Creation of Coastal heathland from Agricultural Land

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EXECUTIVE SUMMARY

The restoration of various forms of lowland heathland in the UK is currently a high priority due to the dramatic losses in the extent and quality of the habitat over recent centuries. The coastal belt of Wales however supports significant areas of dry and maritime heath, yet much of this heathland is restricted to a very narrow strip between the cliff edge and adjacent agricultural land. In Pembrokeshire, Anglesey and the Llŷn Peninsula large areas of the coast are owned by conservation organisations and as such provide opportunities for heathland recreation by widening the coastal belt to include adjacent arable fields and pasture. However, attempts to restore and recreate lowland heathlands are invariably constrained as a result of adverse changes in plant and soil conditions following prolonged past agricultural activity. Most notably, ex-arable soils have elevated levels of soil fertility and pH resulting from regular applications of artificial fertiliser and lime. Soil pH in particular is usually too high for the successful establishment of ericaceous dwarf shrub species such as *Calluna vulgaris,* while sustained agricultural management practices tend to also change soil physical conditions and deplete potential seed-sources often necessitating the need to import seed to restoration sites. Experimental research is therefore necessary to provide greater guidance on the potential for further heathland re-creation specific to coastal strip areas of Wales.

The aim of this five-year project was to evaluate the suitability of a number of re-creation treatments on the success of re-creating 'coastal' heathland vegetation on ex-arable land adjacent to the coast of Pembrokeshire. A large-scale replicated field experiment was set-up in 2004 within a coastal ex-arable field on the Marloes Peninsula with a combination of treatments specifically designed to address problems of raised soil nutrient and high pH levels resulting from a long history of on-site arable management. The soils of the site differ from the sandy soils in many other heathland re-creation studies in that they are stagnogley soils. Treatments involved combinations of soil acidification through different application rates of elemental sulphur (i.e. Low rate of 4 t/ha, High rate of 8t/ha or Nil sulphur), with plus or minus topsoil stripping and with and without the addition of a source of ericaceous seed (via heather brash collected from existing heathland). Between 2004 and 2008 experimental plots were monitored annually for changes in soil nutrients and for their progress towards target coastal heathland communities.

Monitoring of soils indicated that soil stripping had no direct effect on nutrient levels due to the former mixing of nutrients throughout the whole plough layer through tillage, but did change soil physical conditions by reducing the total nutrient pool available to colonising plants and by the greater exposure to the influence of the underlying dense, stony clay loam BG soil horizon.

Applications of elemental sulphur (S) were highly effective at rapidly lowering soil pH to target levels, attaining lowest mean pH values of 4.7 and 3.4 for the Low and High S rates respectively by 2007. However sulphur applications also led to large increases in soil extractable phosphate levels which is known to be one of key potential constraints for successful heathland re-creation. Initial levels of exchangeable calcium recorded were also high as a result of regular past liming yet these were rapidly leached under the influence of the high soil acidity conditions created by sulphur applications. Sulphur applications also induced leaching of other exchangeable cations, although leaching of potassium was generally offset by the dissolution of residual fertilizer, and losses of sodium and magnesium were compensated probably as a result of the input of sea-spray onto the site. The less well drained soils on stripped plots tended to hinder all the leaching processes and thereby favoured the greater accumulation of salts from sea spray.

In terms of development of coastal heathland vegetation results clearly demonstrated that at this site the addition of brash was essential as a seed source for the introduction of a number of key ericaceous/dwarf shrub species such as *Calluna vulgaris*, *Erica cinerea* and *Ulex* gallii., none of which established on plots without the addition of brash. However there was no need for the active introduction of seed of other target 'maritime' forb species as many of these were capable of colonising suitable treatments by natural means.

The early development of heathland communities only occurred where sulphur was applied and with the low rate of sulphur application of 4t/ha appearing the most effective within the timescale of the study. The high sulphur rate of 8t/ha was generally excessive due to toxic effects on plant growth although conditions may become more favourable over time. Although sulphur applications led to much increased extractable phosphate levels this did not prevent the early establishment of ericaceous dwarf shrub species which were first recorded in 2007 and already attaining low mean cover values by 2008 on suitable treatments. Under this Low S treatment it is still too soon to predict which of the topsoil stripping treatments will lead to the most successful re-creation of heathland, however some interesting and contrasting trends in the successional development of vegetation have already emerged: i.e. on the unstripped low-S treatment ericaceous species grew well under the protection of high levels of grass cover yet otherwise these plots had only poorly developed forb cover and thus resemble early-successional stage 'grass-heath' (i.e. NVC 'H8b' community). In contrast, on the less well vegetated grass-poor thin soils of stripped low-S plots ericaceous plants were relatively small but frequent with the more open conditions far more receptive to the establishment of wind-blown seeds of target maritime forb species thus giving a generally more 'maritime heath' (NVC 'H7') character to the establishing community.

The Nil sulphur treatment was unsuccessful in that ericaceous species such as *C. vulgaris* generally failed to establish due to the inherently high pH levels. Moreover, unstripped Nil S plots tended to acquire a dense cover of coarse grasses. Stripped Nil-S plots, on the other hand, supported a generally sparse, grass-herb cover but with high overall levels of species richness and total forb cover.

From the results to date it is clear that all the above processes are still highly dynamic and that the long-term effects of re-creation treatments can only be confidently assessed by additional monitoring of soils and vegetation. Such monitoring should concentrate on the growth and survival of ericaceous species particularly on the low sulphur treated plots together with further monitoring of soil pH and phosphate dynamics. Additional single determinations of sward P, soil extractible Fe and the extent of ericoid mycorrhiza colonization would also be highly informative. Such information would provide further guidance for heathland restoration at other potential sites and have particular relevance to sites within the coastal zone of Wales where similar soils to this study site commonly occur.

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Oherwydd y colledion dramatig ym maint ac ansawdd y cynefin dros y canrifoedd diwethaf, rhoddir blaenoriaeth uchel ar hyn o bryd i adfer gwahanol ffurfiau o rostiroedd iseldir yn y DU. Mae lleiniau arfordirol Cymru, fodd bynnag, yn cynnal ardaloedd helaeth o rostir sych a morol, eto i gyd mae llawer o'r rhostiroedd yma wedi'u cyfyngu i leiniau cul iawn rhwng ochr clogwyn a thir amaethyddol cyfagos. Yn Sir Benfro, Ynys Môn a Phen LLŷn, mudiadau cadwraethol sydd berchen ar ardaloedd helaeth o'r arfordir ac maent o'r herwydd yn rhoi cyfleoedd i ailgreu rhostiroedd trwy ehangu'r llain arfordirol i gynnwys tir âr a phorfa cyfagos. Mae ymdrechion i adfer ac i ailgreu rhostiroedd iseldir bob amser yn gyfyngedig o ganlyniad i newidiadau niweidiol yng nghyflwr planhigion a phridd yn dilyn gweithgaredd amaethyddol maith yn y gorffennol. Yn fwyaf nodedig, mae gan gyn briddoedd âr lefelau uchel o ffrwythlondeb pridd a pH o ganlyniad i ddefnyddio gwrtaith artiffisial a chalch. Mae pH pridd yn arbennig yn rhy uchel fel arfer i sefydlu rhywogaethau gorlwyn rhugaidd megis *Calluna vulgaris*, tra bo arferion rheolaeth amaethyddol dros gyfnod maith yn tueddu hefyd i newid cyflyrau ffisegol pridd gan ddihysbyddu ffynonellau had posib. Mae hyn yn aml yn arwain at yr angen i fewngludo had i'r safleodd adfer. Mae angen gwneud ymchwil arbrofol felly er mwyn rhoi mwy o arweiniad ynghylch y potensial o ail greu mwy o rostiroedd penodol ym mro lleiniau arfordirol Cymru.

Nod y prosiect pum mlynedd yma oedd gwerthuso addasrwydd nifer o driniaethau ail greu ar lwyddiant ail greu llystyfiant rhostir 'arfordirol' ar gyn dir âr cyfagos i arfordir Sir Benfro. Sefydlwyd arbrawf maes wedi'i aml-lunio ar raddfa eang yn 2004 o fewn cae arfordirol ar Benrhyn Marloes oedd unwaith wedi bod yn dir âr. Cafwyd cyfuniad o driniaethau oedd wedi'u llunio'n benodol i ymdrin â'r problemau o faetholynnau pridd uchel ac o lefelau pH uchel o ganlyniad i hanes maith o reolaeth amaethyddol ar y safle. Mae'r priddoedd ar y safle yn gwahaniaethu oddi wrth y priddoedd tywodlyd mewn nifer o astudiaethau ailgreu rhostiroedd eraill a hynny oherwydd eu bod yn briddoedd stagnogley. Roedd triniaethau yn golygu cyfuniadau o asideiddio pridd trwy ychwanegu gwahanol gyfraddau o sylffwr elfennaidd (h.y.Cyfradd isel o 4 t/ha, Cyfradd Uchel o 8t/ha neu Dim Sylffwr), gyda dibriddo plws neu minws a chyda neu heb ychwanegu ffynhonnell o had grugaidd (trwy docion grug a gasglwyd o'r rhostiroedd presennol). Rhwng 2004 a 2008 cafodd lleiniau arbrofol eu monitro yn flynyddol er mwyn edrych ar newidiadau ym maetholynnau'r pridd ac er mwyn gweld a oedd datblygiad tuag at gyrraedd y nod o gymunedau rhostirol, arfordirol.

Wrth fonitro'r priddoedd gwelwyd nad oedd dibriddo yn cael unrhyw effaith uniongyrchol ar lefelau'r maetholynnau oherwydd bod maetholynnau wedi cael eu cymysgu yn y gorffennol drwy holl haen lefel yr aradr wrth drin y tir. Bu iddo, fodd bynnag, newid cyflyrau ffisegol y pridd trwy leihau'r gronfa gyfan o faetholynnau oedd ar gael i goloneiddio planhigion a thrwy fod yn fwy agored i ddylanwad lôm BG glai, garegog a thrwchus y dernynlin bridd.

Roedd ychwanegu sylffwr elfennaidd (S) yn effeithiol iawn i leihau pH pridd yn gyflym iawn hyd at y lefelau targed, gan gyrraedd y gwerthoedd cymedrig pH isaf o 4.7 a 3.4 yn achos y cyfraddau S Isel ac Uchel yn y drefn yna erbyn 2007.
Roedd ychwanegu sylffwr hefyd yn arwain, fodd bynnag, at gynnydd sylweddol yn lefelau ffosffad tynadwy y gwyddir ei fod yn un o'r rhwystrau posib pwysicaf rhag ailgreu rhostiroedd llwyddiannus. Roedd y lefelau o galsiwm cyfnewidiadwy a gofnodwyd ar y dechrau yn uchel hefyd o ganlyniad i galchu rheolaidd yn y gorffennol. Eto i gyd, cafodd y rhain eu trwytholchi o dan ddylanwad cyflwr asidedd uchel y pridd a grewyd trwy ychwanegu sylffwr. Roedd ychwanegu swlffer hefyd yn peri trwytholchi cation cyfnewidiol eraill, er bod trwytholchi

potasiwm yn cael ei leddfu yn gyffredinol gan ddyddodion gweddill gwrtaith ac mae'n debyg fod yr ewyn môr oedd yn tasgu dros y safle yn gwneud iawn am golli sodiwm a magnesiwm. Roedd y priddoedd nad oeddent yn draenio cystal ar leiniau oedd wedi'u dibriddo yn tueddu i rwysto'r holl brosesau trwytholchi a thrwy hynny'n ffafrio'r crynhoad mwy o halen o ewyn môr.

Yn nhermau datblygu llystyfiant rhostiroedd arfordirol roedd canlyniadau yn dangos yn glir fod ychwanegu tocion ar y safle yma wedi bod yn hanfodol fel ffynhonnelll had i gyflwyno nifer o rwyogaethau corlwyni grugaidd allweddol megis *Calluna vulgaris, Erica cinerea ac Ulex gallii*, yr un ohonynt wedi sefydlu ar leiniau heb ychwanegu tocion. Nid oedd angen fodd bynnag mynd ati i gyflwyno had rhywogaethau o blanhigion targed 'morol' eraill gan fod nifer o'r rhain yn gallu coloneiddio triniaethau addas trwy ffyrdd naturiol.

