Consequences of lime and fertiliser application for moorland restoration and carbon balance

Research report to Moors for the Future
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[1] Simon Caporn, Robin Sen, Chris Field,
Elliot Jones, Jacky Carroll, Nancy Dise

Department of Environmental and Geographical Sciences
Faculty of Science and Engineering
Manchester Metropolitan University
Chester StreetManchester
M1 5GD

[1]Email: s.j.m.caporn@mmu.ac.uk

0161 247 3661/1600

Executive Summary

1. A field experiment was established near Holme Moss in the Dark Peak SSSI in the summer of 2006 by researchers at Manchester Metropolitan University (MMU) in collaboration with 'Moors for the Future' to increase scientific knowledge underpinning current landscape restoration on bare and eroded peat soils in the Southern Pennines. The experiment aimed to investigate how 3 different rates of lime (0, 500, 1000 kg ha^{-1} y^{-1}) and fertiliser (0, 183, 365 kg ha^{-1} y^{-1}) application (in 9 factorial combinations) affected: (a) the growth of nurse grasses, (b) the rates of soil CO_2 emissions associated with respiration; (c) associated changes in soil acidity and nutrients.

2. Lime and fertiliser increased establishment of the grass mix in comparison with seeded plots without these treatments. Lime was most beneficial and promoted growth in the absence of added nutrients. In contrast, fertiliser addition was only of benefit when lime was also added. The optimum growth was found when both fertiliser and lime were added together at the maximum rates in the experiment. This rate is the same as applied at the landscape level in current restoration management.

3. The pH of the soil in control plots varied over the year, increasing from approximately pH 3.4 in July 2006 to approximately pH 4.1 in March 2007. Fertiliser had no significant effect on soil pH, but increasing lime tended to raise pH by about 0.4 pH units at most. However, in some months there was no significant lime effect on soil pH.

4. The rates of soil CO_2 efflux (hereafter termed soil respiration) were measured monthly before and after soil treatments and grass seed were applied. Soil respiration in the untreated, unseeded bare peat was low and showed no seasonal change. Rates on these bare peats were significantly lower than measured at 3 other healthy peatlands in the UK (by the same operator) and also lower than measured on soils below vegetation just metres away from the bare soil.

5. No significant changes in soil CO_2 release due to the treatments were recorded until 3 months after application in October 2006, when increasing lime treatment caused a significant step-wise increase in the rate of release of CO_2. There was no clear influence of fertiliser addition. Rates recorded in the highest treatment were significantly greater than average values measured on other peatlands sites around the country at similar soil temperature. It is not known for how long the CO_2 burst in October was maintained but there were no significant differences between any treatments in the following last two months of 2006.

6. In a follow-up experiment in January 2007, soils from bare and adjacent vegetated areas away from the plots were taken to a greenhouse and supplied with lime and fertiliser. Assays ten days later found the soil respiration rate was stimulated much more in the vegetated than in the bare soils. This result suggested that the respiratory response to lime and fertiliser addition of the bare soils was limited by factors associated with the absence of vegetation.

7. Related studies over winter 2006-7 at Holme Moss found that bare soils contained very small culturable populations of both bacteria and fungi in comparison with the adjacent vegetated soils. At the same time the bare soils contained very much higher concentrations of ammonium. It is likely that the ammonium accumulates in these soils as a result of the absence of plant and microbial uptake, and because the bacterial populations and the rates of nitrification are too low to convert it to nitrate.

8. Soils collected for pH assay in March 2007 were assayed for concentrations of water-extractable nutrients. Contrasts have been in investigated so far in the ammonium and nitrate concentrations in response to lime only addition. The nitrate was not influenced by lime treatment but the level of ammonium was significantly reduced in the highest (1000 kg per hectare) treatment plots. The fall in ammonium due to liming is again likely to be a consequence of increased microbial biomass, plant uptake and the conversion of ammonium to nitrate in the process of nitrification.

9. In conclusion, the following interpretation of the results is proposed regarding soil carbon and nutrient cycling. The very small culturable microbe populations explain the low rates of both respiratory CO_2 release and of nitrogen cycling in the untreated bare peat soils. On vegetated soils, the process of photosynthesis supplies carbon to the rooting zone, increasing root and microbial biomass, with a concomitant increase in soil respiration. This effect is further enhanced by liming, which raises the pH and stimulates root and microbial growth. Improved biomass uptake of ammonium together with the higher nitrification rates associated with pH levels of 4 and above then acts to reduce the accumulation of ammonium in these soils. The first stages of this process can now be seen on the treated plots, with a developing pattern of increased soil respiration and reduced ammonium on the limed treatments. .

10. Future research should aim to understand:

- Which specific nutrients are required to stimulate plant growth, both for nurse grass and the succeeding heather vegetation?

- If soil respiration is stimulated by lime addition over the longer time scale?
- If the respired carbon come from the peat or from newly assimilated products of photosynthesis?
- Does any increase in microbial and plant activity also raise the release of DOC?
- What the consequences of lime addition are for mobilizing stored nitrogen in the peat?
- Are the high ammonium concentrations found on the bare peats at Holme Moss typical of the other sites in the region and do these levels (in combination with acidity and imbalance of other nutrients) inhibit natural and facilitated revegetation and microbial rehabilitation?
- The stages by which the bare peats of the Southern Pennines may evolve from being an essentially life-less, inhospitable substrate into a healthy soil, and how this can be enhanced by restoration measures.

1. Introduction

Changing interests in the UK countryside have prompted re-analysis of the efficacy of current restoration treatments in the Dark Peak of the Peak District National Park. Two issues, the long term effects of nitrogen eutrophication on biodiversity at a landscape scale (Negtap, 2001; Lee & Caporn, 1998; Stevens *et al*, 2004), and the loss of carbon stocks from organic soils (Bellamy *et al* 2005) are of particular concern and are potentially impacted by landscape-scale restoration. These issues, however, must be seen in the context of the conservation imperative, driven by the European Habitats Directive and the Government Public Service Agreements to improve the ecological condition of the Dark Peak, 94% of which was classed by English Nature in 2006 as unfavourable.

The most unfavourable areas of land, found over many square km in the Dark Peak, are completely devoid of vegetation. Despite improvements in air quality in recent decades and reductions in grazing pressures in many parts of the region these soil surfaces remain absolutely bare. The habitat quality is extremely poor and the continued erosion results in loss of stored carbon, colouration of drinking water, with attendant treatment costs, and increased sediment loading to reservoirs.

At first, the benefits of restoration of bare ground for the net carbon balance of eroded areas appear obvious because of reduced surface peat erosion and increased plant cover. Vegetation assimilates carbon by photosynthesis and provides a habitat for numerous species. However, the soil amelioration treatments which are used to encourage plant establishment are likely to stimulate soil biological activity and increase the loss of respiratory CO_2. Enhanced microbial action could also speed up decomposition of soil organic matter and increase the leaching of small, dissolved organic compounds (DOC) as well as large particulates (POC) into freshwaters. As well as the disruption of the carbon balance, soil treatments could increase nutrient leaching and harm non-target organisms, such as sensitive *Sphagnum* moss species and soil invertebrates. To weigh up the benefits and costs of soil treatments an improved understanding is needed of the effects on revegetation, soil nutrients and carbon cycling.

2. Aim: this project was designed to address the following research questions:

Question 1. Are the current rates of a lime and fertilizer application, as used in large scale restoration in the Peak District, required for germination, rooting and establishment of the nurse grass crop, or could lower rates be applied?

