 |

*Adjustment factor based on data from https://aglime.org.uk/lime_calculator.php.

Based on the data presented in Tables 2—4, final assumptions for maximum technical uptake potential and implementation cost are presented in Table 5.

**Table 5.** Lime requirements, applications, and deficit for UK arable and grazing land. Land area estimates are taken from the June Agricultural Census (Defra, 2018a).

| **Land use** | **pH** | **Limed?** | **Area** | | **Lime required** | **Lime received** | **Lime deficit** | |
|---|---|---|---|---|---|---|---|---|
| | | | % land use | '000 ha | tonnes $ha^{-1}$ | tonnes $ha^{-1}$ | tonnes $ha^{-1}$ | kt |
| Arable | < 6.5 | No | 30.9 | 1474 | 4.5—6 | 0.0 | 4.5—6 | 6,633—8,844 |
| | | Yes | 8.1 | 386 | 4.5—6 | 3.6 | 0.9—2.4 | 338—918 |
| | > 6.5 | No | 61 | 2910 | 0 | 0 | 0 | 0 |
| Grassland* | < 6 | No | 49.1 | 3609 | 2.6—3.9 | 0.0 | 2.6—3.9 | 9482—14,224 |
| | | Yes | 2.9 | 213 | 2.6—3.9 | 3.4 | 0—0.6 | 0—122 |
| | > 6 | No | 48 | 3528 | 0 | 0 | 0 | 0 |

*Excludes rough grazing classed as mountains, hills, heathland or moorland.

The Scottish Government (2018) reports that 64% and 30% of farms carried out pH testing on arable and grazing land respectively in 2016. Assuming a) that this is representative of the UK as a whole, b) that pH testing is targeted towards land in need of acidity remediation, and c) that the above percentages can be broadly interpreted as percentage of land area, this indicates that there may be around 9% of agricultural which is untested and below the pH threshold. For grassland, based on the same assumptions, a minimum of 22% of grassland can be deemed to be currently below optimum pH, but untested.

The following assumptions are used in the calculation of the marginal abatement cost effectiveness for liming:

1. **Baseline soil acidity.** The simulation is created for land requiring lime application; land areas to which this is applicable are shown in Table 5. The pH distribution of land requiring acidity remediation is interpolated from the data presented in Table 2 (PAAG, 2016).
2. **Soil types.** Distribution of soils into soil type categories (sand, silt, clay or peat) follows the approach of Graves et al. (2011). Land categorised as peat was excluded from this analysis given the likelihood of liming on this land leading to net GHG emissions (Goulding, 2016; Holland et al., 2017).
3. **Lime application rates.** Application rates of lime (in tonnes $ha^{-1}$) required bring soils to the recommended pH are taken from Defra (2017), scaled according to soil type. These applications are assumed to occur with a frequency of 4—6 years (Onwonga et al., 2008; Holland et al., 2019).
4. **Costs of liming.** The following costs are assumed to be associated with the implementation of liming:
    a. Cost of lime of £35 $tonne^{-1}$ (SAC, 2017).
    b. Cost for contractors to spread lime of £2—6 $tonne^{-1}$ (SAC, 2017).
5. **Financial benefits of liming**: Positive crop yield impacts (Li et al., 2018; Holland et al., 2019) are assumed to be associated with liming. Crop yield curve equations as defined by Holland et al. (2019) are implemented for arable crops, and grass biomass increases reported by Fornara et al. (2011) are used to scale grassland estimates. Increases in crop yield are converted into financial terms using value per tonne from SAC (2017). For grassland, production cost savings resulting from increased yield are estimated based on silage production costs from SAC (2017).
6. **Emissions from liming.** The following emissions sinks and sources were assumed to be associated with liming:
    c. Direct $CO_2$ emissions from lime application, using a ranged emission factor of 0.0625—0.12 kg $CO_2$—C kg $lime^{-1}$ (de Klein et al., 2006).
    d. 'Embedded' emissions from lime extraction/production of 0.074 kg $CO_2$-eq kg $lime^{-1}$ (range 0.054—0.089 kg $CO_2$-eq kg $lime^{-1}$) (Kool et al., 2012).
    e. $CO_2$ from diesel used in spreading, using data reported by from Williams et al. (2006).
    f. C sequestration in soil. For croplands, soil C stocks reported by Kemmitt et al. (2006) were used to derive a C response curve for pH remediation of arable land. For grasslands, sequestration rates reported by Fornara et al. (2011) were employed.
7. **Crop production baseline.** For crop production, emissions intensities (in kg $CO_2$-eq tonne $crop^{-1}$) and yields (in tonnes $ha^{-1}$) reported by Williams et al. (2006) and DEFRA (2009) are used. It was necessary to make these assumptions so that the abatement potential could be adjusted for yield impacts.