Dim ond lle yr ychwanegwyd sylffwr y ceid datblygiad cynnar o gymunedau rhostir a chyfradd isel 4t/ha o sylffwr i'w weld fwyaf effeithiol o fewn amserlen yr astudiaeth. Roedd cyfradd uchel 8t/ha sylffwr yn ormodol ar y cyfan oherwydd effeithiau gwenwynig ar dyfiant planhigyn er y gallai amgylchiadau ddod yn fwy ffafriol dros gyfnod o amser. Er bod ychwanegu sylffwr wedi arwain at gynnydd yn lefelau ffosffate tynadwy ni fu iddo rwystro rhywogaeth corlwyn rugaidd gofnodwyd gyntaf yn 2007 rhag sefydlu a chyda thriniaethau addas mae eisoes erbyn 2008 yn cyrraedd gwerthoedd gorchudd cymedrig isel. Yn sgîl y driniaeth
S-Isel yma mae'n parhau'n rhy fuan i ragweld pa un o'r triniaethau dibriddo fydd yn arwain at ail-greu'r rhostiroedd mwyaf llwyddiannus. Sylwyd yn barod, fodd bynnag, ar rai tueddiadau diddorol a gwrthgyferbyniol yn natblygiad olynol llystyfiant:
h.y. roedd y rhywogaethau grugog yn tyfu'n dda dan gysgod lefelau uchel o orchudd glaswellt ar y lleiniau oedd heb eu dibriddo ac a oedd wedi'u trin â lefel S-isel. Eto i gyd dim ond gorchudd o blanhigion porfa sâl iawn eu datblygiad oedd ar y lleiniau yma ac o'r herwydd yn edrych yn debyg i ' wair rhos' yn y cyfnod olynol cynnar (h.y. cymuned NVC 'H8b'). I'r gwrthwyneb, roedd y planhigion grugog yn gymharol fychan ar briddoedd tenau lle y ceid gwair gwael ei lystyfiant ar y lleiniau S-isel a ddibriddwyd. Yn aml gydag amgylchiadau mwy agored roeddent yn fwy goddefol i sefydlu hadau'r rhywogaethau targed o blanhigion porfa morol oedd yn cael eu chwythu gan y gwynt gan roi cymeriad mwy 'rhos forol' (NVC 'H7') i'r gymuned oedd yn sefydlu.

Roedd y driniaeth Dim sylffwr yn aflwyddiannus o safbwynt bod rhywogaethau grugog fel *C vulgaris* yn gyffredinol wedi methu sefydlu oherwydd lefelau pH cynhenid uchel. Ar ben hyn, tueddai lleiniau Dim-S oedd heb eu dibriddo fod â gorchudd trwchus o weiriau bras. Roedd lleiniau Dim-S oedd wedi'u dibriddo, ar y llaw arall, yn cynnal gorchudd o wair perlysieuol tenau yn gyffredinol ond gyda lefelau uchel ar y cyfan o gyfoeth rhywogaethol a gorchudd llwyr o blanhigion porfa.

Mae'n amlwg a barnu oddi wrth y canlyniadau hyd yma fod y prosesau uchod yn parhau'n ddeinamig iawn ac na ellir asesu'n hyderus effeithiau hir dymor triniaethau ail greu ond trwy fonitro mwy ar briddoedd a llystyfiant. Dylai monitro o'r fath ganolbwyntio ar dyfiant a goroesiad rhywogaethau grugog, yn arbennig ar y lleiniau sydd wedi'u trin â lefel isel o sylffwr, a dylid hefyd monitro ymhellach pH priddoedd a dynameg ffosffad. Yn ogystal byddai'n werthfawr iawn pennu mesuriadau unigol glaswellt P, Fe pridd tynadwy a helaethrwydd coloneiddio ericoid mycorhisa. Byddai gwybodaeth o'r fath yn rhoi arweiniad pellach ar gyfer adfer rhostiroedd ar safleoedd tebygol eraill a byddai'n berthnasol iawn i safleoedd o fewn ardal arfordirol Cymru lle y mae priddoedd tebyg i'r hyn a geir ar y safle astudiaeth yma yn gyffredin iawn.

1. INTRODUCTION

The widespread intensification of British agriculture over the last century has resulted in dramatic declines in the extent of lowland heathland of high conservation value throughout the UK (Symes and Day, 2003). However, attempts to restore and re-create such lowland heathlands are invariably constrained as a result of adverse changes in plant and soil conditions following prolonged past agricultural activity. Most notably, ex-arable soils have elevated levels of soil fertility and pH resulting from regular applications of artificial fertiliser and lime. Soil pH in particular is usually too high for the successful establishment of ericaceous dwarf shrub species such as *Calluna vulgaris,* while sustained agricultural management practices tend to also change soil physical conditions and deplete potential seed-sources necessitating the need to import seed to restoration sites. A number of previous studies in the UK (Diaz *et al*. 2008 and 2006; Walker *et. al*. 2004 and 2007; Tibett and Diaz, 2005; Lawson *et.al*., 2004; Owen and Marrs, 2000; Dusford *et.al*. 1998; Pywell *et.al.,* 1994) have investigated the use of a range of restoration managements (e.g. soil stripping and/or sulphur applications) to provide conditions suitable for the re-creation of lowland heathland on ex-arable sites together with evaluating the necessity of importing suitable seed sources. The aim of this study was to evaluate the suitability of a number of such re-creation treatments on the success of restoring forms of 'coastal' heathland vegetation on ex-arable land adjacent to the coast of Pembrokeshire, West Wales.

The coastal belt of Wales supports significant areas of dry and maritime heath, however much of this heathland is restricted to a very narrow strip between the cliff edge and adjacent agricultural land. In Pembrokeshire, Anglesey and the Llŷn Peninsula large areas of the coast are owned by conservation organisations and as such provide opportunities for heathland re-creation by widening the coastal belt to include adjacent arable fields and pasture. It is hoped that the results from this project will provide guidance on the potential for further heathland re-creation on the coastal strip in Pembrokeshire and elsewhere in Wales.

As part of a larger project on restoring heathlands in Pembrokeshire this five year, CCW-funded, study specifically investigated the technical practicalities of recreating coastal heathland on ex-arable farmland using a combination of soil acidification through sulphur application, topsoil stripping and the addition of seed collected from existing heathland. The combination of treatments was designed to overcome problems of raised soil nutrient and high pH levels resulting from the long history of on-site arable management. The specific aim of the project was to assess the success of the various soil treatments in establishing target heathland communities by monitoring long-term changes in vegetation and soil chemistry. The fact that the study site lies within very close proximity of the coast and has poorly drained soils provides a unique assessment of the restoration potential for coastal heath vegetation on ex-arable land.

2. MATERIALS AND METHODS

2.1 Study site

The experiment was sited within a single 2 ha ex-arable field located at Trehill Farm on the Marloes Peninsula, Pembrokeshire (O.S. Ref: SM766082). A map of the site's location and an aerial photograph of the experiment are shown in Appendices 1 and 2. Historically the field had been used at various times for arable cropping and pasture and had been ploughed, limed and fertilised for many years. For the years immediately preceding the experiment the field had been used for successive potato cropping. The individual experimental field is named "Inner heath" and it reportedly supported some form of heathland vegetation in the past, prior to its agricultural use. The field is located about 100 m away from the cliff edge with strong winds/gales and salt spray from the sea clearly having an important influence on the site. In terms of climate the site lies within the same Hyper-oceanic subsector (Bendelow and Hartnup, 1980) as other regions of Wales that are associated with supporting types of coastal heathlands of high conservation value.

The soils of the experimental site are formed on glacial till (boulder clay) within a slightly concave coastal plain. A typical soil profile of the site is described in Appendix 3. The soil type was identified as the 'Brickfield 1' association of cambic stagnogley and stagno-humic gley soils (Soil survey of England and Wales, 1983) and belongs to the major group of surface-water gley soils that are characterized by imperfect drainage and seasonal water-logging.

The soil type and coastal situation of the site therefore provide unique conditions in the UK for studying the re-creation of heathland communities as most previous research on heathland restoration has been conducted on free-drained sandy soils away from immediate coast.

2.2 Restoration Targets

For this study it was not considered necessary or desirable to specify the re-creation of any specific NVC community or sub-community but rather to assess a number of general attributes and associated targets for Lowland/Maritime Heath based on the JNCC Common Standards Monitoring Guidance. However site specific soil and climatic conditions suggest that acceptable possible vegetation targets could include combinations and/or graduations of the following NVC communities: H8b (*Calluna vulgaris - Ulex gallii* Danthonia decumbens sub-community) 'Grass-heath' and H7 (*Calluna vulgaris - Scilla verna*) 'Maritime-heath' (Rodwell, 1991), both of which are represented within patches of unimproved land or narrow strips of coastal cliff vegetation in close proximity to the experimental site.

2.3 Experimental Treatments

The experiment was initially set up during Spring 2004 and consisted of a fully randomized block design involving 2 topsoil-stripping treatments (plus and minus top-soil removal), 3 application rates of elemental sulphur (Nil, Low and High) and with or without the addition of heather brashings as a potential seed source. These 12 treatments were replicated five times within separate blocks giving a total of 60 separate plots. Individual plot size was 10 x 10 m with at least a 5m buffer area between plots. Top-soil removal was achieved by stripping the uppermost 20-30 cm of soil of relevant plots using an excavator in spring 2004. Applications of elemental sulphur (supplied as a mixture of both fine and coarse granules by the near-by Texaco refinery at Milford Haven) were applied to treatments in early August 2004 using a conventional tractor-drawn lime-spreader. Plots were spread with either a low sulphur rate of 4t/ha or a high sulphur rate of 8t/ha or left untreated. The seed source consisted of a mixture of heather and gorse brash that had been previously collected from an area of common land undergoing heathland generation work located c.25 km from the experimental site (Plumstone Mountain, SM913230). Brash collection took place in October 2003 and 2004 to coincide with heather seed ripening. Seed-rich cuttings of *Calluna*, *Erica* spp. and *Ulex gallii*. were collected using a tractor with a double-chop forage harvester to cut and shred the material. After transportation to the site a thin layer of this heather brash was evenly spread over relevant plots.

2.4 Assessments

2.4.1 Soil Assessments

In April 2004, prior to any sulphur application treatments, all experimental plots were assessed to determine baseline soil conditions and initial macro-nutrient concentrations. A total of 10 individual soil cores (2.5cm diameter) were taken from each plot to a depth of 15 cm. On plots without soil-stripping treatment (i.e. where soil depth allowed) a separate set of samples was also taken from the lower 15-30 cm soil horizon. Resulting soil cores were then bulked within each plot and depth zone, air-dried and assessed for the following chemical determinations: pH, exchangeable cations (Ca, K, Na, Mg), Olsen extractable P and soil organic matter by ignition at 650^{o}C. In addition each individual plot was also assessed for average top-soil depth by taking measurements at 5 random locations per plot. Ten soil bulk-density determinations were also recorded from randomly located areas within two individual plots per block (one from a stripped and one from an unstripped treatment per block). In November 2004, after the summer applications of elemental sulphur to relevant treatments, all plots were re-sampled for pH determinations only. Thereafter, during April of each year between 2005 and 2008, annual sets of soil samples were taken for all soil nutrient determinations as above. All chemical analyses were undertaken by analytical staff of the University of Aberystwyth, using standard analytical techniques (MAFF 1986).

2.4.2 Botanical assessments

During June of each year between 2005 and 2008 all plots were assessed for botanical composition. Three permanent (2 x 2m) quadrats were established within each plot with each being assessed for percentage cover of all vascular plant species, bare-ground and brash. In addition, each plot was assessed for the presence of any other plant species found rooted outside the individual permanent quadrats to give an estimate of total species number on a whole plot basis.

2.5 Data analysis

In addition to the individual variables listed above a number of separate response variables were also calculated to further help assess the relative effectiveness of the treatments in terms of their progress towards the re-creation of heathland communities. These were based on the JNCC Common Standards Monitoring Guidance for Lowland Heathland (JNCC, 2004) and included the following: cumulative total cover of dwarf shrubs (i.e. *Calluna vulgaris, Erica cinerea, Erica tetralix, Ulex gallii*); number and cumulative total cover of 'desirable forbs' present (i.e. *Armeria maritima, Hypochoeris radicata, Lotus corniculatus, Plantago lanceolata, Plantago maritima, Potentilla erecta, Rumex acetosella*); cumulative total cover of 'Negative species' present (i.e. *Cirsium arvense, Digitalis purpurea, Epilobium spp. Juncus effusus, Juncus squarrosus, Ranunculus* spp. *Rumex obtusifolius, Urtica dioica*).

In addition, and in particular relation to the coastal situation of the study, two further derived variates were calculated based on the NVC 'H7' Maritime Heath (*Calluna vulgaris - Scilla verna*) community. These included the cumulative total cover of 'H7 constant species' present (i.e. *Calluna vulgaris, Erica cinerea, Plantago maritima, Lotus corniculatus, Potentilla erecta, Plantago lanceolata, Hypochoeris radicata*) and cumulative total cover of 'H7 preferential species' present (i.e. *Armeria maritima, Sedum anglicum, Anthyliss vulneraria, Jasione montana, Plantago coronopus, Centaurium erythraea, Silene uniflora*).