Question 2. How do the soil treatments of lime, fertilizer and grass seeding affect the soil respiratory CO_2 release rate and ultimately the net ecosystem carbon exchange?

Question 3. How do soil treatments affect the losses and mobility of nitrogen and other elements from and within the ecosystem?

3. Objectives:

- Set up experimental plots at Holme Moss;
- Application of treatments (lime / fertilizer) and nurse crop grass seed mix;
- Monitor germination, establishment, rooting of grass plants;
- Monitor changes in gaseous CO_2 loss, soil pH, available nutrients;
- Prepare for more detailed research into effects of restoration treatments on ecosystem services – particularly greenhouse gas fluxes and soil erosion.

4. Methods:

Experimental plots

Following agreement with land owners (Yorkshire Water) and conservation agency (English Nature - now Natural England), the experiment commenced in June 2006 and treatments were completed with seeding the grass nurse crop on August 2nd 2006. The timetable of establishment of the experiment is shown below.

Key dates:

June 7th 2006	Assessed field site with Moors for the Future (M.Buckler)
June 16th 2006	Marked out plots with tape and poles
July 6th 2006	Baseline sampling of soils
July 18th 2006	Applied lime and fertiliser
August 2nd 2006	Added grass seed mix
March 27th 2007	Added heather brash

Plots of 3 x 3 m were marked out using short stakes. Ten plots of different soil treatments were randomized within 4 replicate blocks, giving a total of 40 plots. Prior to any treatments, baseline soil samples were taken for measurement of pH and soil respiration rate – assayed as the rate of CO_2 efflux. Samples have also been stored for future assay of microbial composition and elemental analysis. The lime and fertilizer were then added, followed two weeks later by the grass seed at the rate of 171 kg ha^{-1}.

The grass seed mix was the same as that used by Moors for the Future (MFF) on restoration sites at nearby Black Hill and other local sites in the same summer of 2006 and was applied to all the 9 treatments shown below. The species and cultivars in the mix were:

Festuca rubra rubra cv.Boreal
Lolium perenne cv. Romark
Festuca ovina cv. Bornito
Agrostis castellana cv.Highland
Lolium multiflorum cv. Sultan
Festuca longifolia cv. Ridu

The lime and fertilizer treatments (Table 1) were as advised by MFF. Both are slow release applications and are aimed to encourage rooting and establishment of the grass crop (and heather later). The fertilizer had the ratio of NPK as 11/32.5/16.5, clearly high in phosphorus which was expected to enhance root development. The top rate (100%) of application supplied the equivalent of 40 kg N, 120 kg P_2O_5 and 60 kg K_2O per hectare. The lime was supplied as 'Calciprill' (Omya, UK). In addition to the nine plots (Table 1) with grass seed, a further plot (the tenth) was set up on the bare surface and received no seed and no soil treatment.

Table 1: Soil treatments of lime / fertilizer expressed in terms of kg ha^{-1} applied in July 2006 to experimental plots of 9 m^2 each.

	Zero Fertilizer	50% Fertilizer	100% Fertilizer
Zero Lime	0 / 0	0 / 183	0 / 365
50% Lime	500 / 0	500 / 183	500 / 365
100% Lime	1000 / 0	1000 / 183	1000 / 365

Since the period of this contract, in late March 2007, the 9 plots (Table 1) were topped with heather brash (approximately 1 cm thick) supplied by MFF, with theaim of improving surface stability and seeding with heather (*Calluna vulgaris*). The extra bare control plot was not treated with brash.

Monitoring and measurements

<u>Plant Measurements</u>

Establishment of grass was monitored using a score of 0-5 in August, October and December. This technique was quick and enabled us to track the early establishment in the first half year of the experiment. Scoring was performed without knowledge of the plot layout (i.e. without bias). A more detailed measure of % cover and frequency was made in early March 2007 before the growing season of the second year. This assay used a 1 x 1 m quadrat sub-divided into 25 squares of 20 x 20 cm. Average cover was calculated from the sum of the values for all the squares divided by 25.

<u>Soil Measurements</u>

The changes in soil pH, measured in de-ionised water (2 g fresh soil to 15 ml de-ionised water, were followed using a calibrated pH meter in the laboratory at approximately 20 degrees C to monitor the effects of the lime and fertilizer on soil acidity. An analysis of water extractable nutrients, performed using ion chromatography (Dionex Ltd), was also made on soils sampled from all plots in March 2006. In addition, extracts of ammonium and nitrate in KCl (1 M) were prepared from soils in bare and vegetated soils away from the plots in November 2006. Analysis was by ion chromatography.

Soil respiration has been measured by recording the rate of CO_2 accumulation in a closed chamber system over a 50 second interval. The soil chamber the SRC-1 was linked to an infra-red CO_2 analyser (EGM-4), both made by *PP Systems Ltd*, Hertfordshire, UK. Measurements of CO_2 were made on the soil lying between grass plants where these were present, and were always accompanied by determinations of the soil temperature in the top 10 cm using a thermistor probe attached to the EGM-4.

For a preliminary enumeration of culturable soil bacterial and fungal communities, surface peat samples were taken from exposed bare peat and adjacent vegetated peat at Holme moss in January 2007. Peat collected at the same time from a productive heather moorland located in North Wales (Ruabon) served as a moorland control. For enumeration, 1 g fresh peat samples (n = 4-5) were homogenised for 2 minutes in 9 ml sterile distilled water and the supernatant subjected to repeated 10 fold dilution in further 9 ml sterile distilled water diluants. Dilutions were plated on Tryptone soy agar medium amended with Cycloheximide (50 ppm) and Potato Dextrose agar medium amended with Chloramphenicol (100 ppm) to select for bacterial and fungal growth, respectively. Petri dishes were incubated at 20 °C and colonies counted after 3-5 days incubation. Numbers of culturable bacteria and fungi were expressed as colony forming units (cfu) g^{-1} soil.

At several other occasions (detailed in results section) soils were sampled for: soil respiration, pH, nutrients, plant growth, detailed % cover (once on March 2nd 2007).

5. Results

5.1 Grass growth

Within one month of sowing, and following a period of warm and wet weather after a very hot early July, the germination and growth of grass in the plots was very distinct against the backcloth of the dark brown peat substrate. Closer examination of the individual plants showed that while germination occurred in all plots it was not always accompanied by rooting. The poor root development was most obvious in any plot where lime had not been added.

The grass growth by August 30th 2006 was assessed using an arbitrary score to indicate plant vigour and discriminate simply the good from the plots with poor growth. The survey found that lime was of great benefit to grass establishment and growth; this was true when added alone but increased further where the fertiliser was also added (Figure 1). Fertiliser addition alone had no effect but was beneficial where lime was also present. Overall, there were statistically significant single effects of lime and nutrients and a significant interaction, reflecting the observation that the fertiliser stimulated growth where lime was present but not otherwise. A similar result was gained on October 2nd and also on December 20th.

A detailed % cover assessment of the central 1 square metre in late winter (March 2nd 2007) (Figure 2) revealed a similar picture, but by this time the differences between the best and worst plots were more marked (cover in the remaining outer area of every plot was poorer than the middle portion due to a large edge effect demonstrating the benefits of large experimental plots). In the absence of lime almost all plants had died, but at both the 50% and full lime level the benefits of adding nutrients were very obvious. Due to the very variable cover from plot to plot the only statistically significant effect was due to the lime addition. From the graph and observations in the field, the best grass growth was found where the top rate of both lime and fertiliser were added together.

