Re-creation of heathland on improved pasture using top soil removal and sulphur amendments: Edaphic drivers and impacts on ericoid mycorrhizas

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ABSTRACT
Understanding the factors that drive successful re-creation and restoration of lowland heaths is crucially important for achieving the long-term conservation of this threatened habitat type. In this study we investigated the changes in soil chemistry, plant community and interactions between Calluna vulgaris and symbiotic ericoid mycorrhizas (ERM) that occurred when improved pasture was subjected to one of three treatments (i) acidification with elemental sulphur (ii) acidification with ferrous sulphur (iii) removal of the topsoil. We found that the soil stripping treatment produced the greatest reduction in available phosphate but did not decrease soil pH. Conversely, acidification with elemental sulphur decreased pH but increased availability of phosphate and potentially toxic cations. The elemental sulphur treatment produced plant communities that most closely resembled those on surrounding heaths and acid grasslands. The most important driver was low pH and concomitant increased availability of potentially toxic cations. Plant community development was found to be little related to levels of available soil phosphate, particularly at low pH. The elemental sulphur treatment also produced the best germination and growth of C. vulgaris over 4–5 years. However, this treatment was found to inhibit the development of symbiotic relationships between C. vulgaris and ERM. This may affect the long-term persistence of re-created vegetation and its interactions with other components of heathland communities.

1. Introduction
Lowland heath has become a rare and fragmented habitat in central western Europe and its restoration has long been a UK Biodiversity Action Plan priority (Farrell, 1993; DOE, 1995). Pioneering work centred on developing techniques for heathland re-creation on improved farmland (Marrs, 1985; Smith et al., 1991; Pywell et al., 1994; Marrs et al., 1998). Here success necessitates a reversal of the increased soil pH and residual nutrient availability effected during agricultural improvement so that ericaceous species are not outcompeted by mesotrophic grasses. Heathland re-creation on land cleared of conifers presents fewer of these difficulties (Walker et al., 2004) but success can still be thwarted by poor survival of seed
banks (Eycott et al., 2006) and by the need to remove litter and humus layers (Allison and Ausden, 2006). Wet heathland re-
creation by sod cutting to remove eutrophic top soils can be
particularly difficult to achieve due to both partial loss of
seedbanks and to the high levels of soil ammonium created
as a result of sod cutting (Dorland et al., 2003, 2005). Soil re-
moval is also expensive and so alternative techniques have
been tested for heathland restoration on less eutrophic soils
such as those of heathland degraded by successional change
to woodland or by atmospheric nutrient deposition (Britton
et al., 2000; Mitchell et al., 2000; Niemeyer et al., 2007). Despite
the many challenges involved, particularly for heathland re-
creation on improved farmland, it remains imperative that
techniques are developed for the effective, rapid restoration
of heathlands from a range of starting habitats as existing
fragmented heathlands have been demonstrated to exhibit
extinction debts (Piessens and Henry, 2006).

The approaches used to attempt to return improved farm-
land soil pH and nutrient availability to values more akin to
those of heathland and acid grassland soils can be divided
into two broad groups (i) physical removal or deep ploughing
of the improved top soil (Smith et al., 1991; Aerts et al., 1995;
Allison and Ausden, 2004) and (ii) chemical amendment of
the top soil (Chambers et al., 1996; Dunsford et al., 1998; Owen
et al., 1999; Owen and Marrs, 2000, 2001; Lawson et al., 2004;
Tibbett and Diaz, 2005). Studies using these methods report
different levels of success in producing long-lasting heath-
land and acid grassland communities.