The distribution of each soil and plant variate were checked for normality using probability distribution plots using Genstat versions 8 and 9 and, where necessary using the most appropriate transformations, such as arcsin or square root. Effects of re-creation treatment and interactions between treatments and year were then examined for each soil and vegetation response variable using general analysis of variance (ANOVA) with repeated measures. Where an F probability of <0.05 was obtained Fisher's least significant difference test was used to examine treatment effects. A large number of zeros were present in the individual species data, which made normalisation of the distributions, prior to statistical analysis, not possible for some infrequent species.

3. RESULTS

3.1 Soil assessments

As anticipated the top-soil stripping treatment achieved immediate and significant differences in the prevailing physical soil conditions as assessed in April 2004, with stripped plots having a much reduced mean soil thickness (as defined by the depth of Ap+BG horizons able to be sampled by a soil corer) of 11cm and higher bulk density (mean of 1.1 g/cm^3) when compared with plots left unstripped (30 cm and 0.91 g/cm^3 respectively). However at the time of this initial baseline assessment there were no other statistically significant effects of soil-stripping on available soil macro-nutrient concentrations or pH recorded within the 0-15cm soil layer (Table 1). This was presumably a reflection of the field's long history of fertilizer and lime addition and regular deep ploughing mixing soil nutrients throughout the upper soil horizon. In general however these initial levels of major nutrients were broadly comparable with baseline nutrient concentrations encountered in similar heathland restoration studies carried out within ex-arable situations. Also, the addition of heather brash had no significant effects on any of the soil characteristics monitored throughout the course of the experiment.

Of the different re-creation treatments applied, the addition of Sulphur had by far the most influential effect on soil parameters, with only a few significant effects of soil stripping or interactions between the two factors:-

Effects of Sulphur applications on soil parameters

soil pH.

The addition of differential rates of elemental sulphur applied to plots during summer 2004 had rapid and highly significant effects on mean soil pH values. Even at the November 2004 sampling (i.e. only 6 months after the sulphur application) mean recorded baseline pH values of 7.0 were reduced to 5.60 and 4.25 under the Low and High S rates respectively within the upper (0 to 15cm) soil horizon (Table 1). The deeper (15-30 cm) soil horizon was similarly, although slightly less, acidified by the differential S rates (Table 2). There was even evidence of a slight reduction in the pH values of soil on the untreated control plots at the upper soil horizon probably due to partial and unavoidable contamination during the application process (probably by windblown sulphur particles). Between 2004 and 2008 the two rates of sulphur application continued to produce highly significant differences in levels of soil acidity (Figure 1) with the lowest values attained in 2007 (pH 4.68 and pH 3.39 for the Low and High S rates respectively). During the last sampling in 2008 there was evidence of a possible trend for pH levels to start to rise. However, by the end of the monitoring period pH values in both sulphur application treatments were close to the normal target range for the restoration of heathland communities. There were no observed effects of soil stripping on pH levels.

Exchangeable bases (Ca, K, Na, Mg).

The initial levels of exchangeable calcium recorded at both soil depths sampled were very high, up to ~2800 mg/kg, presumably as a result of regular liming during the former arable use. Under the Low-S treatment more than half of the exch. Ca was removed by leaching from the 0-15 cm layer by 2007; by the same time under the High-S treatment calcium concentrations within the 0-15 cm layer were reduced by 6-7 times compared to Nil-S control (Figure 2; Table 1). Within the 15-30 cm layer of unstripped plots the exch. Ca remained relatively stable under the Nil- and Low-S treatments, but decreased to less than 1000 mg/kg by 2007 under the High-S treatment (Table 2). As also reflected in the data for soil pH, plots treated with the low S rate showed an upward trend in Ca content during the last year of sampling.

Of the other exchangeable bases K^+, Na^+ and Mg^{2+}, all generally tended to decrease through leaching on High-S plots, however there are some annual fluctuations of these elements on Nil- and Low-S treated plots. In particular, there were peaks of exchangeable potassium on the second year of the experiment (2005) and to a lesser extent on the last year (2008) on plots with and without soil stripping within both 0-15 and 15-30 cm layers (Tables 1 & 2, Figure 3). For sodium and magnesium, fluctuations were observed mostly within the surface layer with a slight tendency for an increase under Nil- and Low-S treatments in the later years (Figures 4a, b). Generally, when comparing results from 2004 and 2008 the contents of K^+, Na^+ and Mg^{2+}remained broadly constant or slightly higher under Nil-S treatment, the same or slightly lower under Low-S, and considerably lower under the High-S treatments. The only significant and consistent effect of soil stripping on concentrations of exchangeable bases compared with unstripped plots was slightly higher concentrations of Na and Mg between 2005 and 2007 (Figures 4c, d).

extract. Olsen P. Prior to any sulphur applications mean baseline Olsen P concentrations were typical for recently fertilised ex-arable soils at around 30mg/kg (corresponding to DEFRA index 3) with no difference between the two soil depths sampled indicating the even distribution of P throughout the entire soil plough-depth. Although extract. P levels slightly decreased in untreated control plots throughout the monitoring period there were striking and highly significant increases in extract. P levels where sulphur was applied, particularly on plots treated with high S rates and without soil stripping (Figures 5a, b). For example by the time of the final sampling undertaken in 2008 there was nearly a four-fold difference in recorded extract. P levels between High S and Nil S treated plots within the upper 0-15cm soil level.

Organic Matter. The average content of soil OM estimated by Losses on ignition (LOI) was consistently at around 8% with no significant differences between experimental treatments observed between 2006 to 2008 (Table 1). The significantly higher LOI values of soils sampled from High-S plots recorded in 2005 can most likely explained by the remaining presence of flammable/volatile elemental sulphur within the samples. We chose to discard the LOI data of 2004 which had obviously significantly overestimated the OM content. This only became apparent when subsequent results for LOI were received and by checking against additional determinations of organic carbon and total N undertaken in 2005

3.2 Vegetation assessments

Annual monitoring of vegetation from the outset of the experiment in 2004, when plots were predominately bare-ground, allowed the opportunity to track the early successional changes resulting from the range of different soil conditions created. During the initial two years of monitoring a combination of a large number of arable weed, grassland and maritime species colonised the site but with few members of former group able to persist beyond the third year as total vegetation cover increased. Throughout the whole site this resulted in a progressive decline in overall total number of species recorded between 2005 (98 species) and 2008 (83 species). A complete list of species recorded within all plots between 2005 and 2008 is shown in Table 3. There were highly significant differences in the rates and direction of successional development of vegetation of plots depending on the different re-creation treatments applied:

Effect of Brash addition.

The addition of brash had a highly significant and beneficial effect on the total number of species present (Tables 4 & 5), and in particular on the number and mean cover of key target 'heath' species, able to establish under suitable treatments. This was most notable for important dwarf shrub heathland species such as *Calluna vulgaris*, *Erica cinerea* and *Ulex gallii*, none of which established on plots without the addition of brash. Brash addition also had a positive effect on the cover frequency of some other key target species such as *Molinia caerulea* and *Erica tetralix* although differences in mean cover values for the latter did not quite reach statistical significance. Thus by 2008 the introduction of these key target species via brash application contributed to significantly higher values for a number of important cumulative variables including: total % dwarf shrub cover, total % cover of 'desirable forbs' and total % cover and number of 'H7 constants' (Table 5). The only statistically significant effect of the unbrashed treatment on individual species cover was an increase in *Sagina procumbens* and to a lesser extent *Hypochaeris radicata*, the latter being one of the target forb species for dry heath.

Effects of Soil stripping & Sulphur addition:

Changes in physical soil conditions brought about by topsoil stripping generally had highly beneficial effects on many of the derived measures of plant diversity e.g. topsoil-stripped plots had significantly higher cover values of total forbs, the number and total cover of desirable forbs and cover of 'H7 preferential species', together with higher total mean species numbers at both the individual quadrat and plot scale (Table 5). Soil stripping also significantly benefited the establishment of a number of individual species encountered and notably a number of desirable target maritime species such as *Ulex gallii, Plantago coronopus, Plantago maritima, Sedum anglicum and Hypochaeris radicata* (Table 4). However, in contrast, by 2008 there was no evidence of any beneficial effect of topsoil stripping on the cover of *Calluna vulgaris* (arguably the most important target species) or on associated levels of total ericaceous species which in fact had significantly higher mean cover values on unstripped plots (see later section on ericaceous species). The vegetation cover of unstripped plots was also generally far more grass-dominant with an overall mean of more than 75% total grass cover still remaining by 2008 (Table 5). Moreover these unstripped plots had significantly higher cover values of individual 'coarse' grass species such as *Holcus lanatus* and *Elytrigia repens* and higher total cover values of other 'negative' (weed) species.

The application of different rates of sulphur also produced highly significant effects on the vegetation composition of plots (Figure 6). The high soil acidity created by the High S rate in both stripped and un-stripped treatments resulted in persistently high levels of bare-ground throughout the course of the experiment; maintaining a mean cover of 40% even four years after S was applied. This, when taken together with additionally higher cover levels of both litter and brash (cumulatively totalling a further 11% cover), resulted in the High S treated plots having a sparsely-vegetated appearance with very few individual species present; High-S plots had reduced species numbers at both the quadrat and plot scale compared to both the Nil or Low sulphur rate plots. The only species that had significantly higher mean cover levels on High-S treatments were the grasses *Molinia caerulea* (albeit at very low cover values) and *Elytrigia repens* (Table 4), with the latter seeming particularly tolerant of the extreme acidity and benefiting from the low level of plant competition. *E. repens* however, was generally less successful at colonizing soil-stripped plots. The only other major grass species able to tolerate the conditions under High-S treated plots was *Agrostis stolonifera*, although this was even more frequent on the Low-S and Nil-S treated plots.

In contrast to the High-S treatment, plots treated with either the Nil and Low rates of sulphur showed much higher rates and degrees of re-vegetation and species colonisation, whether with or without the addition of soil stripping (Figure 6). By the time of the 2008 assessment both of these treatments had very little remaining bare ground (mean cover values of <1% for Nil-S plots and 6% for Low-S plots) mostly due to significantly increased levels of grass cover (Figure 7a), primarily *Agrostis stolonifera* and *Holcus lanatus.* Moreover both the Nil and Low-S treatments also had progressively higher levels of total vegetation cover and total forb cover (Figure 7b) which by 2008 led to significantly increased measures of species richness compared with High S plots (Table 5). Although both the Nil and Low-S treated plots were broadly similar in terms of levels of species diversity and composition, a number of important and statistically significant differences had emerged by 2008; for example, Nil-S plots had a higher total forb cover and a greater number of total species, whereas, Low-S plots had a significantly greater cover of 'H7 constants' and greater cover values of a few individual target species such as *Armeria maritima* and, crucially, *Calluna vulgaris.*

The first observations of establishing ericaceous dwarf shrub species were recorded in 2007. By 2008, although mean cover values were still low (i.e. on average less than 2% cover), there were significantly greater cover values of total ericaceous species (Figure 8a), and individually for both *Calluna vulgaris* and *Erica cinerea* (Table 4), on plots that received sulphur applications, although there were no statistical differences between the Low and High S rates. By 2008 there was also evidence that the soil stripping treatment was significantly affecting the establishment of ericaceous species with greater establishment on unstripped plots compared with stripped plots. The cover of another important dwarf shrub *Ulex gallii* was also significantly affected by both sulphur rate (Figure 8b) and soil-stripping treatments (Table 4): however in this case with greater cover occurring on soil-stripped plots and on plots with either the Nil or Low-S rate. Of the other individual forb species considered desirable for the progression towards coastal dry-heath communities there were no clear pattern of response to Nil or Low S treatments with some species tending to be favoured more by the Nil S rate (e.g. *Festuca rubra, Hypochaeris radicata*) and others more frequent under the Low S treatment (e.g. *Armeria maritima, Plantago* spp.) (Table 4). However the mean total cover of 'H7 preferential species' (i.e. 'Maritime heath' specialists) was significantly higher when the Low S rate was applied in combination with topsoil stripping (Table 5).

4. DISCUSSION

4.1 Effects of Sulphur applications on soil conditions.

Results show that the addition of elemental sulphur was highly successful at ameliorating the soil pH conditions to help facilitate the early development of coastal heathland communities. The degrees of soil acidification following both rates of sulphur applied produced pH values within the target range for the restoration of heathland communities i.e. between pH 3.5 to 4.5. These findings generally agree with those first reported by Owen and Marrs (2000) and confirmed by several other more recent studies (e.g. Walker *et. al.* 2007; Tibbett and Diaz, 2005; Lawson *et. al*. 2004). However, there was evidence that pH values started to rise slightly again during the last year of the experiment, probably due to the dissolution of lime or calcareous compounds (e.g. limestone) still present within the soil. It is likely that this process will continue to some degree in the future as observed in studies by Pywell *et al*. (1994), where past liming history was seen to be affecting pH values thirteen years following the cessation of farming. Although low pH is a key soil factor in the establishment of *Calluna*, it was recently found that low pH can also prevent the development of ericoid mycorrhiza in the soil with possible consequences for the survival of newly-grown *Calluna* plants (Diaz *et.al*. 2006 & 2008). It would therefore be advisable to estimate the development of ericoid mycorrhiza in the soils of our site to help predict the future success of the establishment of heathland communities.