Soil acidity (pH)

The pH of the soil varied over the period of the year, increasing from summer to winter in the control plots from approximately pH 3.5 in July 2006 to approximately pH 4.1 in March 2007 (Figure 3). The plots with the full treatment of lime and fertiliser had pH values only 0.1 to 0.2 units higher than the controls. The greatest rise in pH tended to be found at the intermediate fertiliser rate and full lime (see graphs for September and November: Figure 4). However, statistically, fertiliser had no significant effect on soil pH. Statistical analysis found significant effects ($p<0.05$) of lime in August and November and a nearly significant change ($p=0.07$) in July (Table 4). However, in some months there were no significant lime effects (across the range of treatments) on soil pH.

Comparison between the bare and vegetated peat areas (away from the plots) found no difference in pH in either November 2006 (both areas pH 4.2) or April 2007 (both areas pH 3.9) .

Soil respiration rate

The rates of soil respiration, along with soil temperature, were measured monthly before and after soil treatments and grass seeding were applied (Figure 5). In July 2006, prior to any treatments, baseline assays detected a small, significant plot effect, reflecting natural variation across the site. Soil respiration in the untreated, unseeded bare peat was low and showed no seasonal change. Rates on these bare peats were typically 0.05 to 0.1 g CO_2 m^{-2} h^{-1}, significantly lower than measured at 3 other peatlands (Whim bog in Scotland, Ruabon heather moor in Wales and Little Budworth lowland heath in Cheshire by the same operator C. Field) which were around 0.5-1.0 g CO_2 m^{-2} h^{-1} at similar soil temperatures. Rates on the bare peats were also lower than measured on soils below vegetation (data not shown) just metres away from the bare soil.

No substantial changes in soil CO_2 losses due to the treatments were recorded until 5 months after application in October 2006 (Figure 5). At this time, there were several important effects (Figure 6), the first being the rise in soil respiration in the grass-sown plots (zero lime and zero fertilizer). Secondly, the increasing lime treatment caused a significant step-wise increase in the rate of release of CO_2 (Figure 7). Thirdly, there was no clear influence of fertiliser addition, irrespective of the level of lime applied. Following this burst of activity to maximum mean values of approximately 3 g CO_2 m^{-2} h^{-1} in October, there were no significant differences between any treatments in the following two months of 2006 (Figure 5). It is not known for how long the CO_2 burst in October was maintained as measurements were made only on one day, but rates recorded in the highest treatment were significantly greater than average rates measured on other peatlands sites (see previous paragraph) around the country at similar soil temperature.

A greenhouse experiment was used to examine the effects of the lime and fertilizer treatments to soils collected away from the experimental plots on bare areas and soils from under healthy vegetation just a few metres away. Soils were collected in January 2007 and after ten days of incubation in a greenhouse at 15-20 degrees C the soil respiration was measured and showed that the full lime and fertiliser treatment stimulated respiration much more in the previously vegetated areas than in the bare soils (Figure 8).

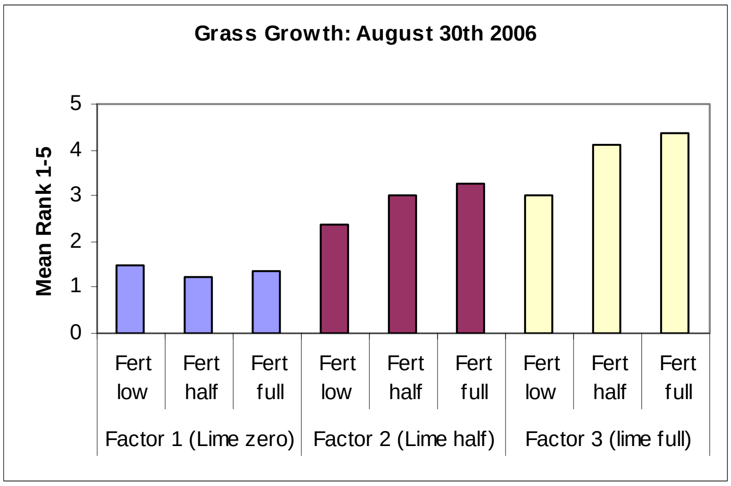
Enumeration of soil bacterial and fungal communities in bare and vegetated areas

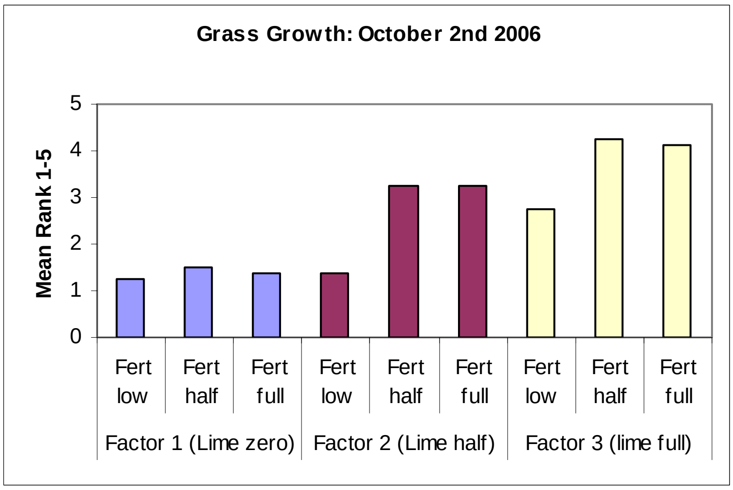
Estimates of culturable bacterial and fungal counts, measured as colony forming units (cfu g^{-1} fresh peat) in bare and vegetated fresh peat samples from Holme Moss and the control heathland site (Ruabon moorland in Wales) sampled in January 2007 are presented (Figure 9). Compared to bare peat, mean bacterial and fungal counts were between 7 and 68 fold higher in the vegetated and control peats. In comparisons of the two vegetated control sites, the fungal count was significantly higher in the Welsh site whilst a higher bacterial count was recorded in vegetated peat at Holme moss.

Soil extractable ammonium and nitrate

Soils were sampled away from the plots in November 2006 to investigate the ammonium and nitrate concentrations (extracted using 1 M KCl) in the bare areas compared with under healthy vegetation. Comparison was also made with soils from Ruabon moorland. The bare soils contained much higher ammonium than the other two vegetated sites., while the nitrate was highest in the Holme Moss vegetated soils. Ruabon soils contained the least of either ion (Figure 10).

In March 2007, soils collected from all the treatment plots for pH measurement were also assayed for concentrations of water-extractable nutrients. Contrasts have been in investigated so far in the ammonium and nitrate concentrations in response to lime addition. The nitrate was not influenced by lime treatment (data not shown) but the level of ammonium was significantly reduced in the highest (1000 kg ha^{-1}) treatment plots (Figure 10).





