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The influence of coal mine spoil physical properties on the spatial distribution of lichen-rich communities

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Abstract

Coal mine spoil tips have been recognised as a UK Biodiversity Action Plan habitat owing to the presence of a host of unique flora and fauna assemblages and, in particular, "lichen heaths." The natural revegetation of abandoned spoil tips in South Wales, UK, has created some of the most dynamic habitats and historic landscapes for lichen colonisation. The sensitivity of lichen habitat to vegetation successional processes and anthropogenic factors is leading to their gradual extinction without intervention. Such is the threat that there is a requirement for the reconstruction of coal spoil tip habitats following the eventual closure of a recently consented surface mine.

While recent colonisation of coal spoil elsewhere has been documented, this has been opportunistic and has not involved the deliberate reconstruction of the habitat following mining. Experience elsewhere indicates that the physical properties of the landform and spoil material are important factors in colonisation. However, little is known about the factors relating to the high rainfall environment in South Wales. In order to provide guidance for the recreation of the lichen habitat, a detailed study was undertaken to determine the relationships between the spatial distribution of vegetation class patches and the physical proprieties of coal mine spoils in South Wales. The aim was to understand the key physical factors aiding the establishment and development of lichen species on the mine spoils.

Lichen-dominant patches were observed in the field during a physical properties survey and sampled for laboratory analysis alongside two other vegetation classes (bare ground and a moss-heather mix). Relationships were identified between vegetation class and physical properties, including slope aspect, slope gradient, slope form, erodibility (through laboratory simulated rainfall experiments) and the particle-size distribution of the slope-forming materials.

The results demonstrate that several physical properties of the coal mine spoil have significant influence on the spatial distribution of vegetation classes. It was found that the lichen-dominant patches were best established on southwest-facing slopes, with slope gradients ranging from 22 to 32°, where higher successional vegetation classes were less abundant.

While this study provides a better understanding of the spatial distribution of vegetation classes in the replication of coal spoil lichen habitats, it also identified that a singular rule-based approach might not be applicable across multiple coal mine spoil habitats without further research owing to the nature of mine spoil sites. Even so, knowing the influence of key physical properties on vegetation distribution will aid design decisions relating to the replication of lichen communities following mine closure.

1 Introduction

In the UK, mine spoil tips have been recognised as biodiversity action plan (BAP) habitats hosting unique flora and fauna assemblages (JNCC, 2010). Despite this, little is known about how or why rare community patches have established and thrive in what were initially barren and isolated landscapes. Lichen communities are fragile and are increasingly under pressure from environmental and anthropogenic factors. The establishment and continued presence of lichen communities in coal mine spoil habitats are under-researched. In other landscapes, lichen species have been identified as having few opportunities in which they can establish and thrive without being destroyed by disturbance or being outcompeted by vascular plant species (Làzaro, 2004). Therefore, determining why coal mine spoils provide suitable habitats for lichen species is fundamental to preventing the gradual loss of rare species.

Although lichen assemblages are poorly understood in coal mine spoil habitats, several studies have explored the role of the landscape's physical properties in determining habitat suitability for lichen. These studies span several regions, mainly within arid and semi-arid environments, where soil, slope forming material and land stability need to be understood.

The influence of slope aspect on the growth and spatial distribution of ground cover types has been studied extensively (Pentecost, 1979; Kutiel and Lavee, 1999; Cantón et al., 2004; Lázaro et al., 2008; Johnson, 2011). Armstrong (1991) identified that aspect preferences differ even amongst similar lichen species. Worsley (1990) and St Clair et al. (1993) identified the potential significance of slope gradient on lichen distribution, as it is a proxy for soil erosion and slope stability (Gray, 2013). Johnson (2011) found lichen growth was negatively affected by steep slope gradients (where average slope gradient was above 28°). Nonetheless, Lázaro (2004) found that lichen species establishment was more successful where the slope-forming materials created a degree of disturbance .