Heathland restoration on improved grassland has focused
on restoring dry heaths and there is encouraging evidence of
some successful re-creation of an ericaceous sward on land
treated by soil stripping (Allison and Ausden, 2004) and partial
success on land chemically amended with elemental sulphur
(Walker et al., 2007; Lawson et al., 2004). However, the number
of success stories reported are low and only one study (Walker
et al., 2007) provides a direct comparison of the efficacy of
these techniques. These authors found that an ericaceous
sward was only established in plots treated with elemental
sulphur and the authors identify high soil pH and high resid-
ual soil P as factors that appear to hinder the development of
an ericaceous sward. This agrees with the findings of other re-
search (Owen and Marrs, 2000; Allison and Ausden, 2004)
although alternate drivers have been suggested, particularly
the high availability of potentially toxic elements in low pH
soils (Tibbett and Diaz, 2005; Lawson et al., 2004). No study
has tested the relative importance of these various potential
drivers underpinning different treatments. Also no study
has yet examined how treatments may affect biotic interac-
tions of re-created ericaceous swards that may determine
their likely long-term persistence. In heathland systems the
symbiotic relationship between Calluna vulgaris and ericoid
mycorrhizal fungi (ERM) has been identified as a key driver
(Read et al., 2004).

In this paper we examine the relative importance of a
range of chemical soil attributes as drivers for the successful
establishment of a dry heathland plant community using
sulphurous amendment and soil stripping techniques. We
also examine the impact of these treatments on the
extent of colonisation of C. vulgaris with symbiotic ericoid
mycorrhiza.

The specific questions addressed are

1. What are the key chemical drivers in the soil that steer
plant community change from a mesotrophic grassland
to acid grassland/dry heathland?

2. Which treatment is most successful at supporting growth
of (sown) C. vulgaris and do the treatments alter the eco-
logical interaction of C. vulgaris with ERM?

2. Materials and methods

2.1. Study area

The study area for this investigation is owned by the National
Trust and is located at 2°04' W, 50°39’ N near Wareham, Dorset,
UK, on two contiguous farms (Newlines Farm and Hartland
Farm) neighbouring Hartland Moor National Nature Reserve
and Middlebere Heath. The site, like the adjacent heathland, lies
on the acidic fluvially-deposited sands, gravels and clays of bag-
shot beds and supported lowland heath until the mid 20th cen-
tury. During the latter half of the 20th century the soil on the
farms was tilled and improved for agriculture by the addition
of rock phosphate (apatite bearing rock Ca10(PO4)6F2) and chalk
and marl (amorphous CaCO3:MgCO3 at a ratio of approximately
30:1) to increase nutrient levels and decrease soil acidity. The
land was used for arable production for a few years and then
converted to intensively fertilised pasture. At the start of the
experiment in 2001 the vegetation was an improved pasture in
which Lolio perenne and Agrostis capillaris were the most con-
stant and abundantly occurring grasses. Other constant and
abundant species were Holcus lanatus and Elymus repens. Festuca
rubra, Anthoxantum odoratum and Dactylis glomerata were also
frequent but varied in their abundance. Forbs made up approx-
imately 10–15% of the sward; Tribum repens was the most abun-
dant species overall but there were frequent more localised
concentrations of Ranunculus repens and a widespread but thin
cover of Hypochoeris radicata and Plantago lanceolata.

2.2. Experimental design

Soil treatments were compared in a single, fully factorial
experiment replicated over 10 fields, five on each farm. Fields
were chosen to be as homogeneous as possible and treatment
plots were arranged at random on each field. Areas of heath lay-
ing immediately adjacent to the fields were also sampled to
provide a target both in terms of soil chemical status and plant
community re-creation. Two sulphur amendment methods, a
soil stripping method and a control were compared:

(i) An elemental sulphur treatment in the form of Brime-
stone 90™ an agricultural fertilizer that consists of
90% S and comes in an easy-to-apply pellet rather than
power state. This is converted to sulphuric acid by
microbial oxidation of sulphur to sulphuric acid.