A Monte Carlo simulation (Mersenne seed = 2605, repeats = $10^5$) was conducted to synthesise the uncertainties reported in the above assumptions. For arable land, four case study crops (wheat, potatoes, field beans and oilseed rape) were considered; the choice of these crops was made in order to provide a broad overview of the effects of pH on different crop types, and in light of the data available to quantify yield responses to pH remediation (Holland et al., 2019).

**Results for arable land**

Calculated on the basis of emissions intensity, the abatement potential was, on average, -0.377 ± 0.383 tonnes $CO_2$-eq $ha^{-1}$ $year^{-1}$, meaning that in the majority of scenarios, liming resulted in a net increase in emissions intensity. While this was variable for different crops (largely depending on yield effects), the vast majority of scenarios suggested a low likelihood of net abatement occurring (Fig. 1). The emissions intensity abatement estimate is calculated to account for differences in yield as well as emissions, and is derived from the net difference between the emissions intensity of crop production (in kg $CO_2$-eq tonne crop$^{-1}$) with and without lime amendments, scaled to equivalent production per hectare.

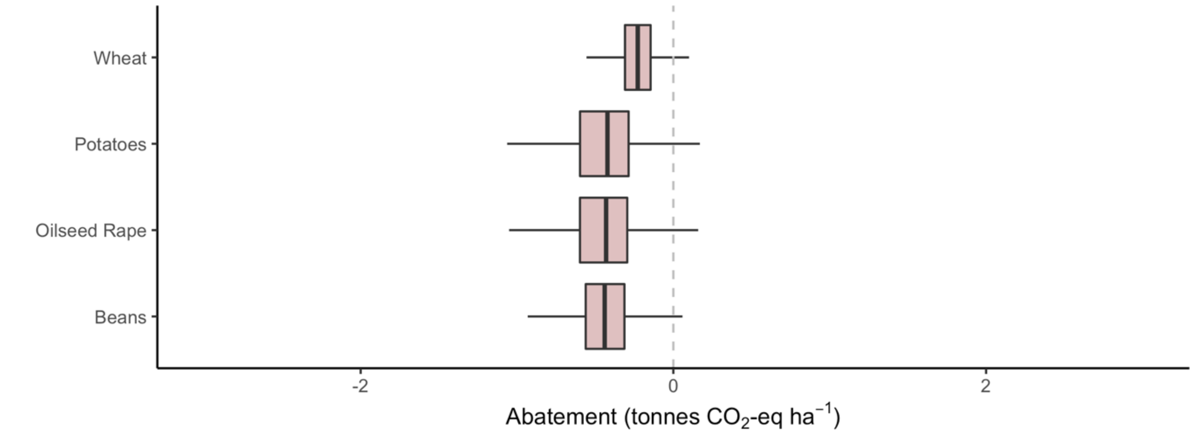


**Fig. 1.** Abatement from implementation of liming on cropland, calculated based on emissions intensity (controlling for yield effects). Negative abatement implies a net increase in greenhouse gas emissions intensity.

Baseline pH value is highly influential in determining whether or not net abatement is achieved. Fig. 2 shows the correlation between baseline pH and GHG abatement from liming for each of the crops considered; lower starting pH values allow for greater yield and soil carbon improvements as a result of liming, increasing the abatement potential of the measure.