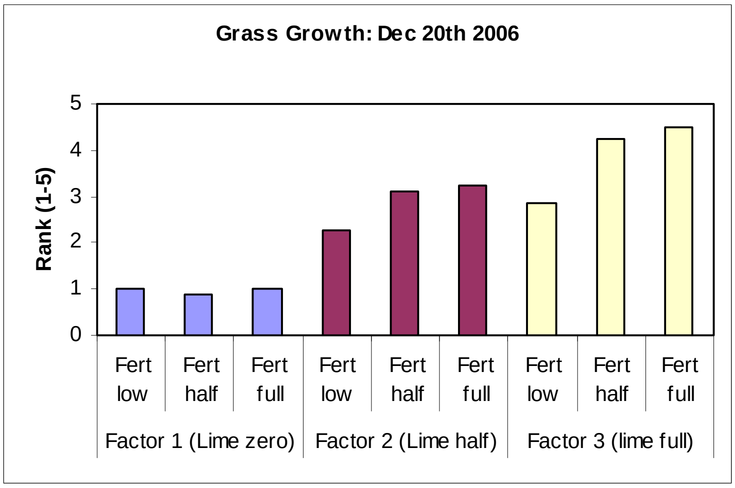


Figure 1: Grass growth scored on a 0 to 5 scale. (see Table 1 for details of lime and fertiliser rates). At each date there were significant effects of lime, fertilizer and an interaction between the two factors.

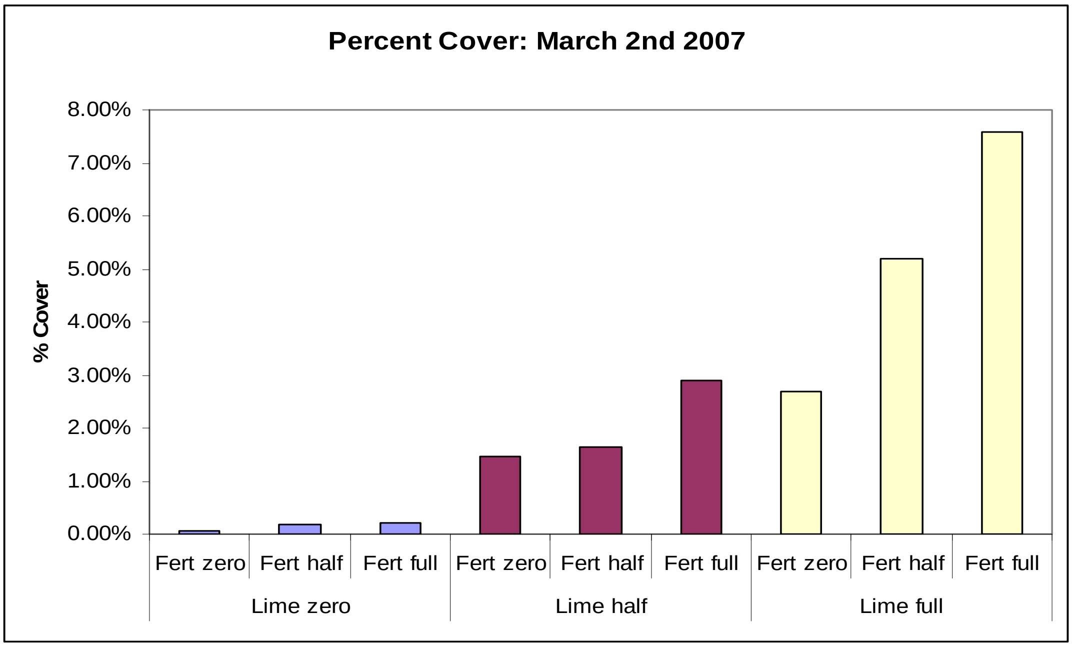
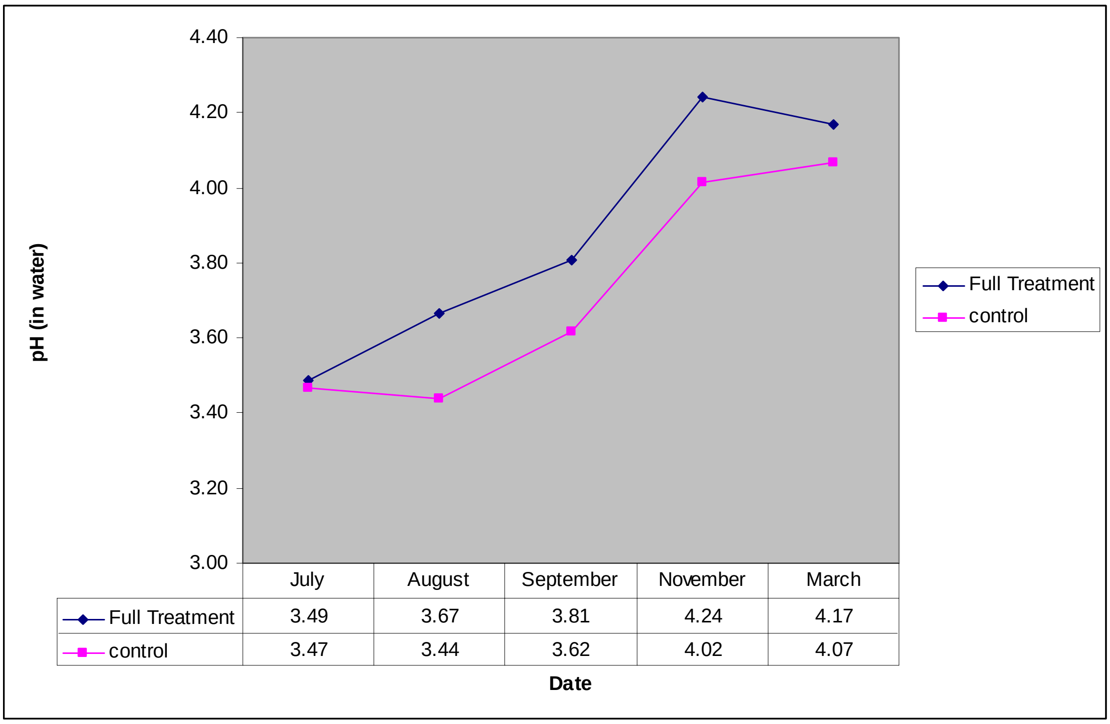


Figure 2: Grass cover (%) scored using a 1 m^2 quadrat with 25 grid squares on March 2nd 2007 (following lime and fertiliser addition on 18th July and grass seeding on August 2nd 2006) (see Table 1 for details of lime and fertiliser rates). There was a significant effect of lime ($P = 0.0001$) but not fertilizer ($P = 0.068$).



	July	August	September	November	March
Full Treatment	3.49	3.67	3.81	4.24	4.17
control	3.47	3.44	3.62	4.02	4.07

Figure 3: Soil pH (water extract) from experimental plots showing only the control (pooled data from all eight plots not receiving lime and fertiliser) and the full lime and fertiliser treatment (for details see Table 1), following lime and fertiliser addition on 18th July and grass seeding on August 2nd 2006.