(ii) A ferrous sulphate treatment in the form of Mistrale
“Wet Copperas” 50™ a wet powder sold as a moss killer
and which contains 13% sulphur and 19% iron. Iron sul-
phate causes an acidification effect and it can bind
The elemental sulphur, ferrous sulphate treatments and control were each applied as one 50 m × 50 m plot on each of the 10 fields. These treatments were applied at the same dose levels and were both applied in two stages; 2000 kg ha⁻¹ was applied in May 2000 and a further 1600 kg ha⁻¹ at the end of March 2001. Both treatments were applied directly onto the existing sward with no physical disturbance of the soil. The total dose of 3600 kg ha⁻¹ lies within the range reported as successful in supporting the growth of acid grassland and ericaceous species by previous research (Owen and Marrs, 2000). At the start of April 2001 the soil stripping treatment was set up as one 20 m × 20 m plot in a random location in each of the same 10 fields. It was not possible to make these plots the same size as the sulphur treatments plots due to financial limitations regarding disposal of the stripped soil and concerns that stripping larger areas may damage archaeological features. To minimise the effect that this difference in size of plot could have on results, no samples were collected from the outer 3 m edge of each plot. This prevented over-sampling of any stoloniferous species that were able to colonise the edges of plots. Soil was stripped down to a depth of 20 cm. Plots were fenced to exclude cattle. In November 2001 C. vulgaris clippings were harvested from adjacent heathland at Middlebere and were immediately sown onto a random half of each plot. Clippings were spread at a rate of twice the area cut to obtain clippings (Pywell et al., 1995). This paper reports only the results from areas where heather clippings were applied as no ericaceous sward developed in the unseeded half of the plots.

2.3. Soils

Soils were sampled from the Ao horizon (typically 0–15 cm depth) at the end of the initial heathland re-creation stage in June 2003. Soil was collected from 25 separate stations, sampled in a W pattern across each plot and then combined into a single, homogenous composite sample. Soil samples were also collected from 10 random 40 m² plots of adjacent dry heathland on Hartland Moor and Middlebere Heath to provide a target soil condition for amended soil. All soil samples were air dried and passed through a fine (<2 mm) sieve prior to analyses. Soils were analysed for a range of chemical parameters including pH, extractable Mg, K, Ca, Olsen P, Mn, Al, Fe and SO₄ using standard methods (Page et al., 1982; MAFF, 1986).

2.4. Plants and mycorrhizas

In June 2006 the percentage cover of each vascular plant species was measured by visual estimation in 10 randomly located 2 m × 2 m quadrats per (i) half of each plot sown with C. vulgaris, (ii) adjacent heathland (iii) adjacent acid grassland. The relative abundance for each species on each plot was then calculated by dividing total percentage cover data for each plant species per quadrat by the total plant cover per quadrat. The composition of the vegetation community on each plot was compared using relative abundance data for each species as plots varied greatly in their total abundance of plant cover. The extent of ERM colonisation was examined in three randomly selected plants per plot. Extent of ERM colonisation was scored for each plant as the percentage of random fine root sections (ca. 1 cm lengths) with evidence of ERM structures (Diaz et al., 2006, modified from Standberg and Johansson, 1999).

2.5. Data analysis

Univariate data analysis was carried out using SPSS v11. Multivariate analysis of the interaction between soil parameters and species distributions was carried out using Canonical Correspondence Analysis (CCA) in CANOCO 4. (ter Braak and Smilauer, 1998). A standard analysis was carried out on untransformed data. Multivariate analysis of the differences in plant community composition across plots was carried out using non-metric multi-dimensional scaling of square root transformed data (MDS) and analysis of similarity (ANOSIM) between treatments within the software package PRIMER 5 (Clark and Warwick, 2001).

3. Results

3.1. Chemical changes in the soil

Treatments showed significant differences in many soil attributes both between the treatments on the farmland soils and between these treatments and the target heathland soils (Table 1). The greatest change in soil pH occurred in the elemental sulphur treatment with a downward shift of 1.6 pH units compared to a 0.3 unit shift for ferrous sulphate. The mean pH of the stripped plots was slightly higher than the control by 0.2 of a pH unit, although it should be borne in mind that this treatment does not alter the soil chemistry but merely exposes a lower horizon. The basic cations, K⁺ and Mg²⁺ were significantly depleted by the elemental sulphur and soil stripping treatments although concentrations in the heath were well above those found in any of the field plots. Soil phosphorus remained low across all treatments but was approximately double the control and heathland values in the elemental sulphur treated plots. The lowest Olsen P values were in the soil stripped plots. Of the potentially toxic cations, Al³⁺ and Mn²⁺, Al showed no significant differences across treatments due to large within-treatment variation whereas Mn²⁺ did differ with treatment, but only slightly. As expected, levels of SO₄ were considerably higher in the elemental sulphur treated soils.