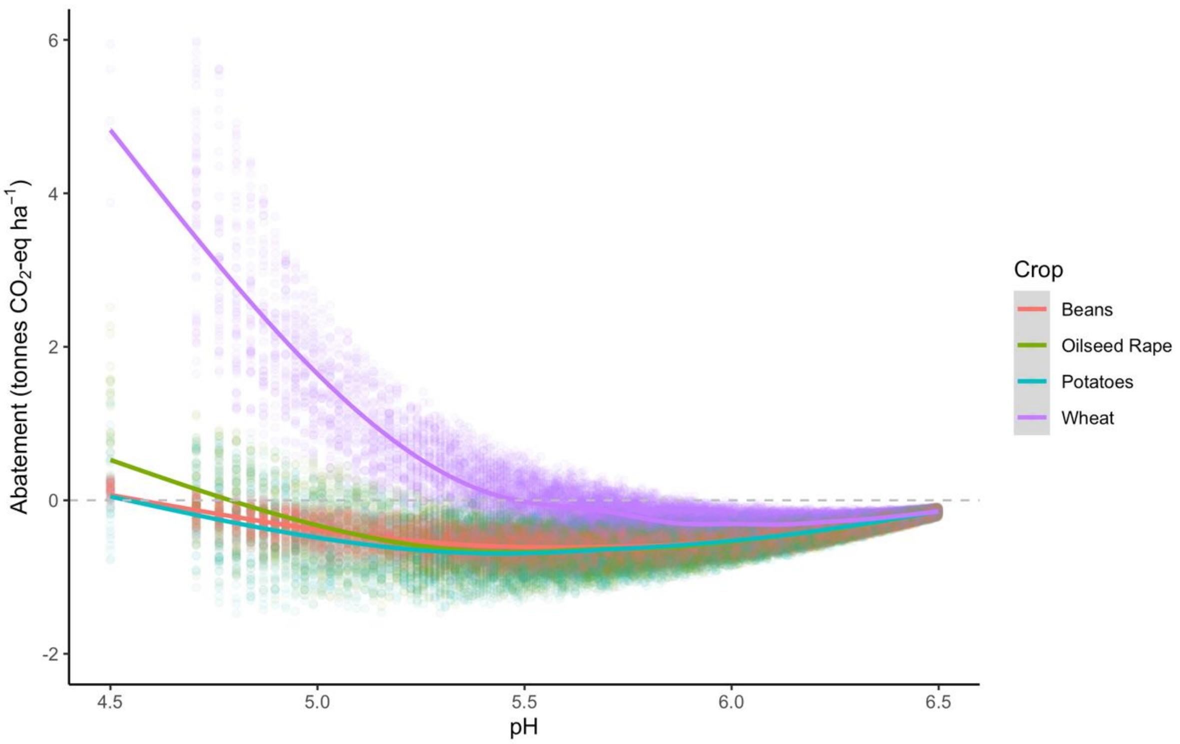


**Fig. 2.** The effect of baseline pH on the emissions intensity abatement potential of liming.

Based on this analysis, where soil baseline pH is below 5.5, the introduction of liming practices for wheat production appears likely to represent net GHG abatement. For other crops and soils of pH higher than this baseline, it is unlikely that liming will reduce emissions intensity.

Based on the simulation results, it was possible to identify a trade-off between yield improvements and soil carbon sequestration. Lime was applied to all simulation runs to a target pH of 6.5; this is the recommended pH for arable land (Defra, 2017), and necessary in order to achieve yield improvements according to the response curves derived by Holland et al. (2019). However, the SOC response curve fitted to data supplied by Kemmitt et al. (2006) showed maximum soil C occurring around pH 6 (Fig. 3). Based on this, liming actually reduced C stocks in some scenarios with a higher baseline pH, contributing to the net loss of abatement potential. Liming to a lower pH (e.g. 6) would have prevented this from occurring, but would have reduced the applicability of the measure to a small subset of low-baseline-pH scenarios; based on data from PAAG (2016), only 17% of arable land is below pH 6.