Slope morphological features identified as influencing the spatial distribution include slope position (referring to the position on a slope) and slope form (referring to shape of the slope profile) (Gray, 2013; Mao et al., 2014). Cerdà (1998) identified that lichen species were most abundant on the uppermost parts of a slope. The uppermost section of a slope (the summit or shoulder) is often associated with lower availability of water and nutrients, thus reducing competition on the highest section of a slope face, leading to notable differences in vegetation distribution (Cerdà, 1998; Maggi et al., 2005; Lázaro et al., 2000; Tang et al., 2010). Cantón et al. (2004) found lichen did not inhabit the most stable concave slopes, preferring linear slopes for establishment. As spoil tips exhibit a discontinuous variety of complex slope forms, this could account for the patchy nature of vegetation across a spoil tip.

Lázaro et al. (2008) and Humphries (2013) suggest that a degree of erosion could be pivotal in maintaining population assemblages of lichen and other lower plant species. The particle-size distribution (PSD) of spoil material influences both soil water dynamics and susceptibility to erosion (Eldridge and Greene, 1994; Sheoran et al., 2010); therefore, despite expected homogeneity of parent material, PSD changes across a spoil type could cause the vegetation patches present in a mine spoil habitat, as Lalley et al. (2006) found that PSD had a significant effect on lichen growth.

This study aimed to ascertain whether relationships exist between physical site conditions and the spatial distribution of different vegetation species, particularly the lichen species found in coal mine spoil habitats. Comparisons of physical properties across vegetation types and spoil tips were surveyed, sampled and analysed to investigate whether causal relationships exist between physical site properties and lichen spatial distribution.

2 Materials and methods

2.1 Studied area

The study was undertaken on a group of mine spoil tips to the north of Llwydcoed, Aberdare (+51° 44' 35.19" N, −3° 25' 54.21" W), South Wales, UK (Figure 1). The climate in this region is temperate, and Aberdare is subject to an annual mean of 1674.2 mm of rainfall (average 1981–2010), with the rain often falling in high-intensity episodes (Chambers and Garwood, 2000; Met. Office UK, 2014). The spoil tip site was previously a surface mine that operated post-1847. Although the spoil tips across the site are of unknown ages, it is believed they are between 135 and 155 years old (Cotswold Archaeology, 2013).

The mine spoil forms a rolling landscape of predominately southwest-facing tips (Figure 1), but not all spoil tips have all eight cardinal sides. Many spoil tips to the northeast of the site only have east to west/northwest slope faces owing to the nature of the land beyond the coal spoil site, which comprises sheep-rearing fields. Running down the south of the site is a small watercourse, which has incised the spoil tips directly next to it. The spoils found at the lowest altitude across the site are dominated by bracken vegetation. No lichen-dominant or bare ground vegetation patches are present across these spoils.

Humphries and Leverton (2012) identified that 73 of the 95 spoil tips at the study site are made up of laminar grey mudstone and laminar hard grey mudstone. Five spoils were eliminated from the group because the spoil tips exceed a safe slope gradient to survey and sample. In the lower section of the site, a further five spoil tips were eliminated, as bracken had outcompeted all other vegetation. Finally, Humphries and Leverton (2012) also found two spoil tips that did not host any lichen-dominant patches; these were consequently removed from the subset under consideration for sampling. Owing to time constraints in both the field (surveying and collecting samples) and the laboratory analysis, it was only practical to investigate 10% of the remaining 61 spoil tips. Of the six spoils selected via a random sampling technique, five were made up of the laminar grey mudstone (spoil tips 33, 36, 56, 61 and 71) and one spoil was made up of the laminar hard dark grey mudstone (spoil tip 5) (Figure 1).

2.2 Site survey design

The site survey investigated the physical properties of the selected spoils in relation to three of the six vegetation classes identified by Dickinson et al. (2013) to create a comparative analysis across the three vegetation classes (bare ground, lichen-dominant and moss-heather mix). For the physical properties survey, each vegetation class was identified in three locations on each spoil tip and surveyed by using 20 by 20 cm quadrats (following the methodology of Dickinson et al., 2013). This equated to 54 quadrats (as all three vegetation classes were present on each of the six selected spoil tips, with three replications). Each quadrat point was mapped using a Trimble GEOXH unit GPS with Terrasync, which records 10–30 cm accuracy range when conditions are favourable.