The soil acidification due to S applications also induced leaching of exchangeable bases, particularly Ca. However the losses of exchangeable bases through leaching were generally offset by two main factors. Firstly, the upward trend in Ca observed in the last year and the peak of K in the second year of experiment can be accounted for by the dissolution of residual fertilizers and lime. Secondly, the irregular increases in Na and also Mg are probably as a result of the input of sea-spray onto the site which is obviously a highly significant factor in such coastal situations. Indeed, in work by Malloch (1972) it was shown that at a distance of 100 m from the coast sea-spray can deposit more than one kilogram of sodium per hectare per day.

A potentially adverse side effect of the application of sulphur was an increase in soil Olsen available phosphate concentrations. The release of phosphate was presumably a result of the breakdown of calcium phosphate complexes (residual phosphate fertilizers) due to the high soil acidity levels created. This is an anticipated and commonly observed effect where elemental sulphur is applied to soil at high rates (Walker *et.al*., 2007; Diaz *et.al.* 2003 and 2008). Yet its nature is still not fully understood, because an opposite effect of lowering Olsen P was observed on sulphur-treated brown sands and explained by P sequestration in organic matter and its adsorption on mineral particles (Owen *et.al*., 1999). It seems unlikely that soil type/composition is the sole reason for the different responses of P following soil acidification, because the trend of rising Olsen P was observed in similar sulphur-treated brown sands (Walker *et.al*., 2007), and also in weakly podzolized sands (Diaz *et.al.* 2003) and the cambic stagnogley soils in our study. It appears that the higher the S dose and initial P content in ex-arable soil, then the greater increase in Olsen P that follows. However such increases in Olsen P are reported to be only a short-period effect (Walker *et.al*., 2007; Diaz *et.al.* 2008) and we therefore assume that in this experiment P levels will soon start to decrease, although this will clearly require further monitoring.

In our study without sulphur additions available phosphate tended to decrease gradually over time presumably through partial leaching and consumption by plants. However by the end of the monitoring period extractable P levels on plots treated by the Nil, Low and High sulphur rates corresponded to DEFRA P indices 2, 4 and 6, respectively i.e. all still above the level generally recommended by DEFRA for restoration of botanical diversity (i.e. indices 0 and 1). However, other recent work has shown that Olsen P of acid iron-rich soils is very weakly assimilated by swards, i.e., sward P remains low despite high soil Olsen P, and therefore, Olsen P may indeed be a poor indicator of plant-available phosphate in such situations (Tibbett and Diaz, 2005; Diaz *et.al*. 2008). This is probably the case in this site where soils were judged to be iron-rich due to observations of rusty mottles and iron oxide concentrations. Moreover evidence of the early establishment of heathland plant communities (see later) also indicates that high Olsen P in soil may not be a limiting factor in this study. Nevertheless in any further monitoring it would be informative to measure the contents of sward P and extractable Fe in soil.

4.2 Effects of soil stripping on soil conditions

In this study topsoil stripping did not result in any significant reductions of nutrient concentrations or organic matter within the surface layer due to the former mixing of nutrients throughout the whole plough layer through tillage. However in practice, topsoil removal probably led to a decrease in the total 'nutrient pool' exploitable by plant roots because only a thin layer of topsoil was left remaining. The appearance of a dense, stony clay loam BG horizon close to the surface within such stripped plots also implies that soil physical conditions were significantly altered, i.e. soils present on stripped plots were generally wetter and harder. As a result the less well drained soils on stripped plots hindered all the leaching processes and favoured the greater accumulation of salts from sea spray. This would account for the higher observed percentages of exchangeable bases (Ca^{2+}, K^{+}, Na^{+} and Mg^{2+}) on stripped plots compared to unstripped plots. At the same time, the process of acid-induced release of phosphate appeared less developed on stripped plots, which presumably had lower reserves of residual phosphate fertilizers compared to unstripped plots.

4.3 Effects of re-creation treatments on vegetation

In common with many other heathland re-creation studies on ex-arable land, seed addition (via brash) was seen to be essential at this site for introducing propagules of key ericaceous species such as *Calluna vulgaris* and *Erica cinerea* and other important target dwarf shrubs such as *Ulex gallii*. Therefore on similar ex-arable coastal sites situated far from existing heathland such brash additions would be highly advisable. However in this study the close proximity of other naturally occurring maritime forb species found growing on the nearby cliff edge resulted in high rates of natural colonisation without the need for any further active seed introductions of maritime species. A number of other desirable maritime species have yet to colonise the experimental area (e.g. *Scilla verna*, *Thymus praecox, Viola riviniana, Galium saxatile*) but their presence also on cliff sides close to the site experimental indicate that they may well colonise certain plots in the future as favourable conditions continue to develop.

The different soil re-creation treatments had highly variable effects on the successional development of vegetation. Within the timescale of the project it was established that the

High S rate (8t/ha) was too high with the acid-induced toxicity of soil producing poor results in terms of the development of target vegetation types. i.e. after four years stripped plots still maintained high levels of bare ground with only a few acid-tolerant plants or alternatively patchy species-poor grass-heath on unstripped plots (see photographs shown in Appendix 6). However even with the unpromising early indications of this High S treatment some *Calluna vulgaris* plants were able to establish despite the high soil acidity and in future may well even benefit from the combination of generally open vegetation with areas of grass offering some protection for establishing seedlings in the exposed coastal conditions. In the future there is also the possibility that new ericaceous seedlings may emerge if and when soil acidity decreases over time. This is of particular relevance to this study as it has been shown that the long-term success of *Calluna* establishment is determined by the development of ericoid mycorrhiza and that the survival of newly-grown *Calluna* on sulphur-treated sites is uncertain due to poorly developed mycorrhiza (Diaz *et.al*. 2006 and 2008).

The Nil sulphur treatment was also generally unsuccessful in that ericaceous species such as *C. vulgaris* generally failed to establish due to the inherently high pH values. Moreover, unstripped Nil S plots tended to acquire a dense cover of coarse grasses (such as *H. lanatus* and *A. stolonifera*) which are likely to inhibit any further establishment of dwarf shrub and forb species. Stripped Nil-S plots, on the other hand, supported a generally sparse, grass-herb cover with higher overall levels of species richness and total forb cover. This treatment also appeared the most favourable for the establishment of *Ulex gallii* (see photographs shown in Appendix 4).

To date the Low rate of sulphur (4t/ha) appeared the most beneficial treatment for the establishment of ericaceous species and target heathland communities. This agrees with findings of other related studies such as Owen and Marrs (2000) and Walker *et al*. (2007). Under this treatment, despite the aforementioned excess levels of extractable phosphate, the early establishment of target heathland species such as *Calluna vulgaris, Erica* spp. and *Ulex* spp indicated the sites potential for supporting heathland communities. Although the overall cover of these dwarf shrub species is still low this is the usual case for such experiments with rapid increases in shrub cover only occurring four or five years after initial seedling establishment. Under this Low S treatment it is still too soon to predict which specific re-creation treatment will be the most successful at creating coastal heathland yet there were some interesting and contrasting trends emerging in the successional development of vegetation due to the different effects of +/- topsoil stripping; most strikingly the changes in soil physical conditions brought about by topsoil removal resulted in differences in the degrees of overall vegetation cover, particularly grass domination, which in turn had important implications for the further development of either 'grass-heath' or 'maritime heath' type communities: i.e. on the unstripped low-S treatment ericaceous species grew well under the protection of high levels of grass cover yet otherwise these plots had only poorly developed forb cover and thus resembled early-successional stage grass-heath (NVC 'H8'b community). Whereas on the less well vegetated grass-poor thin soils of stripped plots ericaceous plants were relatively small but frequent (personal observation) and with the more open conditions far more receptive to the establishment of wind-blown seeds of target maritime species thus giving a generally more 'maritime heath' (NVC 'H7') character to the establishing community (see photographs shown in Appendix 5). The conditions created by Low S and soil stripping also tended to be more effective at suppressing the growth and colonisation of potentially 'negative' (weed) species such as *Cirsium* spp., *Urtica dioica,* *Rumex* spp. and *Digitalis purpurea* particularly under the additional stress of prevailing sea spray.

As the successional development of vegetation of plots is still at an early stage it is clearly too soon to confidently ascertain which re-creation treatments will lead to the most successful restoration of coastal heathland. However, from the results to date we can draw the following preliminary conclusions:

1. Brash was essential as a seed source for the introducion of key ericaceous/dwarf shrub species. However there was no need for the active introducion of seed of other 'maritime' forb species as many of these were capable of colonising suitable treatments by natural means (i.e. by wind and/or animal dispersal).

2. Soil pH levels became suitable for heathland development only where sulphur was applied. To date, sulphur addition at the low rate of 4t/ha was the most effective at lowering the soil pH to a suitable range with the high rate of 8t/ha being generally excessive having highly toxic effects on plant growth. However this could change over time if further dissolution of soil based calcium occurs. Sulphur applications also led to much increased extractable P levels but this did not prevent the early establishment of ericaceous dwarf shrub species.

3. Within the timescale of the experiment the beneficial effect of soil stripping was still unclear with no direct benefit of topsoil stripping on the establishment of the overall total cover of dwarf shrub species. Indeed unstripped plots resulted in a greater cover of total ericaceous species whereas stripped plots had significantly higher cover values of *Ulex gallii*. However topsoil stripping did create soil conditions that favoured the development of forb-rich 'maritime' vegetation, particularly when combined with the Low rate of sulphur.

4. From the results to date it is clear that all the above processes are still highly dynamic and that the long-term effects of re-creation treatments can only be confidently assessed by additional monitoring of soils and vegetation, particularly the further growth and colonisation of ericaceous species. In addition, to acquire a greater understanding of the dynamics of these species due to the different treatments it would be advisable to carry out population biology studies including assessments of seedling recruitment together with individual plant growth and survival rates. In terms of soils the most important variables to monitor include: a) pH and calcium; to understand the dynamics of acidification with consecutive leaching of calcium and release of phosphate from rock fertilizer dissolution, and b) extractable phosphate; the role and long term dynamics of P is a crucial factor in heathland restoration. Additional single measurements of sward P, soil extractible Fe and the extent of ericoid mycorrhiza colonization would also be highly informative in further elucidating the processes governing heathland development of the particular soils of the experimental site.

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Table 1. Summary of soil monitoring data 2004 to 2008 (0 – 15 cm soil depth). Mean effects of soil stripping, sulphur application rates and soil/Sulphur combinations.