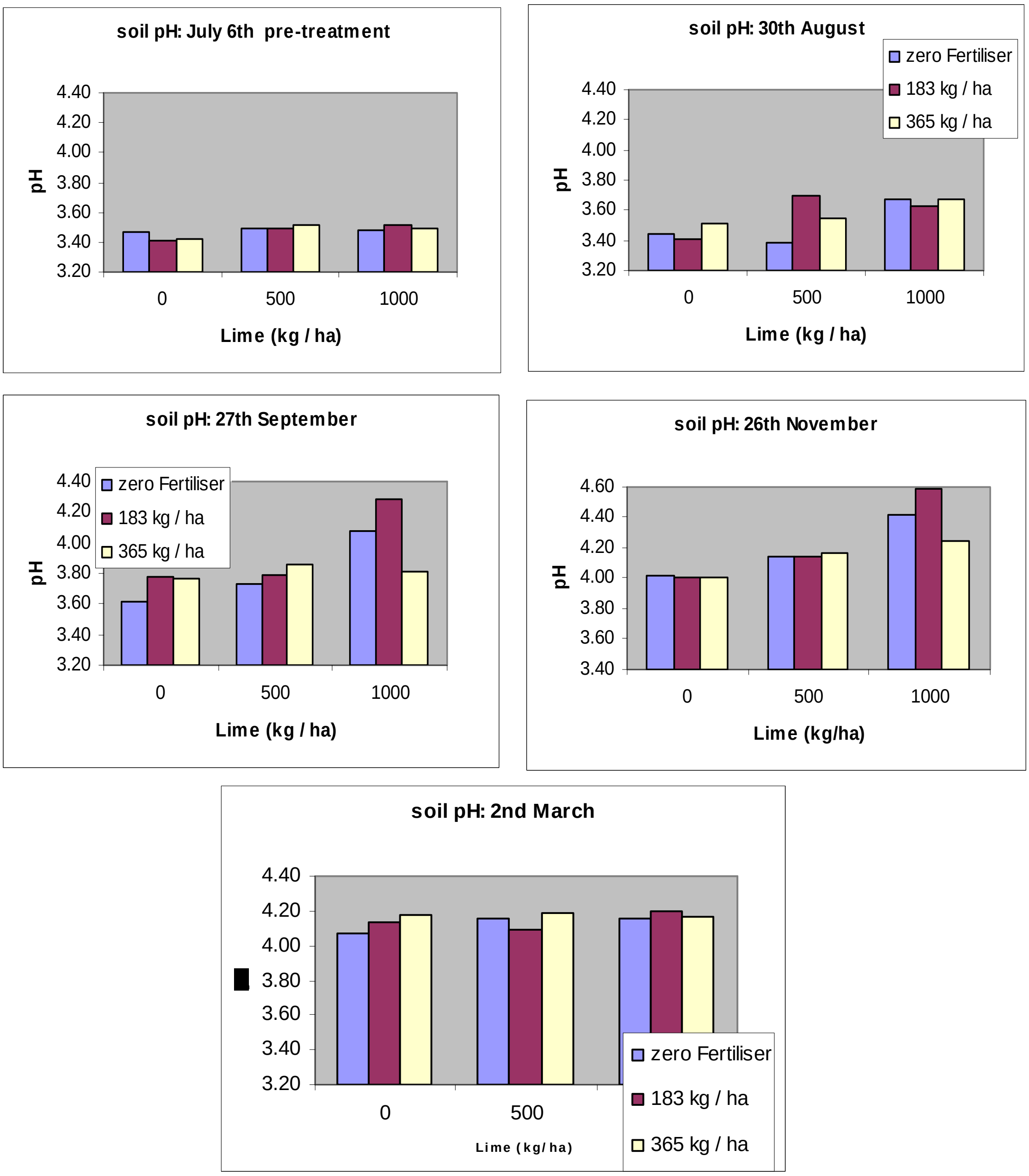


Figure 4: Soil pH (water extract) from experimental plots at each sampling date, following lime and fertiliser addition on 18th July and grass seeding on August 2nd 2006 (for rates see Table 1) . There were statistically significant effects of lime in August and November, but no other significant effects.

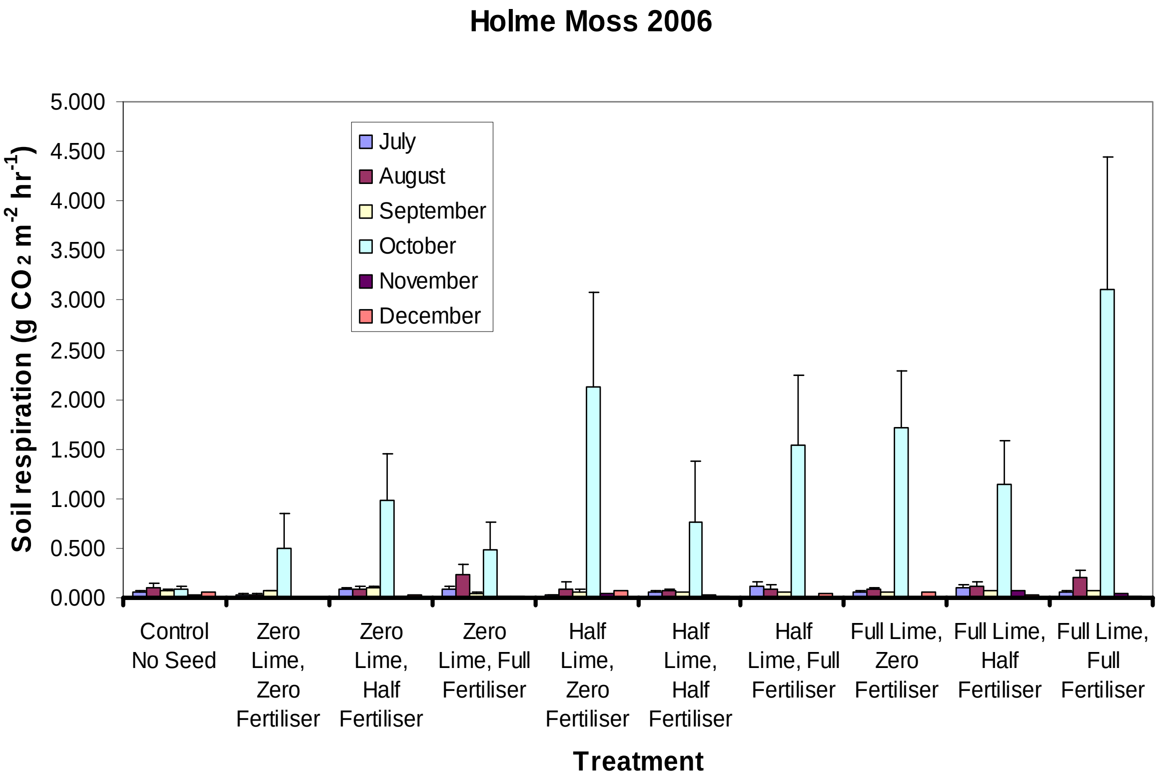


Figure 5: Soil respiration (mean & standard error) at Holme Moss in 2006 in plots after different lime and fertilizer treatments. The July measurements took place before treatments. On the far left are data from the bare control plots; the next bar shows the plots that were seeded but without lime and fertilizer. Several rates in November and December were very close to zero. In each month, measurements took place over approximately 2-3 hours in the middle of one day. There were no significant differences between any of the treatments, but there was a small significant plot difference (P = 0.03) in July before anything had been added, reflecting the natural variation across the site.