Spoil material samples from each of the 54 sampling points were collected for laboratory analysis. Samples for erodibility analysis were collected with minimal disturbance using containers with a base of 130 by 105 mm and a depth of 40 mm. An additional circa-50 g sample of the material (at approximately 0–10 cm depth) below the vegetation cover was taken for particle-size determination.

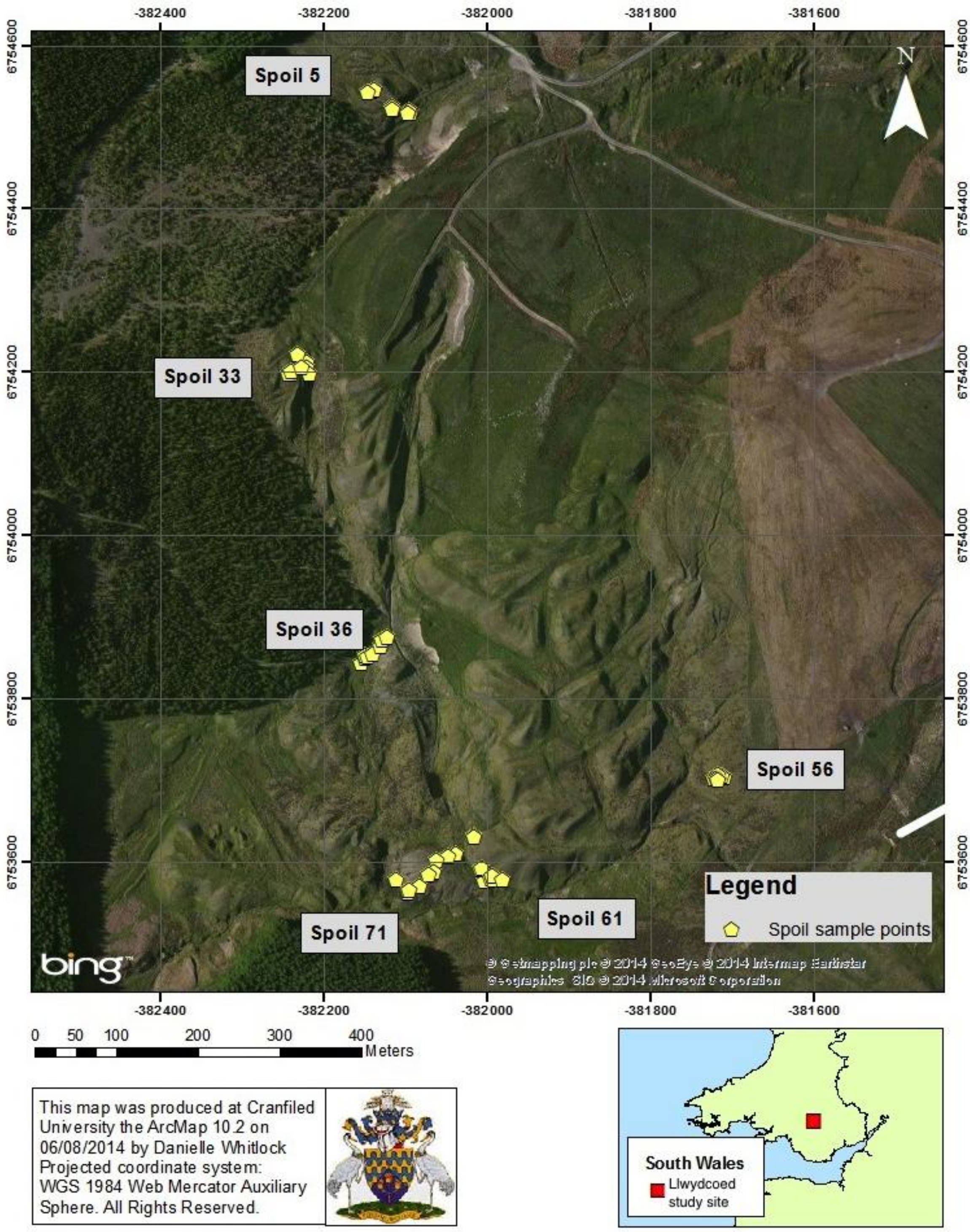

Figure 1 Location of Llwydcoed study area (insert) and sampling points on orphan coal spoil tips