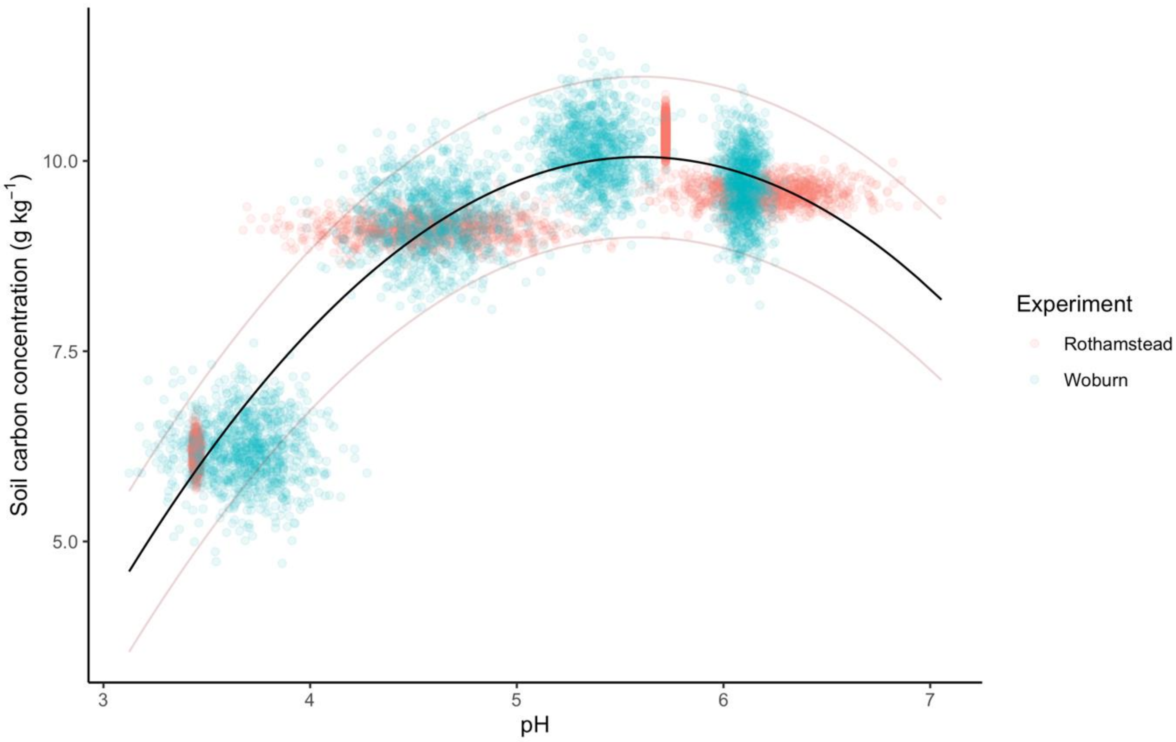


**Fig. 3.** The model used to predict soil C response to pH changes in the arable scenarios ($y = -0.888x^2 + 9.9843x - 17.795$, $R^2 = 0.89$. $p < 0.0001$). Model is based on normalised data from Kemmitt et al. (2006).

Despite the low likelihood of abatement, yield improvements contributed to an estimated average negative cost for this measure of 2017£ -82.56 ha$^{-1}$. This cost was variable between crops, with wheat and beans both having a high probability of net negative costs (Fig. 4). Oilseed rape showed the lowest likelihood of negative cost for this measure.

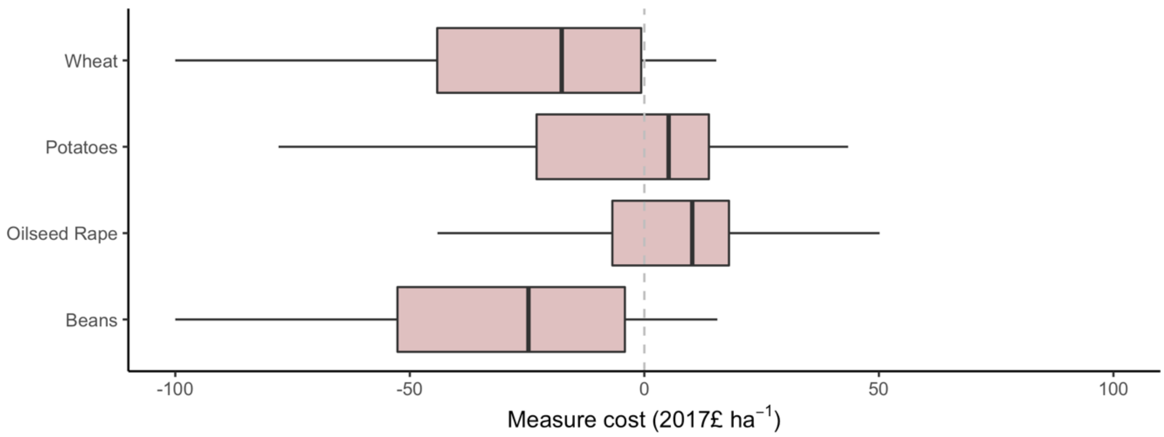


**Fig. 4.** Net cost of implementing liming practices in arable cropping land.

**Results for grassland**

By comparison to cropland, increased C sequestration rates (modelled according to Fornara et al., 2011) and reduced application requirements meant that liming was, on average, a net emissions sink regardless of yield improvements. Emissions abatement resulting from liming of grassland was predicted in 98% of scenarios. Calculated on an area basis, a net GHG impact of -0.56 ± 0.42 tonnes $CO_2$-eq ha$^{-1}$ year$^{-1}$ was estimated for liming implementation on grassland.