Soil parameters	Sample Date	Means of sulphur rates and soil-stripping treatments						L.s.d. (5%)	Means Sulphur rates			L.s.d. (5%)	Means Soil stripping		L.s.d. (5%)
		Nil S		Low S		High S									
		Unstrip.	Strip.	Unstrip.	Strip.	Unstrip.	Strip.		Nil S	Low S	High S		Unstrip.	Strip.	
pH	Apr. '04	6.98	7.21	7.01	6.97	6.93	7.01	0.313ns.	7.1	7.0	7.0	0.221ns	6.99	7.09	0.181ns
	Nov. '04	6.82	6.69	5.47	5.73	4.01	4.49	0.624ns.	6.76	5.60	4.25	0.439***	5.43	5.64	0.358ns.
	Apr. '05	6.75	6.57	4.90	5.65	3.44	3.47	0.539ns.	6.66	5.28	3.45	0.382***	5.03	5.23	0.311ns.
	Apr. '06	6.87	6.65	5.31	5.84	3.60	3.79	0.585ns.	6.76	5.58	3.69	0.413***	5.26	5.42	0.337ns
	Apr. '07	6.59	6.38	4.29	5.08	3.36	3.42	0.721ns.	6.48	4.68	3.39	0.510***	4.75	4.96	0.416ns.
	Apr. '08	6.44	6.21	5.42	5.43	3.51	3.49	0.499 ns.	6.33	5.42	3.50	0.353***	5.12	5.05	0.288 ns.
Ca, mg/kg	Apr. '04	2698	2829	2753	2669	2608	2973	369 ns.	2764	2711	2791	261ns.	2686	2824	213ns.
	Apr. '05	1999	2128	1420	1613	613	995	397.2 ns	2064	1576	804	280.8***	1579	1344	229.3 *
	Apr. '06	2105	2056	1231	1590	277	562	354.6 ns.	2080	1411	419	250.8***	1204	1403	204.8 ns.
	Apr. '07	1673	1625	826	1182	214	389	350.2 ns.	1649	1004	302	247.6***	905	1065	202.2 ns.
	Apr. '08	1854	1723	1173	1238	165	274	307.6ns	1788	1206	220	217.5***	1064	1078	177.6ns
K, mg/kg	Apr. '04	138	146	136	145	154	151	15.2ns.	142	141	152	10.75ns.	143	147	8.78ns.
	Apr. '05	248	238	188	199	142	164	42.7 ns	243	194	153	30.2 ***	200	193	24.6 ns.
	Apr. '06	205	173	146	146	94	96	30.3 ns.	189	146	95	21.23***	148	138	17.34 ns.
	Apr. '07	182	156	119	131	90	92	25.68 ns.	169	125	91	18.16***	130	126	14.83 ns.
	Apr. '08	215	181	155	152	106	97	24.21ns	198	153	102	17.12***	159	143	13.98*
Na, mg/kg	Apr. '04	274	210	213	186	239	209	48.5 ns.	242	199	224	34.3ns.	242	201	28.0ns.
	Apr. '05	237	338	147	210	123	220	74.4 ns	288	178	171	52.9***	169	356	42.9***
	Apr. '06	167	217	99	161	93	110	41.26 ns.	192	130	102	29.18***	120	163	23.8 ***
	Apr. '07	213	251	144	206	90	152	49.2 ns.	232	175	121	34.95***	149	203	28.53***
	Apr. '08	229	218	159	184	104	139	29.4ns	224	172	122	20.79***	164	181	16.98ns
Mg, mg/kg	Apr. '04	236	222	224	224	243	236	18.0 ns.	229	224	239	12.7ns.	234	227	10.4ns.
	Apr. '05	230	258	126	198	114	155	49.6 ns	244	162	135	35.1***	157	204	28.6**
	Apr. '06	219	222	97	157	40	57	42.87 ns.	220	127	49	30.31***	119	145	24.75 *
	Apr. '07	212	223	97	158	80	111	28.51 ns.	218	127	96	20.16***	130	164	16.46 *
	Apr. '08	287	243	149	170	44	48	41.00ns	265	160	46	28.99***	160	154	23.67ns
Olsen P, mg/kg	Apr. '04	26.7	26.4	29.7	25.8	29.6	26.7	5.17ns	26.6	27.7	28.1	3.66ns	28.7	26.3	2.996ns.
	Apr. '05	18.0	18.7	43.2	26.6	45.1	36.4	8.68*	18.3	34.9	40.8	6.14***	35.4	27.2	5.01**
	Apr. '06	24.2	21.4	66.8	40.6	102.0	66.5	23.26ns.	22.8	53.7	84.3	16.45***	64.3	42.8	13.43**
	Apr. '07	13.3	12.0	53.1	27.9	55.7	49.7	11.98*	12.6	40.5	52.7	8.47***	40.7	29.8	6.92**
	Apr. '08	21.8	17.2	53.3	32.1	80.5	66.8	11.72ns	19.5	42.7	73.6	8.29***	51.9	38.7	6.77***
Tot. N, %	Apr. '05	0.35	0.36	0.35	0.34	0.39	0.34	0.036ns	0.36	0.35	0.37	0.025ns	0.37	0.35	0.02ns
Corg., g/kg	Apr. '05	44.1	45.1	43.9	45.1	46.7	44.6	4.57ns.	44.6	44.5	45.7	3.23ns.	44.91	44.92	2.64 ns.
LOI %	Apr. '05	8.04	8.41	8.70	8.88	9.77	9.33	0.876***	8.23	8.79	9.55	0.619***	8.84	8.87	0.506ns.
	Apr. '06	8.43	8.11	8.11	7.96	8.78	8.53	0.928ns.	8.27	8.03	8.65	0.656ns.	8.44	8.20	0.536ns.
	Apr. '07	8.82	8.71	8.57	8.48	9.73	8.85	1.054 ns.	8.76	8.52	9.29	0.750 ns.	9.04	8.86	0.61 ns.
	Apr. '08	8.03	8.07	8.22	7.79	8.22	7.95	0.930 ns.	8.20	8.00	8.08	0.658 ns.	8.26	7.94	0.537 ns.

Table 2. Summary of soil monitoring data 2004 to 2008 (15–30 cm soil depth). Mean effect of sulphur rate (unstripped plots only).

Soil parameters	Sampling date	Means Sulphur rate			
		Nil	Low	High	L.s.d. (5% level)
pH	April 2004	6.9	7.1	6.8	0.26ns
	November 2004	7.09	6.40	5.56	0.297***
	April 2005	6.74	6.15	5.65	0.259***
	April 2006	7.04	6.57	5.93	0.333***
	April 2007	6.72	6.03	4.93	0.384***
	April 2008	6.58	6.26	4.73	0.340***
Ca, mg/kg	April 2004	2907	2778	2716	423 ns.
	April 2005	2114	2230	2177	355.3 ns.
	April 2006	2148	2187	1921	342.1 ns.
	April 2007	1857	1737	830	415.8***
	April 2008	2023	1829	758	411.7***
K, mg/kg	April 2004	150	157	150	27.0ns.
	April 2005	166	176	199	30.3ns.
	April 2006	144	162	180	29.58ns.
	April 2007	136	132	111	32.83ns
	April 2008	155	144	124	26.61ns
Na, mg/kg	April 2004	158	145	164	24.7 ns.
	April 2005	176	143	123	36.8*
	April 2006	161	125	106	27.54**
	April 2007	209	179	105	42.25***
	April 2008	201	152	96	22.7***
Mg, mg/kg	April 2004	212	210	224	25.3 ns.
	April 2005	173	164	166	34.7 ns.
	April 2006	169	161	135	34.61 ns.
	April 2007	170	142	56	29.47***
	April 2008	180	147	61	23.48***
Olsen P, mg/kg	April 2004	26.1	29.2	31.8	6.41ns.
	April 2005	19.1	23.2	23.6	4.16ns.
	April 2006	22.0	28.8	29.4	8.13ns.
	April 2007	14.2	18.7	32.3	8.17***
	April 2008	16.3	23.0	48.0	8.03***
Tot. N, %	April 2005	0.34	0.35	0.37	0.043ns.
Corg., g/kg	April 2005	42.0	44.7	44.4	5.90ns.
LOI %	April 2005	7.59	7.71	8.23	1.073ns.
	April 2006	7.94	7.74	8.46	0.931ns.
	April 2007	8.58	8.66	8.99	1.147ns
	April 2008	7.70	7.61	8.20	1.118ns

Table 3. Individual species recorded within experimental plots between 2005 and 2008.

Species	Years 2005	2006	2007	2008
Dwarf shrubs				
Calluna vulgaris		+	+	+
Erica cinerea			+	+
Erica tetralix			+	+
Ulex gallii	+	+	+	+
Ulex europaeus	+	+	+	+
Grasses				
Agrostis capillaris	+	+	+	+
Agrostis stolonifera	+	+	+	+
Aira praecox	+	+		
Alopecurus geniculatus	+			+
Anthoxanthum odoratum		+	+	+
Arrhenatherum elatius	+	+	+	+
Avena fatua	+	+		
Bromus hordeaceus	+	+	+	+
Catapodium marinum	+			
Cynosurus cristatus		+		+
Dactylis glomerata	+	+	+	+
Elytrigia repens	+	+	+	+
Festuca rubra	+	+	+	+
Holcus lanatus	+	+	+	+
Lolium perenne	+	+	+	+
Mollinia caerulea			+	+
Poa annua	+	+	+	+
Poa trivialis	+	+	+	+
Sedges				
Carex demisa			+	
Rushes				
Juncus bufonius	+	+	+	+
Juncus effusus			+	+
Forbs				
Achillea millefolium	+	+	+	+
Anagallis arvensis	+	+	+	+
Anthyllis vulneraria	+	+	+	+
Arctium minus	+	+	+	+
Armeria maritima	+	+	+	+
Bellis perennis	+	+	+	+
Beta vulgaris	+	+	+	
Brassica rapa	+			
Capsella bursa-pastoris	+			
Centaurium erythraea	+	+	+	+
Cerastium glomeratum	+	+		
Cerastium fontanum	+	+	+	+
Chamaenerion angust.		+	+	+
Chenopodium album	+	+	+	+
Cirsium arvense	+	+	+	+
Cirsium palustre				+
Cirsium vulgare	+	+	+	+
Cochlearia danica	+			
Coronopus didymus	+	+		
Crepis capillaris	+	+	+	+
Crithmum maritimum	+			
Daucus carota	+	+	+	+
Digitalis purpurea	+	+	+	+
Epilobium ciliatum	+	+	+	+
Epilobium parviflorum	+	+	+	+
Eupatorium cannabium		+	+	+
Euphorbia helioscopia	+			
Fumaria muralis	+			
Geranium dissectum	+	+	+	+
Gnaphalium uliginosum	+	+		
Heracleum sphondylium	+	+	+	

Species	Years 2005	2006	2007	2008
Forbs (continued)				
Hypericum humifusum	+	+	+	+
Hypochaeris radicata	+	+	+	+
Jasione montana	+	+	+	+
Kickxia elatine	+	+	+	
Leontodon autumnalis		+	+	+
Leontodon hispidus	+	+	+	
Lepidium heterophyllum	+			
Lotus corniculatus	+	+	+	+
Lotus pedunculatus			+	+
Matricaria discoidea	+			
Myosotis arvense	+			
Odontites vernus	+	+	+	+
Persicaria maculosa	+	+	+	+
Plantago coronopus	+	+	+	+
Plantago lanceolata	+	+	+	+
Plantago major	+	+	+	+
Plantago maritima	+	+	+	+
Polygonum aviculare	+	+	+	+
Potentilla anserina	+	+	+	+
Potentilla erecta		+	+	+
Prunella vulgaris		+	+	+
Pulicaria dysenterica	+	+	+	+
Ranunculus acris		+		
Ranunculus flammula				+
Ranunculus repens	+	+	+	+
Rubus fruticosus agg.	+	+	+	+
Rumex acetosa				+
Rumex acetosella	+	+	+	+
Rumex crispus	+	+	+	+
Rumex obtusifolius		+		+
Sagina procumbens	+	+	+	+
Sedum anglicum	+	+	+	+
Senecio jacobaea	+	+	+	+
Senecio vulgaris	+		+	+
Silene dioica	+		+	
Silene uniflora	+	+	+	+
Solanum dulcamara	+			
Sonchus arvensis	+	+	+	+
Sonchus asper	+	+	+	+
Spergula arvensis	+	+	+	
Spergularia rupicola	+	+	+	+
Stachys arvensis	+	+		
Stachys officinalis	+		+	
Stellaria media	+	+	+	+
Taraxacum aggregate	+	+	+	+
Teucrium scorodonia	+	+	+	+
Thymus polytrichus	+	+	+	+
Trifolium arvense	+	+		
Trifolium dubium	+	+	+	+
Trifolium hybridum	+			
Trifolium pratense	+			
Trifolium repens	+	+	+	+
Tripleurosper. inodorum	+	+	+	+
Tripleurosper. maritin.	+	+	+	
Tusillago farfara	+	+		
Urtica diotica				+
Veronica chamaedrys	+			
Veronica officinalis		+		
Veronica serpyllifolia	+	+	+	+
Vicia hirsuta	+	+	+	+
Vicia sativa	+	+	+	+
Viola arvensis	+	+	+	
Total number of spp.	98	92	83	83

Table 4. Effects of re-creation treatments on the mean cover (%) of the 30 most abundant species, June 2008.