2.3 Methods

2.3.1 Physical properties survey

All slope characteristics and vegetation classes of each quadrat were identified visually using the photographic classification described in Dickinson et al. (2013). The quadrat orientation (aspect) was determined using the eight cardinal directions with a compass. Slope gradient was determined in the field with a clinometer for each sample. Slope position was determined by splitting each slope face into three equal sections: the “top” samples found on the summit and typically in the upper shoulder of the slope, the “middle” samples found within the shoulder and upper footslope, and the “bottom” samples at the footslope and the toeslope.

2.3.2 Laboratory analysis

To determine the spoil materials’ erodibility, a pressurised nozzle rainfall simulator located in the Cranfield University Soil Management facility was used to produce rainfall events. High-intensity rainfall events were chosen for the experiment. This was in order to obtain measurable quantities of eroded material for each vegetation class and to recreate the high-intensity rainfall events that are becoming increasingly common across the UK (Mullan, 2013; Foulds et al., 2014; Smith et al., 2014; Met. Office UK, 2014). The samples were subject to a mean rainfall intensity of 42.2 mm hr^{-1} (standard deviation = 0.68 mm hr^{-1} and coefficient of variance = 1.6 mm hr^{-1}). The intensity was produced using a LECHLER 460.788.17.CE nozzle 2 m above the sample. A water pressure of 0.7 bar was applied to each sample at a constant rate for 15-minute durations. Initially, each sample was saturated in a water bath overnight to ensure all air was removed from the material and bring all samples to a standard soil moisture condition before rainfall simulation was conducted.

The samples were contained in splash cups (internal diameter 74 mm, internal depth 50 mm) and a 19 cm diameter sieve receiver was used to collect any eroded material. After the application of rainfall, eroded material was placed onto pre-weighed Whatman no 2, 150 mm filter paper (weighed using a four decimal place balance). The filter papers, after air-drying, were oven-dried for one hour and 20 minutes (at 105°) and weighed.

The PSD analysis was conducted in accordance with the British Standard (BS) Operating Procedures 7755 Section 5.4:1998 *Determination of particle-size distribution in mineral soil material — Method by sieving and sedimentation*. The material samples were initially air-dried for 24 hours before being sieved to separate particles that were ≤2 mm in size. Samples of 10 g of particles ≤ 2mm in size were treated with hydrogen peroxide to produce a slurry, which was dispersed using a buffered sodium hexametaphosphate solution before the particle-size fractions were determined by pipette extraction.

2.3.3 Statistical analysis

Categorical data were analysed through the Fisher exact test (because the sample size did not comply with the requirements of Chi-square). All other data were tested for normality using the Shapiro-Wilk test. If the data were normally distributed, a factorial analysis of variance (ANOVA) was used for analysis. All statistics were carried out using SPSS *Statistics* 22, applying a confidence level of 95%. All boxplot diagrams illustrate the median and interquartile range in results exploring physical parameters across vegetation classes. The whiskers show minimum and maximum values, excluding outliers.

3 Results

3.1 Physical properties survey

The cardinal directions were analysed via the factorial ANOVA to determine the influence of slope aspect on lichen spatial distribution. With a 95% level of confidence and a p-value of 0.031, the test indicated that slope aspect does influence the spatial distribution of vegetation classes. Figure 2 shows that lichen-dominated vegetation was found in abundance on southwest-facing slopes.