Overall the elemental sulphur treated plots were the most acidic with a substantial loss in chemical fertility, except for phosphate which was high when compared to the controls. The soil stripped plots showed little difference in pH but were substantially lower in fertility. The ferrous sulphate treated plots showed little difference to the control for all attributes measured.

3.2. Plant community response

Species composition, particularly, relative abundance of the species, differed between treatments across the farmland plots. Table 2 shows the effect of treatment on the relative
abundance of the species that, together, made up 90% of the total mean vegetation cover for each treatment. Other species that occurred with a frequency of at least 10% and that had a mean % cover of at least 0.5% across are given in Fig. 1.

All treatments except the ferrous sulphate treatment had significant effects on the relative abundance of all species except *A. capillaris* and *H. lanatus* (Table 2). The elemental sulphur treatment and the soil stripped treatment provided

### Table 1 – Mean soil attributes for each treatment 3 years after application of the treatment compared to control plots and target heathland plots

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>Control</th>
<th>Elemental sulphur</th>
<th>Ferrous sulphate</th>
<th>Soil stripped</th>
<th>Heathland</th>
<th>All comparisons</th>
<th>Kruskal Wallis</th>
<th>All farmland plots Kruskal Wallis</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Mean</td>
<td>5.6</td>
<td>4.0</td>
<td>5.3</td>
<td>5.8</td>
<td>4.5</td>
<td>34.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.19</td>
<td>0.18</td>
<td>0.16</td>
<td>0.22</td>
<td>0.75</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Mean</td>
<td>8.0</td>
<td>15.8</td>
<td>10.7</td>
<td>4.4</td>
<td>7.1</td>
<td>25.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.61</td>
<td>2.22</td>
<td>1.41</td>
<td>0.75</td>
<td>0.46</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>Mean</td>
<td>24.8</td>
<td>15.8</td>
<td>25.5</td>
<td>10.9</td>
<td>74.4</td>
<td>37.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>1.98</td>
<td>1.28</td>
<td>2.29</td>
<td>2.11</td>
<td>6.89</td>
<td>12.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ca</td>
<td>Mean</td>
<td>1387.0</td>
<td>666.5</td>
<td>1354.0</td>
<td>502.0</td>
<td>612.0</td>
<td>27.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>119.51</td>
<td>170.07</td>
<td>133.59</td>
<td>107.84</td>
<td>30.46</td>
<td>11.59</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>Mean</td>
<td>54.4</td>
<td>22.1</td>
<td>54.2</td>
<td>27.3</td>
<td>113.6</td>
<td>36.7</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>4.28</td>
<td>1.59</td>
<td>3.20</td>
<td>4.45</td>
<td>11.59</td>
<td>27.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mn</td>
<td>Mean</td>
<td>1.8</td>
<td>1.5</td>
<td>2.5</td>
<td>0.4</td>
<td>0.8</td>
<td>27.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.28</td>
<td>0.38</td>
<td>0.35</td>
<td>0.07</td>
<td>0.25</td>
<td>23.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Fe</td>
<td>Mean</td>
<td>392.6</td>
<td>399.0</td>
<td>486.7</td>
<td>677.1</td>
<td>464.0</td>
<td>7.2</td>
<td>0.127</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>60.34</td>
<td>59.54</td>
<td>50.16</td>
<td>299.08</td>
<td>66.61</td>
<td>5.1</td>
<td>0.165</td>
</tr>
<tr>
<td>SO4</td>
<td>Mean</td>
<td>9.1</td>
<td>51.9</td>
<td>9.2</td>
<td>10.1</td>
<td>11.1</td>
<td>18.4</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>1.37</td>
<td>23.63</td>
<td>1.05</td>
<td>2.81</td>
<td>1.68</td>
<td>16.9</td>
<td>0.001</td>
</tr>
<tr>
<td>Al</td>
<td>Mean</td>
<td>19.9</td>
<td>42.9</td>
<td>14.5</td>
<td>85.0</td>
<td>19.0</td>
<td>0.7</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>5.95</td>
<td>10.63</td>
<td>3.85</td>
<td>40.65</td>
<td>4.71</td>
<td>0.4</td>
<td>0.939</td>
</tr>
</tbody>
</table>