Species	Means of sulphur rates and soil-stripping treatments						L.s.d.	Means Sulphur rates			L.s.d.	Means Soil stripping		L.s.d.	Means Brash treatments		L.s.d.
	Nil S		Low S		High S												
	Unstrip.	Strip.	Unstrip.	Strip.	Unstrip.	Strip.	(5%)	Nil S	Low S	High S	(5%)	Unstrip.	Strip.	(5%)	+Brash	-Brash	(5%)
Dwarf shrubs																	
Ulex gallii	1.27	2.56	0.33	2.33	0.00	0.30	1.113*	1.91	1.18	0.15	0.787**	0.43	1.73	0.642***	2.16	0.00	0.642***
Calluna vulgaris	0.00	0.09	2.48	0.73	1.61	1.00	1.128 ns.	0.04	1.61	1.30	0.797**	1.36	0.61	0.651*	1.97	0.00	0.651***
Erica cinerea	0.00	0.00	0.26	0.04	0.30	0.36	0.309 ns.	0.00	0.15	0.33	0.219*	0.19	0.13	0.179 ns.	0.32	0.00	0.179***
Ulex europaeus	0.00	0.40	0.38	0.00	0.00	0.00	0.464 ns.	0.20	0.19	0.00	0.328 ns.	0.13	0.13	0.268 ns.	0.26	0.00	0.268 ns.
Grasses																	
Agrostis stolonifera	45.3	29.0	36.3	37.1	7.10	20.0	8.92***	36.3	36.7	13.6	6.31***	29.0	28.7	5.15ns	32.3	25.4	5.15**
Elytrigia repens	9.30	1.90	27.0	3.10	38.0	12.5	8.08**	5.60	15.0	25.2	5.72***	24.8	5.80	4.67***	17.5	13.1	4.67**
Holcus lanatus	30.4	17.3	21.6	10.7	1.10	1.80	6.84*	23.9	16.2	1.40	4.84***	17.7	10.0	3.95***	12.8	14.8	3.95 ns.
Agrostis capillaris	0.98	1.78	2.42	1.34	1.77	0.99	2.081 ns.	1.38	1.88	1.38	1.472 ns.	1.72	1.37	1.202 ns.	1.44	1.65	1.202 ns.
Festuca rubra	1.31	1.06	1.37	0.22	0.03	0.00	0.897 ns.	1.18	0.79	0.02	0.634**	0.90	0.43	0.518 ns.	0.56	0.76	0.518 ns.
Arrhenatherum elatius	2.61	0.02	0.33	0.20	0.00	0.00	1.496*	1.31	0.27	0.00	1.058*	0.98	0.07	0.864*	0.38	0.67	0.864 ns.
Molinia caerulea	0.00	0.01	0.06	0.05	0.38	0.53	0.333 ns.	0.01	0.06	0.45	0.235***	0.14	0.20	0.192 ns.	0.34	0.00	0.192***
Dactylis glomerata	0.30	0.06	0.10	0.03	0.00	0.03	0.237 ns.	0.18	0.07	0.02	0.167 ns.	0.13	0.04	0.137 ns.	0.16	0.02	0.137 ns.
Forbs																	
Sagina procumbens	0.43	27.1	0.34	11.3	0.17	0.61	6.548***	13.9	5.84	0.39	4.630***	0.31	13.0	3.781***	4.42	8.92	3.781*
Senecio jacobaea	3.39	2.12	1.24	1.66	0.01	0.27	1.082 ns.	2.76	1.45	0.14	0.765***	1.55	1.33	0.625 ns.	1.43	1.46	0.625 ns.
Plantago coronopus	0.07	3.20	0.00	4.12	0.03	1.27	2.012 ns.	1.63	2.06	0.65	1.423 ns.	0.03	2.86	1.162***	0.97	1.93	1.162 ns.
Spergularia rupicola	0.00	0.10	0.00	1.02	2.85	2.17	1.704 ns.	0.05	0.51	2.51	1.205***	0.95	1.10	0.984 ns.	0.40	1.65	0.984*
Plantago maritima	0.45	1.93	0.57	2.11	0.10	0.58	0.972 ns.	1.19	1.34	0.34	0.688*	0.37	1.54	0.561***	0.83	1.09	0.561 ns.
Trifolium repens	0.05	1.79	0.02	2.01	0.00	0.07	1.097*	0.92	1.02	0.03	0.776*	0.02	1.29	0.633***	0.33	0.98	0.633*
Crepis capillaris	1.01	1.31	0.27	0.33	0.00	0.13	0.472 ns.	1.16	0.30	0.07	0.334***	0.43	0.59	0.273 ns.	0.53	0.48	0.273 ns.
Plantago lanceolata	0.80	0.86	0.05	0.93	0.00	0.03	0.872 ns.	0.83	0.49	0.02	0.616*	0.28	0.61	0.503 ns.	0.59	0.30	0.503 ns.
Silene uniflora	0.00	0.00	0.00	0.00	1.72	0.00	1.074*	0.00	0.00	0.86	0.759*	0.57	0.00	0.620 ns.	0.13	0.44	0.620 ns.
Trifolium dubium	0.03	1.25	0.00	0.42	0.00	0.00	0.552**	0.64	0.21	0.00	0.390**	0.01	0.56	0.319 ns.	0.26	0.31	0.319 ns.
Hypochaeris radicata	0.16	0.68	0.03	0.37	0.00	0.03	0.323 ns.	0.42	0.20	0.02	0.228**	0.06	0.36	0.186**	0.11	0.32	0.186*
Digitalis purpurea	0.12	0.00	1.00	0.00	0.08	0.00	0.785 ns.	0.06	0.50	0.04	0.559 ns.	0.40	0.00	0.453 ns.	0.36	0.04	0.453 ns.
Sedum anglicum	0.02	0.01	0.00	0.28	0.00	0.85	0.559 ns.	0.01	0.14	0.42	0.395 ns.	0.01	0.38	0.323*	0.08	0.31	0.323 ns.
Rumex acetosella	0.18	0.00	0.00	0.11	0.03	0.67	0.784 ns.	0.09	0.05	0.35	0.554 ns.	0.07	0.26	0.452 ns.	0.28	0.05	0.452 ns.
Anthyllis vulneraria	0.02	0.37	0.00	0.44	0.00	0.00	0.441 ns.	0.19	0.22	0.00	0.311 ns.	0.01	0.27	0.254*	0.17	0.12	0.254 ns.
Vicia sativa	0.41	0.27	0.11	0.02	0.00	0.00	0.284 ns.	0.34	0.06	0.00	0.201**	0.17	0.09	0.164 ns.	0.17	0.10	0.164 ns.
Taraxacum agg.	0.50	0.11	0.02	0.03	0.00	0.00	0.202**	0.31	0.03	0.00	0.143***	0.17	0.05	0.117*	0.09	0.13	0.117 ns.
Armeria maritima	0.04	0.10	0.18	0.23	0.00	0.01	0.198 ns.	0.07	0.21	0.00	0.140*	0.07	0.11	0.11 ns.	0.10	0.09	0.114 ns.

Note: Desirable species listed as H7 and H8 constants (Rodwell, 1991) are shown in bold.

Table 5. Effect of re-creation treatments on derived variates

Derived variates (Mean values)	Means of sulphur rates and soil-stripping treatments						L.s.d.	Means Sulphur rates			L.s.d.	Means Soil stripping		L.s.d.	Means Brash treatments		L.s.d.
	Nil S		Low S		High S												
	Unstrip.	Strip.	Unstrip.	Strip.	Unstrip.	Strip.	(5%)	Nil S	Low S	High S	(5%)	Unstrip.	Strip.	(5%)	+Brash	-Brash	(5%)
Total cover of ericaceous spp., %	0.01	0.09	2.79	0.77	1.91	1.38	1.290ns.	0.05	1.78	1.64	0.912***	1.57	0.75	0.745*	2.31	0.01	0.745***
Total cover of *Ulex* spp., %	1.27	2.96	0.42	2.33	0.00	0.30	1.179ns.	2.11	1.38	0.15	0.833***	0.56	1.86	0.680***	2.42	0.00	0.680***
Total cover of dwarf shrubs, %	1.28	3.05	3.20	3.11	1.91	1.68	1.943ns.	2.16	3.16	1.79	1.374ns.	2.13	2.61	1.122ns.	4.73	0.01	1.122***
Total cover of all grasses, %	88.8	51.4	89.4	52.9	48.4	36.1	11.46**	70.1	71.1	42.3	8.10***	75.6	46.8	6.62***	65.7	56.6	6.62**
Total cover of all forbs, %	9.9	42.3	5.2	26.2	5.3	7.2	8.53***	26.1	15.7	6.2	6.03***	6.8	25.2	4.93***	12.7	19.4	4.93**
Total cover of 'desirable forbs', %	1.85	3.57	0.83	3.78	0.13	1.32	1.893 ns.	2.71	2.31	0.73	1.339*	0.94	2.89	1.093***	1.95	1.88	1.093***
Total cover of 'H7 constant spp'.,%	1.63	3.56	3.40	4.21	2.01	2.01	2.060 ns.	2.60	3.80	2.01	1.457*	2.34	3.26	1.189 ns.	3.85	1.75	1.189 ***
Total cover of 'H7 preferential' spp., %	0.14	3.79	0.18	5.14	1.75	2.17	2.495*	1.97	2.66	1.96	1.764 ns.	0.69	3.70	1.441***	1.48	2.92	1.441***
Total cover of 'negative' spp., %	4.18	2.34	2.35	1.81	0.26	0.27	1.370 ns.	3.26	2.08	0.26	0.969***	2.26	1.47	0.791*	2.07	1.67	0.791*
Total spp. number	9.67	14.9	8.27	12.0	3.50	7.53	1.921 ns.	12.3	10.2	5.52	1.359***	7.14	11.5	1.109***	10.0	8.6	1.109***
Total spp. number per plot #	20.0	26.6	17.5	20.9	12.1	16.2	5.39 ns.	23.3	19.2	14.1	3.81***	16.5	21.2	3.11**	20.1	17.7	3.11 ns.
Total forb number	5.57	10.7	4.13	8.03	1.33	3.77	1.738 ns.	8.13	6.08	2.55	1.229***	3.68	7.50	1.004***	6.04	5.13	1.004***
Number of 'desirable forbs'	0.77	1.60	0.33	1.43	0.07	0.40	0.456 ns.	1.18	0.88	0.23	0.323***	0.39	1.14	0.263***	0.69	0.84	0.263***
Number of 'H7 constant' spp.	0.63	0.87	0.40	1.53	1.37	0.77	0.467 ns.	1.08	1.12	0.58	0.330**	0.63	1.22	0.270***	1.16	0.70	0.270***

(n.b. all above variates are mean values per quadrat, except for # which is calculated on a whole plot basis)

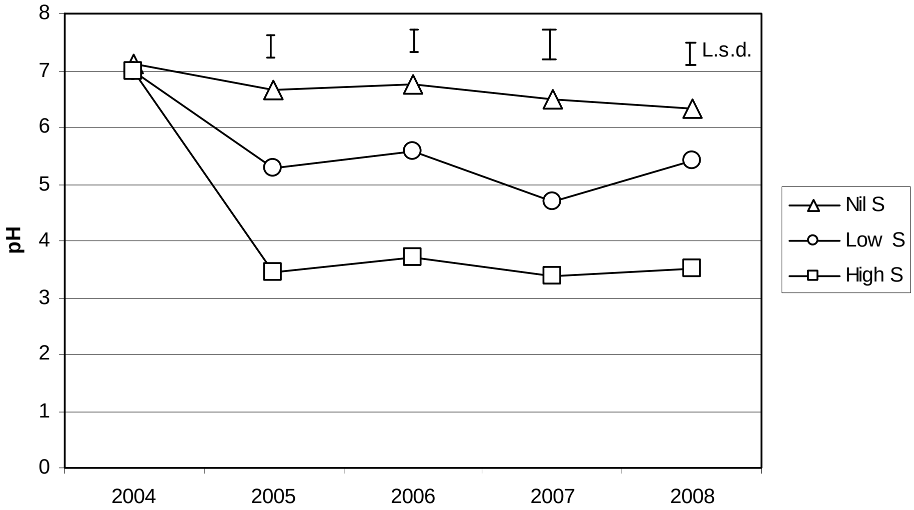

Figure 1. Effect of sulphur rates on soil pH (0-15 cm depth, mean of stripped and unstripped plots)

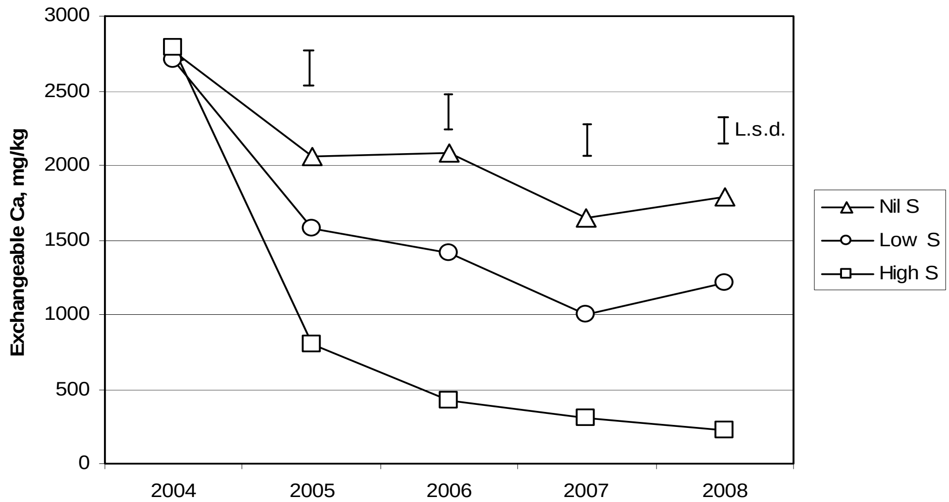

Figure 2. Effect of sulphur rates on soil exch. Ca (0-15 cm depth, mean of stripped and unstripped plots)