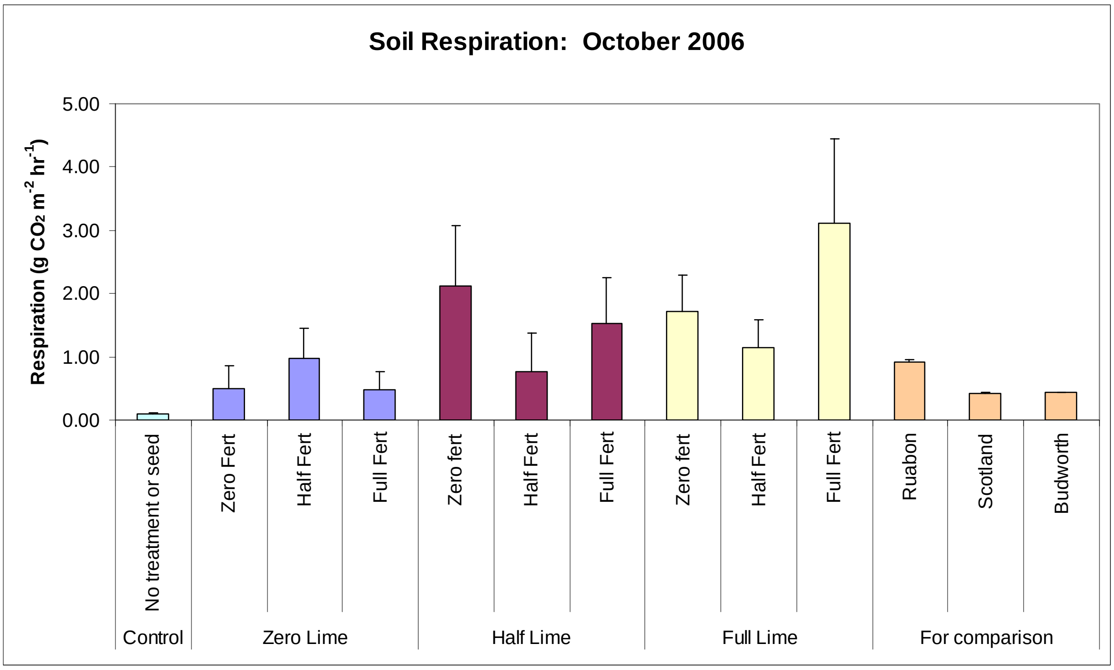


Figure 6: Soil respiration (mean & standard error) at Holme Moss on 20th October 2006 in plots after different lime and fertilizer treatments on July 18th and grass seeding on August 2nd 2006. There were no significant differences between any of the individual ten Holme Moss treatments (P = 0.13, One-way Anova). For comparison with three healthy vegetated sites in the UK, typical respiration rates at equivalent temperatures are shown on the right.

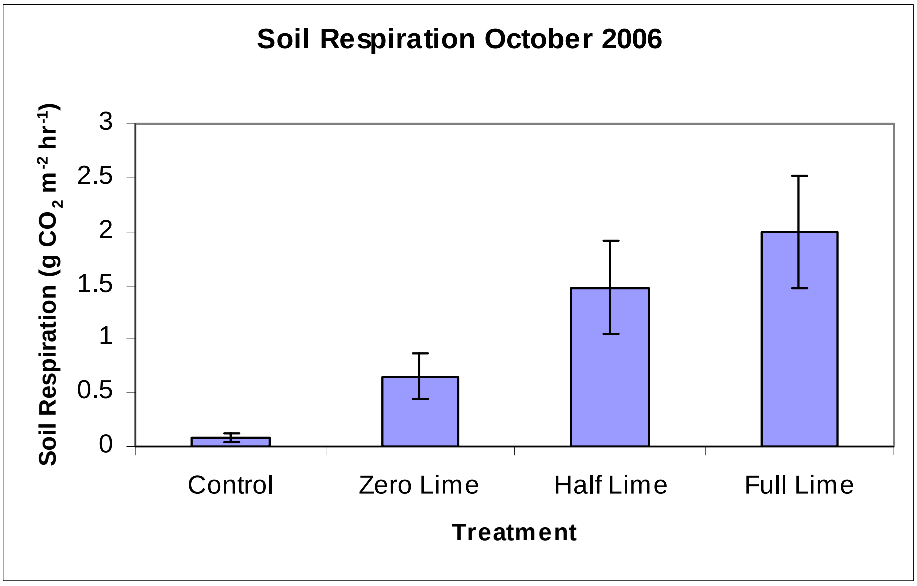


Figure 7: Soil respiration (mean & standard error) at Holme Moss on 20th October 2006 in plots after different lime and fertilizer treatments on July 18th and grass seeding on August 2nd 2006. For each lime treatment, the data for the three rates of fertilizer application have been pooled (since there were no differences between fertiliser treatments). There was a statistically significant difference between the above four treatments (P = 0.049, One-way Anova).

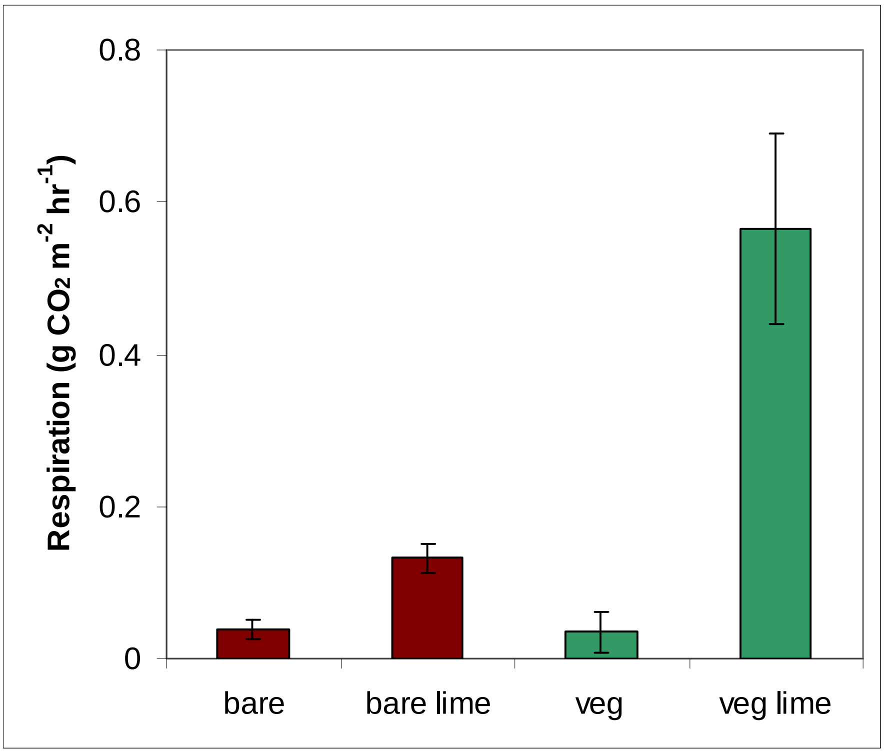


Figure 8: Soil respiration (mean & standard error) of peat from bare areas and beneath vegetation (*Empetrum* and *Eriophorum*) that were incubated in a greenhouse at 15-20 deg C for ten days after treatment with a mixture of lime and fertilizer at the standard rates (equivalent to 1000 kg lime ha^{-1} and 365 kg fertilizer ha^{-1}. There were significant differences between soil types, significant effects of the (lime and fertilizer) treatment and a significant interaction term (Two-way Anova). Data of Jamie Parker, MMU.