*N = 10 per group. Kruskal Wallis results are presented for comparison across all groups (including the heath) and for comparison between only the treatment plots on the farmland.*

### Table 2 – Mean relative abundance of the species that, together, constituted 90% of the mean vegetation cover of all treatments on both Hartland and Newline farm

<table>
<thead>
<tr>
<th>Species</th>
<th>Control</th>
<th>Elemental sulphur</th>
<th>Ferrous sulphate</th>
<th>Soil stripped</th>
<th>All comparisons</th>
<th>Kruskal Wallis</th>
<th>All farmland plots Kruskal Wallis</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Agrostis capillaris</em></td>
<td>Mean</td>
<td>24.1</td>
<td>34.7</td>
<td>24.8</td>
<td>19.1</td>
<td>2.24</td>
<td>0.524</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>7.1</td>
<td>7.6</td>
<td>6.8</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Anthoxanthum odoratum</em></td>
<td>Mean</td>
<td>6.5</td>
<td>1.2</td>
<td>7.3</td>
<td>3.2</td>
<td>8.55</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>2.4</td>
<td>1.0</td>
<td>3.4</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Elymus repens</em></td>
<td>Mean</td>
<td>5.8</td>
<td>1.0</td>
<td>10.3</td>
<td>0.0</td>
<td>15.26</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>2.9</td>
<td>1.0</td>
<td>5.1</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Festuca rubra</em></td>
<td>Mean</td>
<td>4.6</td>
<td>0.0</td>
<td>4.9</td>
<td>0.2</td>
<td>11.63</td>
<td>0.009</td>
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<td>2.9</td>
<td>0.0</td>
<td>4.2</td>
<td>0.2</td>
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<tr>
<td><em>Holcus lanatus</em></td>
<td>Mean</td>
<td>13.1</td>
<td>11.8</td>
<td>17.7</td>
<td>10.9</td>
<td>2.55</td>
<td>0.467</td>
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<td>SE</td>
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<td>4.6</td>
<td>6.0</td>
<td>4.8</td>
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</tr>
<tr>
<td><em>Lolium perenne</em></td>
<td>Mean</td>
<td>23.6</td>
<td>0.0</td>
<td>15.2</td>
<td>0.7</td>
<td>26.65</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>4.1</td>
<td>0.0</td>
<td>4.4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Ranunculus repens</em></td>
<td>Mean</td>
<td>7.0</td>
<td>0.0</td>
<td>3.6</td>
<td>0.4</td>
<td>11.96</td>
<td>0.008</td>
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<td>0.0</td>
<td>1.9</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Rumex acetosella</em></td>
<td>Mean</td>
<td>2.2</td>
<td>40.0</td>
<td>7.5</td>
<td>28.3</td>
<td>13.60</td>
<td>0.003</td>
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<td>9.4</td>
<td>1.6</td>
<td>8.5</td>
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<td><em>Trifolium repens</em></td>
<td>Mean</td>
<td>7.4</td>
<td>0.0</td>
<td>0.6</td>
<td>3.1</td>
<td>23.46</td>
<td>&lt;0.001</td>
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<td>0.0</td>
<td>0.4</td>
<td>1.5</td>
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<tr>
<td><em>Ulex europeaus</em></td>
<td>Mean</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>21.2</td>
<td>28.78</td>
<td>&lt;0.001</td>
</tr>
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<td></td>
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<td>0.0</td>
<td>0.0</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*N = 10 per group. All species except *U. europeaus* had a frequency of occurrence of >10% and a mean % cover of >2% across all plots. *U. europeaus* was the remaining species with high relative abundance in the soil stripped plots.*
A high relative abundance of related to levels of any of the above environmental variables. With high levels of SO₄²⁻ and Fe and SO₄²⁻ resulting species-environment biplot (Fig. 1)) were pH, Ca, Al, species abundances (i.e. those with the longest arrows in the environmental variables correlating with differences in plant applications. CCA results indicate that the most important ing in the still high relative abundance of this species in both not of

rub = Anthoxanthum odoratum; Bro mol = Bromus mollis; Cal vul = Calluna vulgaris; Cer fon = Cerastium fontanum; Dac glo = Dactylis glomerata; Ely rep = Elymus repens, Fes rub = Festuca rubra; Hol lan = Holcus lanatus; Hyp rad = Hypochaeris radicata; Lol per = Lolium perenne; Poa pra = Poa pratensis; Pla lan = Plantago lanceolata; Ran rep = Ranunculus repens; Rum ace = Rumex acetosella; Sen jac = Senecio jacobaea; Tar off = Taraxacum officinale agg.; Tri dub = Trifolium dubium; Tri rep = Trifolium repens).