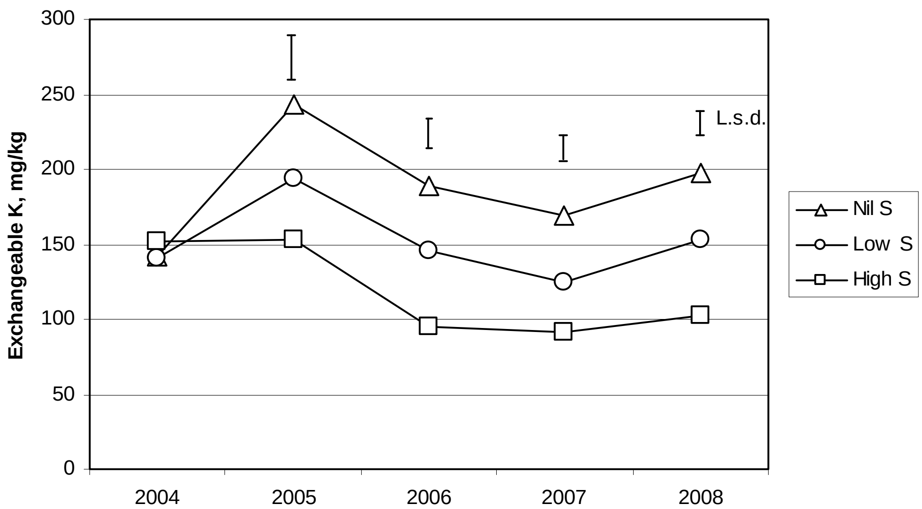

Figure 3. Effect of sulphur rates on soil exch. K (0-15 cm depth, mean of stripped and unstripped plots)

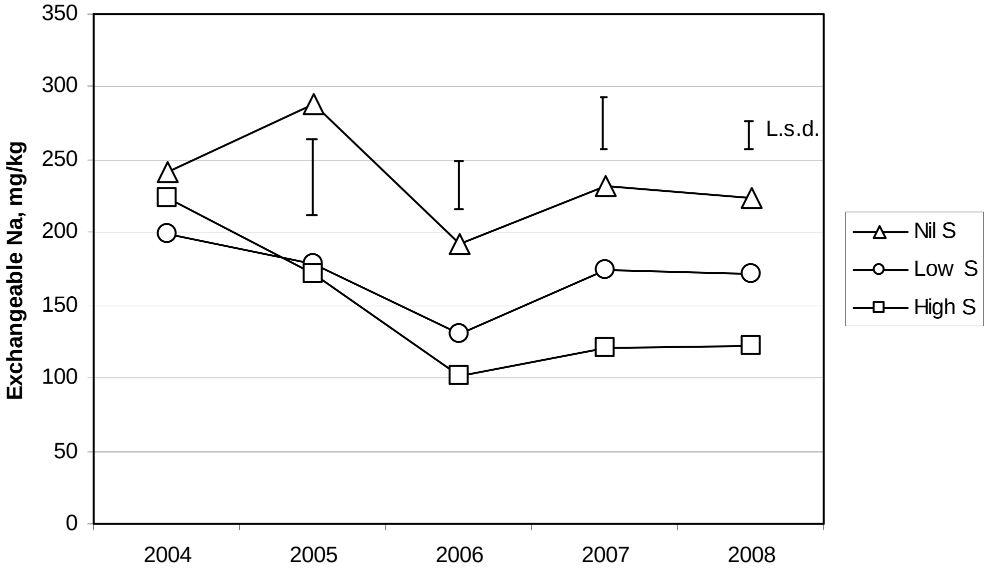

Figure 4a. Effect of sulphur rates on soil exch. Na (0-15 cm, mean of stripped and unstripped plots)

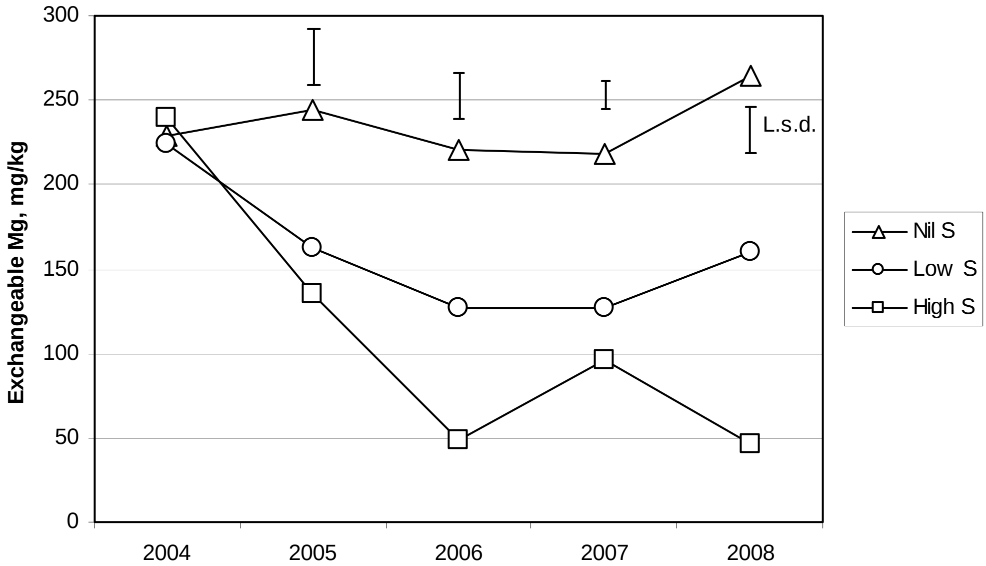

Figure 4b. Effect of sulphur rates on soil exch. Mg (0-15 cm, mean of stripped and unstripped plots)

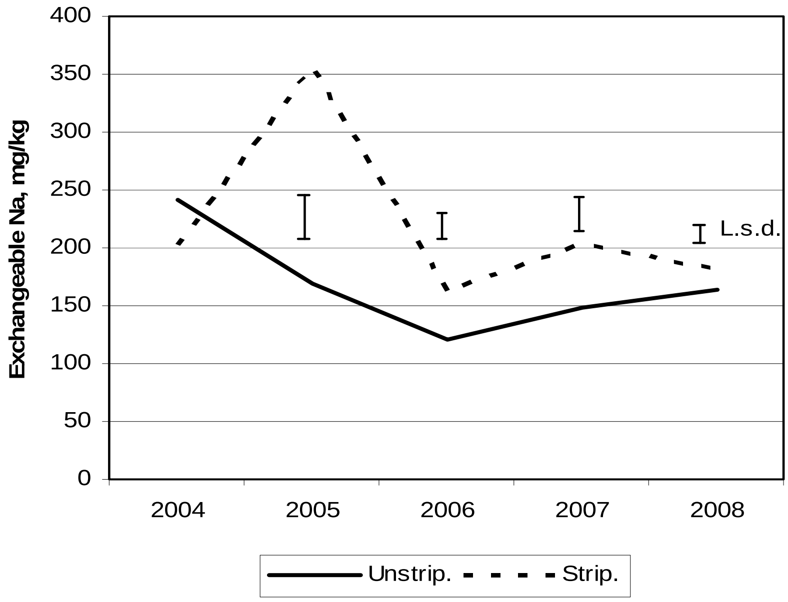

Figure 4c. Effect of stripping on soil exch. Na (0-15 cm, mean of S rates)

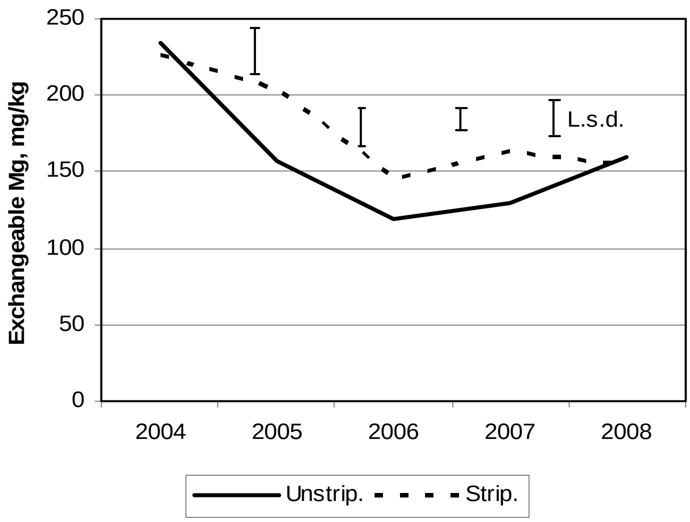

Figure 4d. Effect of stripping on soil exch. Mg (0-15 cm, mean of S rates)

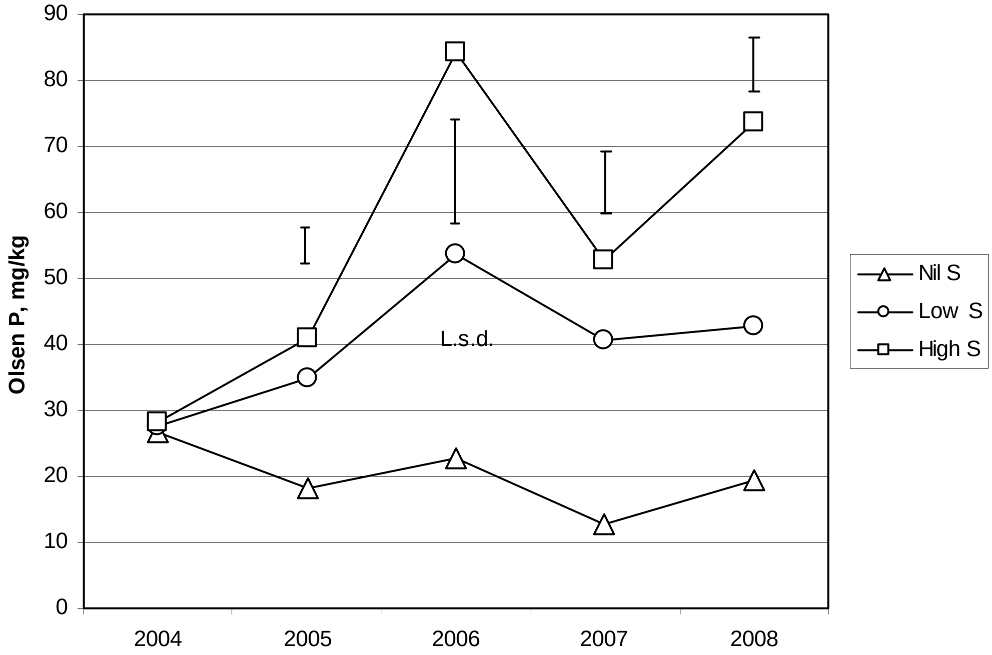

Figure 5a. Effect of sulphur rates on soil Olsen P (0-15 cm, mean of stripped and unstripped plots)

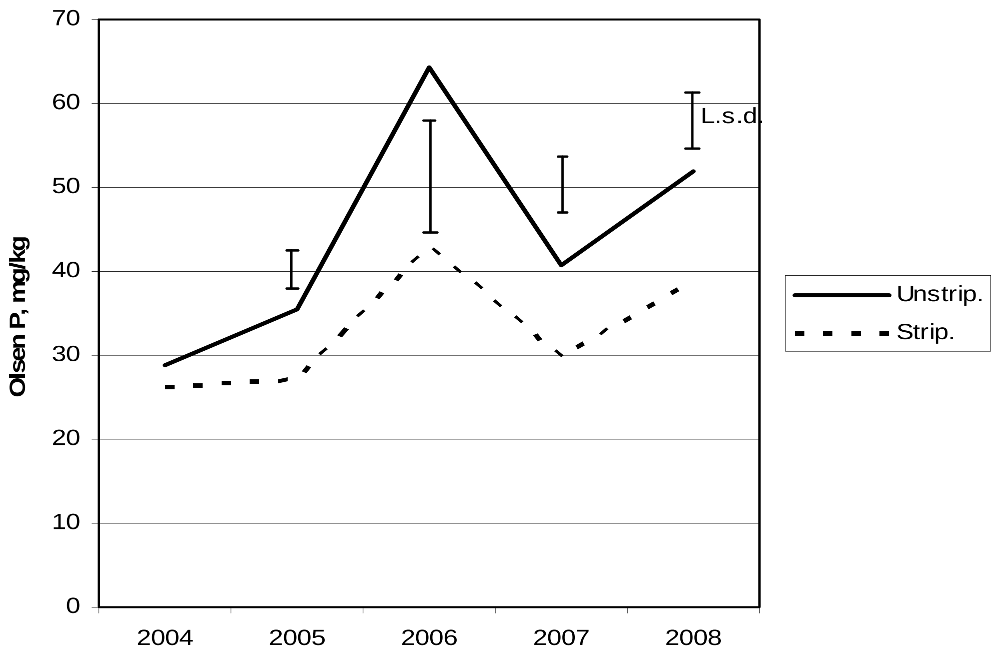

Figure 5b. Effect of stripping on soil Olsen P (0-15 cm, mean of S rates)