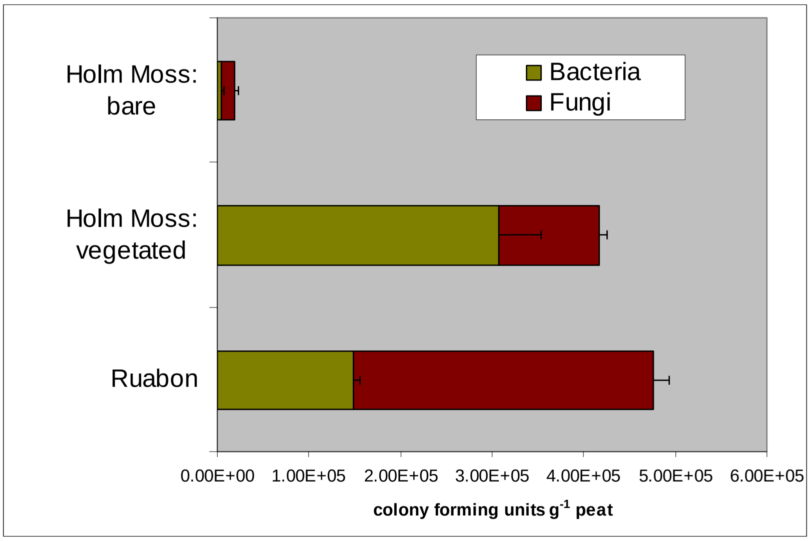


Figure 9: Bacterial and fungal counts (cfu g^{-1} peat ± Standard deviation) in fresh bare and vegetated peat from Holme Moss and a productive *Calluna vulgaris* dominated heathland peat from North Wales (Ruabon), sampled in January 2007.

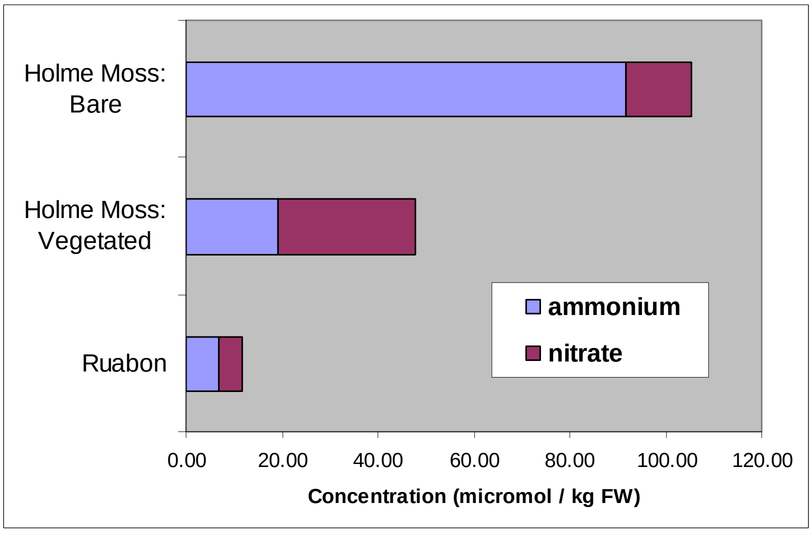


Figure 10: Ammonium and nitrate concentrations in fresh bare and vegetated peat from Holme Moss and a productive *Calluna vulgaris* dominated heathland peat from North Wales (Ruabon), sampled and extracted in 1 M KCl in November 2006 by 3rd Year students of class EG 3210.

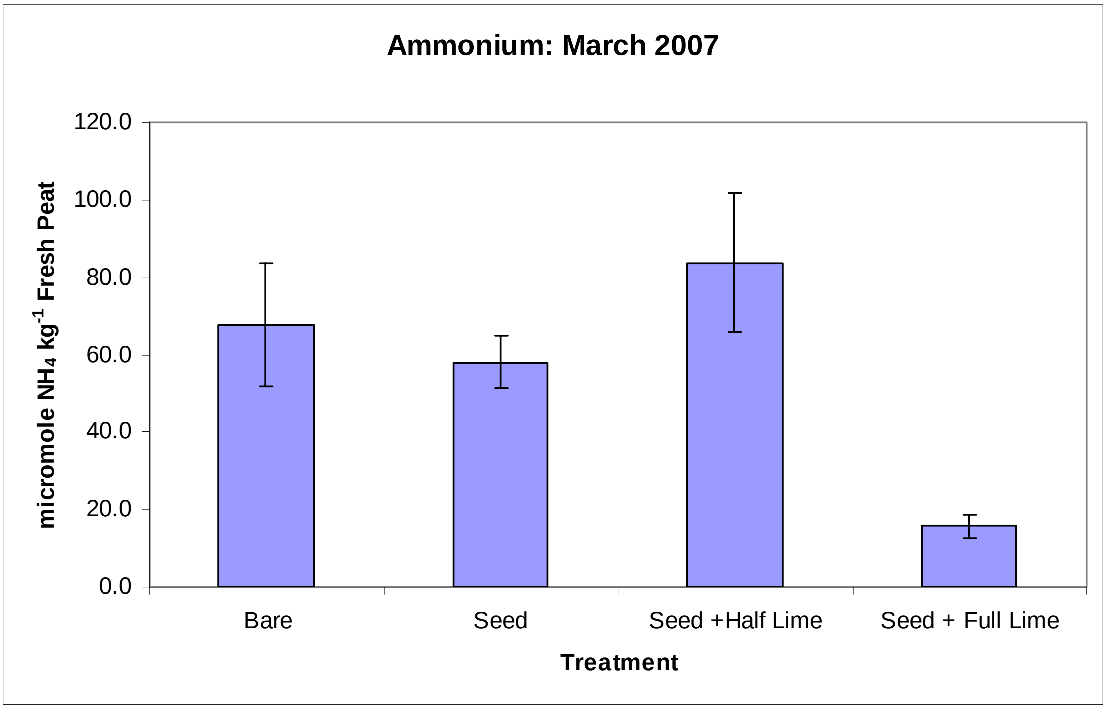


Figure 12: Ammonium concentrations in water extracts of soil collected in March 2007 from the four plots in the experiment which had not received fertiliser. There was a statistically significant effect of treatment, with the full lime treatment containing less ammonium than the others.

6. Discussion

The restoration experiment, started at Holme Moss in July 2006, generated greater knowledge of the chemical and biological properties of the bare, eroding soil and the consequences of restoration treatments. The research described was limited to the early stages of the restorative process and continuation of this experiment into the next stage of heather establishment and development of an ecological community is essential. Discussion of the results gained so far is presented by addressing the three questions stated in the Introduction section.

Are the current rates of a lime and fertilizer application used in large scale restoration in the Peak District required for germination, rooting and establishment of the nurse grass crop, or could lower rates be applied?

The nurse grass germinated on all plots including the bare, unamended peat when soil conditions were moist and warm, but rooting and subsequent establishment as young seedlings was very poor without lime and fertiliser treatments. Growth improved in soil treated with lime but fertiliser alone had no effect. The response to fertiliser demonstrated a classic interaction in that nutrients benefited growth only when lime was also added. Indeed, by the time of the detailed cover measurements in March 2007 grass had either almost or totally died out in those plots where lime was absent (Figure 2). The assessment of grass cover in March 2007 found very low mean values not exceeding 8% in the central square metre. It seems likely that the deterioration of the grass cover over winter could have been lessened if brash had been added at an earlier stage (heather brash was added in late March 2007).

The obvious benefits for plant growth of adding a combined soil treatment of lime with fertiliser support the standard restoration practice, and the best growth in this experiment occurred at the full treatment which is equivalent to the standard landscape application rate of 1000 kg lime ha^{-1} and 365 kg fertiliser ha^{-1}. Reducing treatments to half the full rate reduced the success of the nurse grass and at the landscape scale would not be of value unless wider benefits (e.g. ecological, carbon balance) of lower rate of amendments were shown.