strong suppression of T. repens and three of the most competitive mesotrophic grasses; E. repens, F. rubra and L. perenne but not of H. lanatus. The bare ground produced in the first stage of both treatments was colonised by Rumex acetosella, resulting in the still high relative abundance of this species in both treatments 2 years after the completion of the treatment applications. CCA results indicate that the most important environmental variables correlating with differences in plant species abundances (i.e. those with the longest arrows in the resulting species-environment biplot (Fig. 1)) were pH, Ca, Al, Fe and SO₄⁻². Interestingly, the arrow for P is small, suggesting that this was a relatively unimportant factor in determining species distribution compared to variation in pH and extractable Fe and Al concentrations.

Mesotrophic species particularly associated with high pH and Ca are nearest the bottom of the biplot, i.e. L. perenne, E. repens and Bromus mollis. Two competitive forbs that were prevalent only where pH and Ca levels were high and Al and Fe levels were low were T. repens and Senecio jacobaea. Species associated with plots where pH was lowest and Al and Fe levels were relatively high were C. vulgaris, R. acetosella, A. odoratum and A. capillaris. Levels of SO₄²⁻ and Mg²⁺ were not strongly related to levels of any of the above environmental variables. A high relative abundance of Trifolium dubium was associated with high levels of SO₄⁻² but not particularly with high/low pH or Al/Fe.

The MDS analysis showed that the treatment plots closest in terms of their overall community composition to the target heathland plots after 3 years were the elemental sulphur plots (Fig. 2). Significant differences at P < 0.001 were found between all treatment groups apart from the control and ferrous sul-

Fig. 1 – CCA biplot for all soil attributes and all species with a frequency of occurrence of >10% across all plots. (Ach mil = Achillea millefolium; Agr cap = Agrostis capillaris; Ant odo = Anthoxanthum odoratum; Bro mol = Bromus mollis; Cal vul = Calluna vulgaris; Cer fon = Cerastium fontanum; Dac glo = Dactylis glomerata; Ely rep = Elymus repens, Fes rub = Festuca rubra; Hol lan = Holcus lanatus; Hyp rad = Hypochaeris radicata; Lol per = Lolium perenne; Poa pra = Poa pratensis; Pla lan = Plantago lanceolata; Ran rep = Ranunculus repens; Rum ace = Rumex acetosella; Sen jac = Senecio jacobaea; Tar off = Taraxacum officinale agg.; Tri dub = Trifolium dubium; Tri rep = Trifolium repens).

3.3. Growth of sown C. vulgaris and ericoid mycorrhizal colonisation

Calluna vulgaris grew only on the elemental sulphur and soil stripped plots; above-ground biomass was greatest on the elemental sulphur plots despite these plants having significantly lower levels of colonisation by ERM (Whitney U = 0, P < 0.001; Fig. 3). Shoots of C. vulgaris growing on the elemental sulphur treatment plots were found to have significantly lower concentrations of P than those growing on the heaths; mean levels of P in shoot were 1592 mg l⁻¹ for plants on the sulphur

Fig. 3 – MDS plot showing the extent of similarity in overall plant community composition of the 10 plots from each treatment.

Fig. 3 – Effect of treatments compared to control mesotrophic grasslands and target adjacent heathland and acid grassland on (a) growth of C. vulgaris and (b) the extent to which C. vulgaris roots are colonised by ERM.
plots and 954 mg l\(^{-1}\) for plants growing on the heath (Mann Whitney \(U = 92.0, P = 0.009\)). Pearson correlation analyses indicated a significant negative relationship between ERM colonisation and shoot \(P (r = -0.35, P = 0.029)\).