The area basis for calculation of liming abatement potential in grassland disregards the effect of any change in grass yield. High variability in grass production practices means it is not possible to include this element in the calculation of abatement, though grass production was assumed to increase by an estimated 6% (Fornara et al., 2011). Assuming a reduction in production costs per tonne resulting from increased yield, the marginal abatement cost for grassland was estimated on a per-hectare basis at -25 £ tonne $CO_2$-eq$^{-1}$, with negative costs in 83% of scenarios and costs below the social cost of carbon (SCC) in 99% of scenarios (SCC based on a value of £66.10; Department for Business Energy & Industrial Strategy, 2018) (Fig. 5).

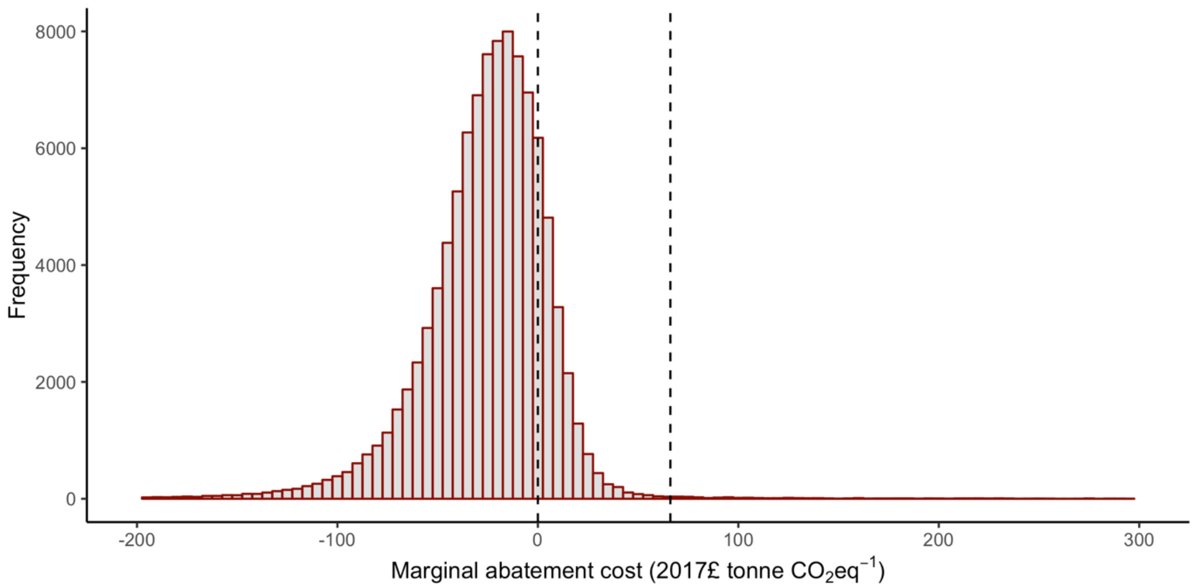


**Fig. 5.** Estimated variation in marginal abatement costs for liming in UK grassland. Vertical dashed lines indicate costs of zero and the SCC (£66.10).

The cost of lime applications was low, such that if production cost savings were excluded (i.e. assuming zero revenue resulting from liming), the mean marginal abatement cost rose only to 44.52 £ tonne $CO_2$-eq$^{-1}$. Abatement was strongly influenced by baseline pH, with lower pH baseline values giving potential for greater abatement (Fig. 6).