Several underlying questions arise from the observations of the treatment effects on grass growth in the light of our knowledge of the soil properties. One month after seeding, the pH had only increased by 0.1 - 0.3 pH units in the lime plots yet the grass growth was significantly better suggesting that these plants are very sensitive to soil acidity. It is also likely that the 'Calciprill' lime contains other nutrients in addition to calcium such as magnesium, potassium and trace elements and these could also explain, in part, the effect of the lime. However, Richards *et al* (1994) working on highly acid peat on Kinder Scout found that the promotion of growth of cotton grass by lime was almost entirely due to its effect on pH, and that calcium alone had little effect. In our work, raising pH apparently enabled plants to make better use of the nutrients in the fertiliser. The observation that nutrients improved growth (when lime was added) is important since it confirms standard practice but it is not apparent which nutrients are actually required and whether more effective fertiliser application could be made.

Regarding nutrient requirements, it is unlikely that nitrogen is in short supply. Moorland soils in remote areas are typically low in available nitrogen, but the Southern Pennine hills have received high rates of nitrogen deposition for at least the past century (Fowler *et al* 2004) and John Lee and colleagues concluded after research on *Sphagnum* in the 1970s-1990s that excessive inputs of nitrogen pollution were a very likely cause of poor recovery of these bryophytes - despite the dramatic decline in sulphur air pollution (Lee 1998). In addition, it is generally found that mineralization is accelerated in drained or drying peat (Holden *et al*, 2004) resulting in generation of available ammonium, phosphate and potassium and other ions. The potassium is easily depleted in runoff but ammonium binds to soils and is more likely to accumulate. In the current research, analysis of the bare peats found that available forms of nitrogen were elevated well above concentrations in the Welsh control site and ammonium levels were much higher in the bare soils than the vegetated ones at Holme Moss (Figure 10). Concentrations of ammonium may even be super-optimal or toxic for plants and microbes. Support for this notion comes from studies on Dutch heaths where the combination of high soil ammonium and acidity had negative effects on the growth and survival of certain sensitive flora (Dorland *et al*. 2003, Van den Berg *et al*. 2005). They further found that liming improved heath restoration due to three key changes: the raising of the pH, the reduction in free ammonium (due to nitrification – see below) and the provision of base cations (calcium, magnesium, potassium) in the lime. In the Dutch heaths the highest levels of ammonium reported were around 600-750 µmole kg dry soil (Dorland *et al* 2003, 2005). In the present work the concentrations were around 90 µmole kg *fresh soil* (Figure 10) which, if estimated on the basis of dry weight (fresh/dry weight ratio was not measured), could have approached the Dutch values.

Potassium deficiency in Southern Pennine peats was suggested by the restoration work on Kinder by Richards *et al* (1992) and the comparative studies of peat chemistry in different bogs around the country by Skeffington *et al* (1997). Similarly, recent analyses of bog pool water sampled within a kilometre from the restoration site (Caporn *et al* 2006) found that only potassium and manganese were at concentrations lower than in pools in the healthy Migneint blanket bogs of North Wales while other nutrients including nitrate, ammonium, magnesium were higher at Holme Moss. Another potentially limiting nutrient in the bare peats is phosphate and restoration trials by Anderson and colleagues found that slow release phosphate was particulary good at enhancing revegetation (Anderson *et al* 1997). Following experiments at Robinsons Moss and soil analyses, Skeffington *et al* (1997) also suggested that phosphate, potassium and calcium were important nutrients limiting revegetation.

In conclusion, lime is essential for the promotion of growth on the bare peats at Holme Moss, while it is unlikely that any nitrogen application is required. Various other studies suggest that phosphate and potassium application, in addition to the lime, may be the most important nutrients in demand by young vegetation on the eroded peat at Holme Moss, but research is needed to establish this requirement.

How do the soil treatments of lime, fertilizer and grass seeding affect the soil respiratory CO_2 release rate and ultimately the net ecosystem carbon exchange?

Following application of soil treatments in July there was no immediate response in soil respiration captured in measurements over the next 2 months, but by October a marked stimulation due to liming (Figure 7) was seen. However, by November and December the onset of winter appeared to have suppressed microbial activity (Figure 5). The increase in soil respiration due to grass seeding in the absence of lime and fertilizer in October could be explained by the increase in availability of a fresh carbon source from the young seedlings or perhaps the turnover of their roots in autumn. Rates recorded in the highest treatment were significantly greater than average values measured on other peatlands sites around the country at similar soil temperature. If they were maintained in later years they could have a major negative impact on the carbon balance of the recovering ecosystem. However, the increased CO_2 assimilation of a vegetated surface may outweigh the losses. Further regular measurement is required to monitor this dynamic situation.

The extremely low culturable bacterial and fungal counts in the bare peat at Holme moss, compared to adjacent vegetated peat at Holme moss and the moorland control at Ruabon (Figure 9), highlights the problems of bare, eroded peats for two critical groups of soil microbes. Low fungal and bacterial counts also provide support for the concomitant low soil respiration rates of the bare peat control plots. Highly acidic conditions (*ca*. pH 3.5-4.0) are sub-optimal for growth of plant beneficial soil microbial communities such as plant growth promoting rhizobacteria (PGPR) and even root symbiotic mycorrhizal fungi, particularly ericoid mycorrhizal fungi that support heathland plant communities (Smith and Read, 1997). We speculate that when soils were re-vegetated there was an increase in labile (available) carbon and a concomitant increase in soil microbial respiration. This was enhanced further by liming which increased root and microbial populations and their activity. Stimulation of plant growth increased photosynthesis and the supply of carbon which was available for respiration. These tentative conclusions are supported by the greenhouse experiment comparing soils from bare and vegetated areas (Figure 8) indicating that the respiratory response to lime and fertiliser addition of the bare soils under warm conditions was limited by factors associated with the absence of vegetation – probably labile carbon and microbes.

How do soil treatments affect the losses and mobility of nitrogen and other elements from and within the ecosystem?

The concerns here are widespread, including changes in stored nutrients and elements such as carbon, nitrogen and metals, but also in the fate of the elements applied in the restoration. This project has only managed to ‘scrape the surface’ regarding the changing availability of nutrients and elements following restoration and a larger study of element budgets is required in relation to restoration treatments. The rising pH has implications for the mobility of a range of elements which might become more soluble (e.g. DOC, Evans *et al* 2006) or less soluble (e.g. metals). Our finding of the increase in soil respiration in October following liming (Figure 7 and 8), indicates that there is potential for increased microbial activity which would not only release CO_2 but possibly also other small dissolved carbon compounds (DOC) which could originate from the peat or from the establishing vegetation. Results from Holme Moss suggest that increasing microbial activity after liming and revegetation might have accelerated the soil bacterial nitrification process which converted a portion of the large pool of stored ammonium into nitrate, the more mobile form of soil nitrogen. The significant drop in ammonium in the limed plots (Figure 12) was consistent with this idea and while we did not record a concomitant increase in nitrate, the latter ion (being more mobile than ammonium) may already have leached towards the streams and rivers. Alternatively, the excess ammonium may have been taken up by either the plants or the increasing microbial biomass. Future research incorporating lysimeters and other samplers of soil solution could explore the fate of the mobilized nitrogen pool.

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