4. Discussion

4.1. Key soil changes driving changes in the plant community

Heathland restoration on farmland modified by soil acidification using sulphur produces a markedly different edaphic environment for plant growth to that produced by soil removal. Whilst both techniques aim to reduce pH and residual soil fertility (particularly phosphate), results from this investigation indicate that, in practice, soil acidification with elemental sulphur reduced pH and concentration of basic cations, \(K^+\), \(Mg^{2+}\) and \(Ca^{2+}\) more effectively than did soil removal. However soil removal produced the greatest reduction in the availability of phosphate, a macronutrient that is often a key limiting factor controlling the growth of competitive grasses (Grime, 1977). Application of elemental sulphur caused a large increase in available P and the ferrous sulphate treatment did have lower available P compared to the elemental sulphur treatment. Consequently, our findings agree with those of Walker et al. (2004) who report that this treatment was effective in reducing available P in a sandy soil in East Anglia. However, we found that the treatment was entirely unsuccessful in terms of recreating low nutrient acidic vegetation communities as it only bound some of the P produced by the soil acidification and only produced a minor drop in pH.

Overall plant community response to edaphic conditions across all treatments indicated that low soil pH was a much more important determinant of success than low residual phosphate. By contrast, Allison and Ausden (2004) report successful establishment of ericaceous swards on high pH soils (5.9–6.8) as long as residual P was very low (below a mean of 5.2 mg kg\(^{-1}\)). Although \(H^+\) can have direct toxic effects on plants (Kinraide, 2003) the CCA analysis in the present study indicates that the strongest driver for plant community shifts away from mesotrophic grassland communities is likely to be the increased phyto-availability of the toxic species of aluminium. This agrees with other work that has shown that acid intolerant plants, such as mesotrophic grasses, are typically lost from swards due their sensitivity to \(Al^{3+}\) released in soils at low pH (Huang et al., 1996; Mossor-Pietraszewska, 2001; Rout et al., 2001). Rumex acetosella, a species occurring frequently on our elemental sulphur plots is known to be tolerant to \(Al^{3+}\) as it exudes detoxifying organic acids into the rhizosphere in response to high levels of \(Al^{3+}\) (Schöttelndreier et al., 2001).

4.2. Establishment of acid grassland and ericaceous swards

The elemental sulphur treatment produced the greatest competitor release from mesotrophic species in our study. Competition from mesotrophic grasses and forbs such as \(T. repens\) has been cited as the major cause of mortality of \(C. vulgaris\) seedlings in previous studies; proposed mechanisms include competition for water and possibly for light (Davy et al., 1998; Lawson et al., 2004). Previous work by Owen and Marrs (2000) found that sulphur applied at similar rates of 0.4 kg m\(^{-2}\) on light sandy soils in East Anglia reduced competition from some competitive mesotrophic species but not others, most notably not \(E. repens\) and \(H. lanatus\). The current study found similar responses for \(H. lanatus\) but not \(E. repens\) which was almost entirely eliminated from the elemental sulphur plots. Our field observations support the hypothesis presented in Owen and Marrs (2000) that \(E. repens\) succeeds in occupying acidified land by using its stoloniferous nature to encroach inward from non-acidified edges. We propose that the minimisation of edge-effects in our larger plots (50 m × 50 m) is an important advantage of large plot size; we have observed \(E. repens\) strongly suppressing growth of \(C. vulgaris\) in acidified plots that measured only 4×4 m. The success of \(H. lanatus\) in colonising sulphur treated soils is consistent with it commonly being an important early competitor in habitat re-creation schemes (Green, 1990) as it has good seed dispersal, some tolerance to herbivory, can grow at a range of soil pH (Beddows, 1961) and is tolerant to a range of metals (McGrath et al., 1980).

Top soil removal was found to produce similarly strong initial suppression of competitive grasses as the elemental sulphur treatment but \(Ulex europaeus\) germinated and grew much better in the soil stripped plots than in the elemental sulphur plots. \(C. vulgaris\) seed germination and growth requires consistently high ambient humidity (Gimingham, 1972) and the soil stripped plots lacked the thick layer of organic matter that was produced on the elemental sulphur plots as a result of mesotrophic grassland vegetation being killed by the acidification effect.