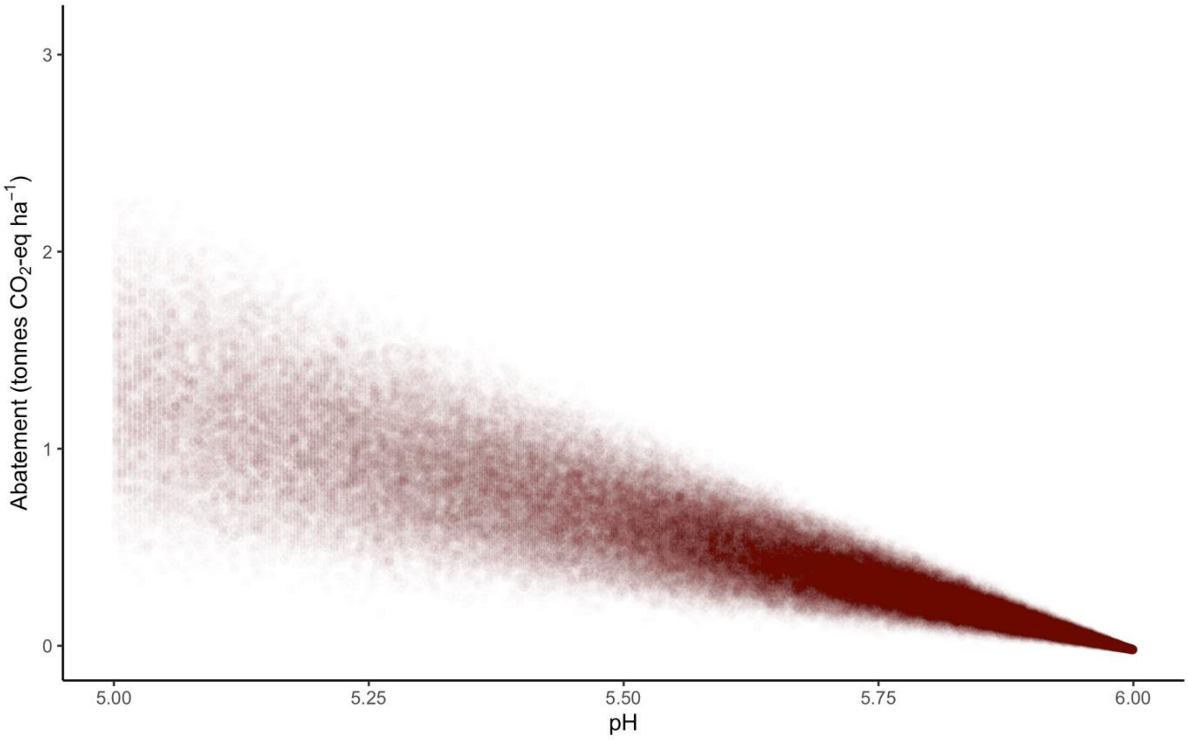


**Fig. 6.** Relationship between baseline pH and abatement potential for liming on grassland.

*Applicability, current uptake, and potential additional maximum uptake*
The net abatement resulting from liming cropping land is likely to be negligible or negative (i.e. a net emission source) for arable production systems. In general, the abatement potential of liming in cropping land is highly dependent on yield improvements and soil carbon sequestration; small changes in these variables can strongly impact the abatement potential of liming arable land. **It is not recommended that cropland is limed beyond current practice as a GHG mitigation measure.**

The marginal abatement cost of liming grassland is very likely to be negative or less than the SCC. This abatement potential does not rely on yield improvements, but does assume substantial soil C sequestration to offset the emissions associated with lime application. Where this sequestration is not realised, abatement will be minimal or negative. Given the potential for net abatement at costs below the SCC, **it is recommended that improved grassland on mineral soils below pH 6 is limed is a GHG mitigation measure.**

Defra (2018a) estimates a total area of 7.35 million ha of improved grassland in the UK. Data from PAAG (2016) and Defra (2018b) suggests that 49.1% of this land is below target pH and unlimed, and analysis by Graves et al. (2011) estimates that 3.7% is on peatland and therefore unsuitable for pH remediation. This leaves a potential applicable land area of 3.34 million hectares. Table 7 shows the theoretical abatement potential of liming this land for GHG mitigation.

**Table 7.** Potential abatement for uptake of liming practices in grassland.

| **Additional uptake (% area)** | 25% | 50% | 75% | 100% |
|---|---|---|---|---|
| **Abatement (kt $CO_2$-eq)** | 467 | 934 | 1,402 | 1,869 |

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