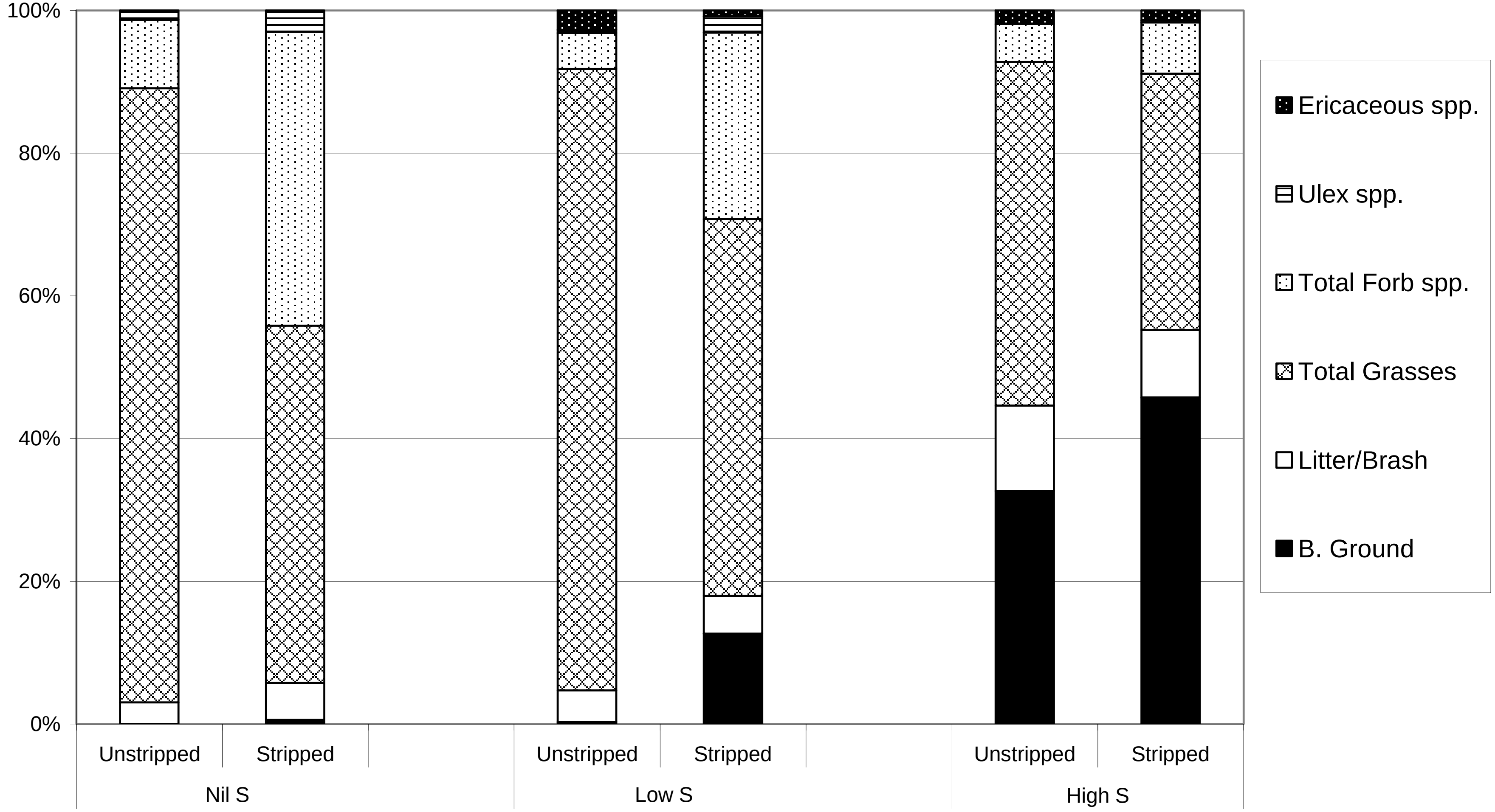

Figure 6. Effect of Sulphur rate and soil stripping on mean % cover of plant groups, June 2008

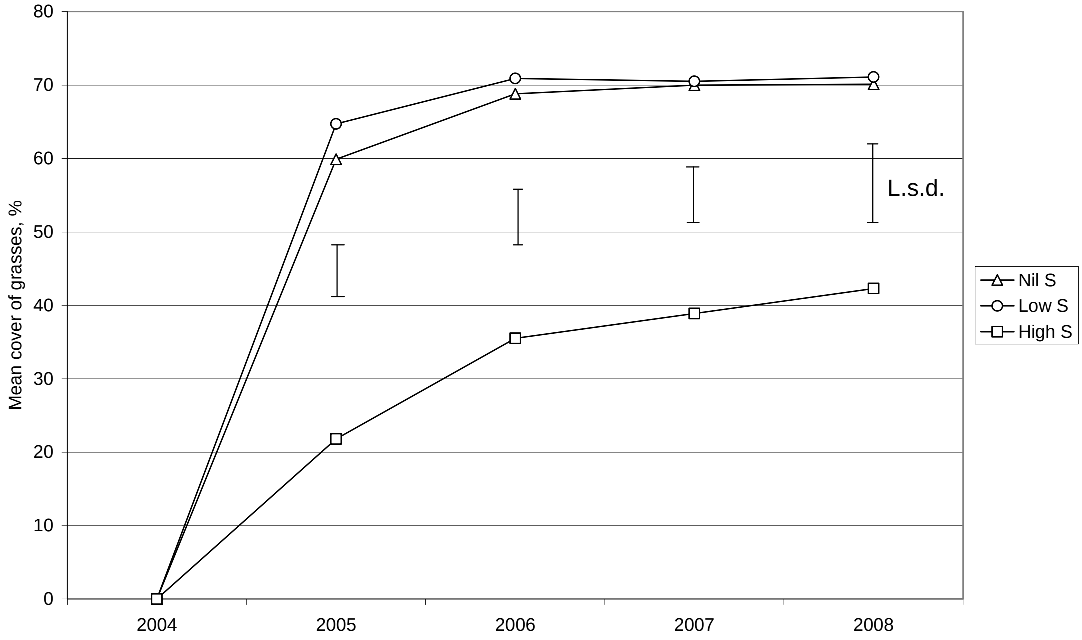

Figure 7a. Effect of sulphur application rates on mean cover of total grass species

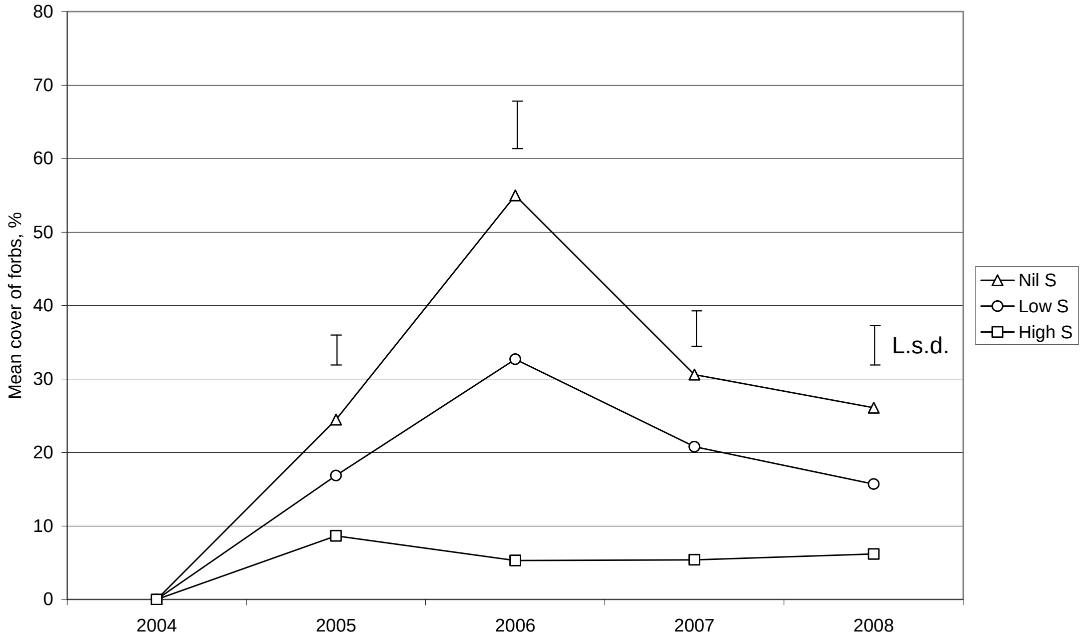

Figure 7b. Effect of sulphur application rates on mean cover of total forb species

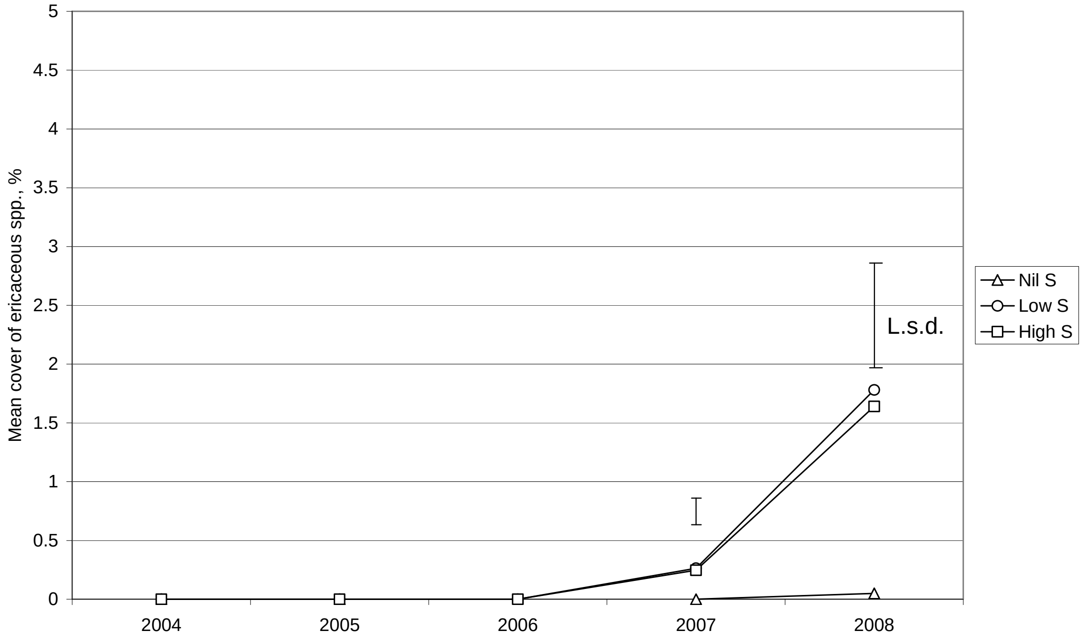

Figure 8a. Effect of sulphur application rates on mean cover of total ericaceous species

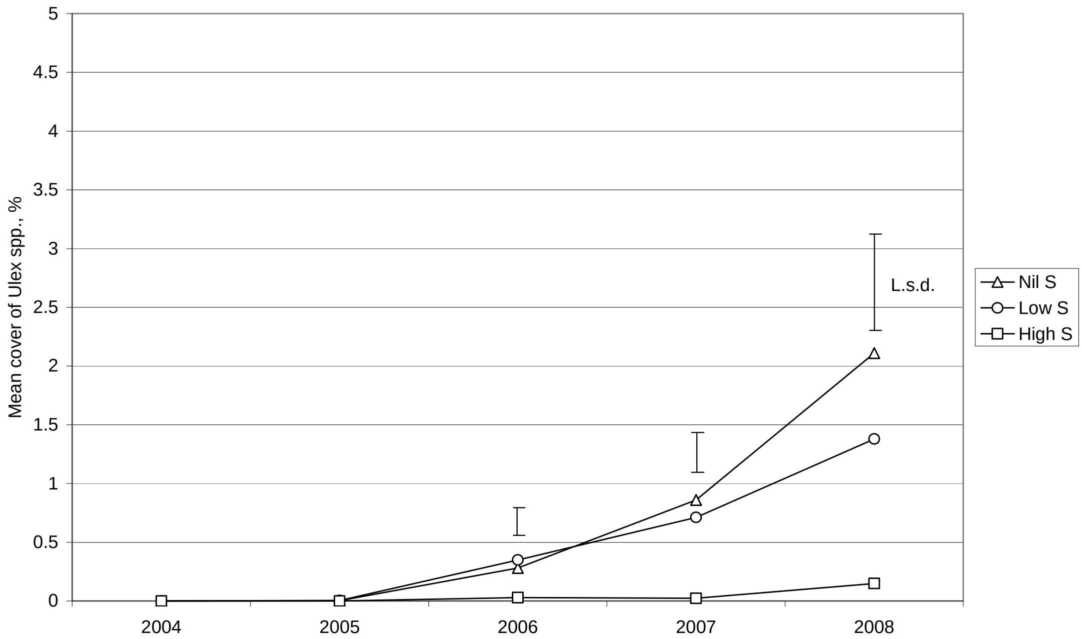

Figure 8b. Effect of sulphur application rates on mean cover of *Ulex* spp.