Our finding of some establishment of ericaceous species on high pH soils of soil stripped plots agrees with those of another 6 year-long study of heathland establishment on improved agricultural soils (Allison and Ausden, 2004) where soil stripping also produced comparably high soil pH (mean ± SE was 6.52 ± 0.13). Other studies have also found that soil stripping successfully reduced concentrations of extractable P to levels comparable to heathland soils (Aerts et al., 1995; Chambers et al., 1996) and so it may be that, under high pH conditions, the crucial driver is indeed low residual soil fertility.

4.3. Colonisation of \(C. vulgaris\) by ericoid mycorrhizas

Soil stripping was found to cause no suppression of colonisation of \(C. vulgaris\) by ERM in our study which suggests that either the ERM spores were still present in the remaining soil horizons or became re-introduced with the heather clippings. This finding contrasts with a study of arbuscular mycorrhiza

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(AMF) colonisation in Arnica montana (Vergeer et al., 2006) which found that most AMF spores occurred in the upper 10 cm soil layer and that turf cutting significantly reduced colonisation. The finding that C. vulgaris plants growing on elemental sulphur plots have very low colonisation by ERM despite being several years old follows earlier observation (Diaz et al., 2006) that seedling C. vulgaris plants growing on sulphur treated plots had low colonisation by ERM compared to seedlings growing in chemically unmodified heathland soils. This result suggests that whilst the use of elemental sulphur as a heathland re-creation treatment can produce dense ericaceous swards, these swards experience suppression of colonisation of C. vulgaris by ERM symbionts.

The mechanisms by which ERM colonisation remain low and the functional impacts on vegetation dynamics remain unclear and require further investigation. Low levels of mycorrhizal colonisation on the elemental sulphur plots may be related to either the relatively high availability of nutrients, particularly phosphate, or high availability of potentially toxic elements in the soil. High P has been shown to suppress mycorrhizal colonisation due to the high energetic cost to the plant in providing mycorrhizas with photosynthate (Marschner and Bell, 1994). However, it should be noted that whilst ERM fungi have been shown to play a role in acquiring P from organic sources for their host plant (Myers and Leake, 1996) N acquisition is generally thought to be a more important in the plant – ERM symbiosis (Bannister and Norton, 1974; Read et al., 2004; but see Standberg and Johansson, 1999). Nitrogen fertilization in the form of ammonium nitrate does not appear to suppress ERM colonization of C. vulgaris (Johnsson, 2000) but concentrations of other forms of N may affect colonisation levels. Long-term monitoring of the extent of ERM colonisation will be needed to determine if colonisation levels increase as available nutrient levels decrease.

5. Conclusions and practical implications

This study has shown that soil acidification and soil stripping can both re-create heathland and acid grassland plant communities but that there are important differences in both the underlying mechanisms and the nature of the ericaceous sward created. Soil stripping is most effective at lowering residual phosphate levels and so providing control of competitive grasses by that means. However, Ulex europeus grew strongly in the relatively high pH soils.

On soils with high availability of phosphate, soil stripping may fail to sufficiently reduce P and here the key driver to successful control of competitive grasses was found to be to reduce soil pH and thus increase availability of potentially toxic cations. C. vulgaris grew well in these conditions but failed to develop strong colonisation by symbiotic ERM. This may have important implications for the long-term persistence of re-created vegetation and for its interactions with other components of heathland communities.

Ultimately, the decision to re-create heathland on improved pasture requires a weighing up of the potential advantage of providing timely reduced fragmentation and mitigation of extinction debt against the acceptance of some potentially important limitations of methods used. Soil stripping is expensive, damages archaeological features and works best on lightly improved soils which may often be more easily converted to heathland in just a few decades using well managed extensive grazing. Acidification with elemental sulphur can produce ericaceous swards on soils with high residual phosphate but the resulting heathlands are different in terms of at least one important ecological interaction, C.vulgaris-ERM symbiosis. Further research is needed to establish to what extent such re-created heathlands can go on to develop the species communities and ecosystem processes typical of existing heathlands.

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