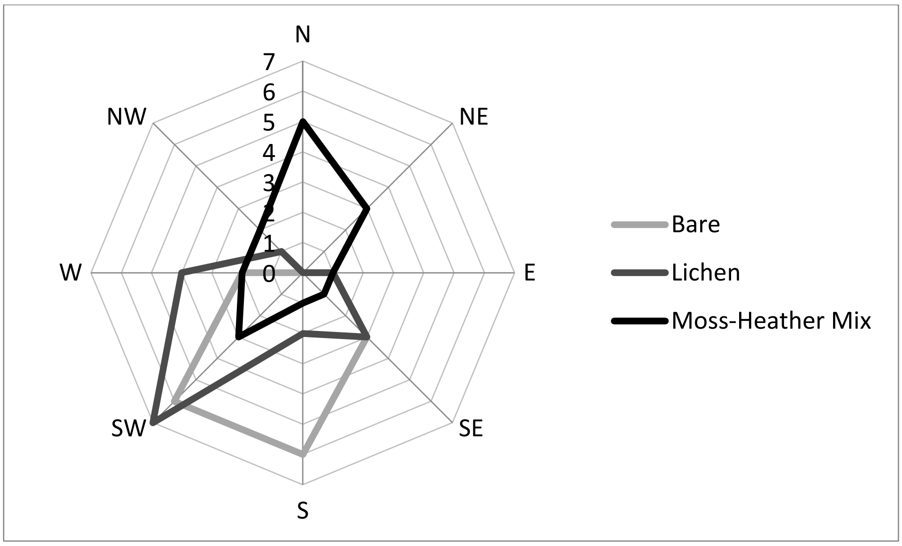

Figure 2 Rose diagram identifying the number of samples found on each slope aspect across the three vegetation classes

The range in slope gradient values for each vegetation class is shown in Figure 3. Lichen-dominant vegetation had the most limited distribution based on slope gradient. The factorial ANOVA indicated that slope gradient does influence the spatial distribution of lichen ($p = 0.002$).

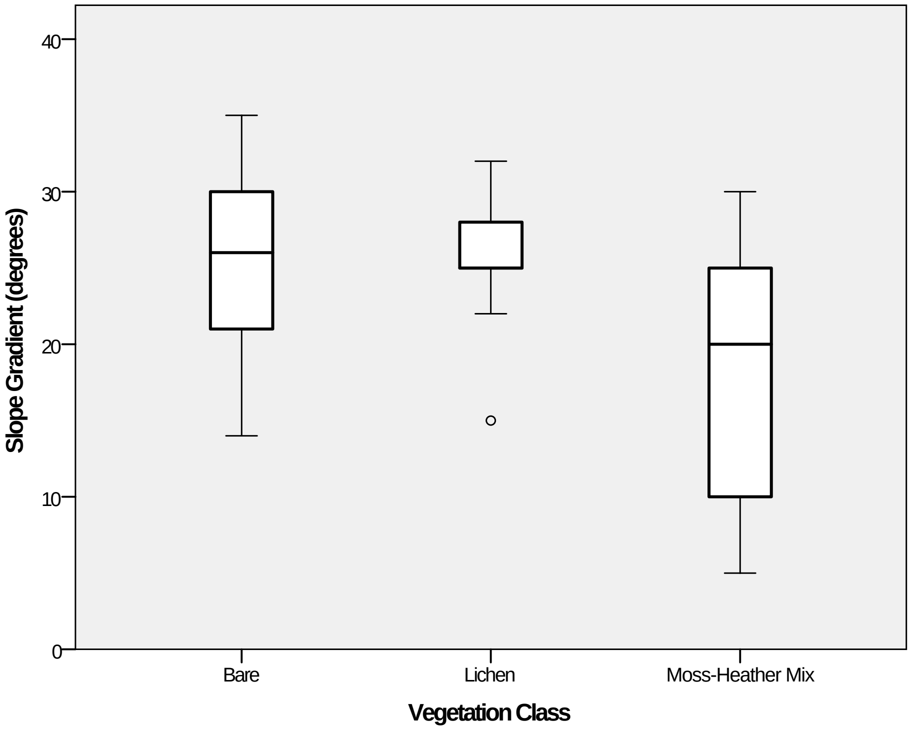

Figure 3 Boxplot of the range in slope gradients across each vegetation class

All three vegetation classes were present across the three slope positions (Figure 4). In particular, the moss-heather mix alongside other higher successional classes was present in abundance across all slope positions. Lichen and bare vegetation were less frequent across the top and bottom slope positions. However, there is insufficient evidence to suggest that slope position affects lichen distribution ($p = 0.392$).

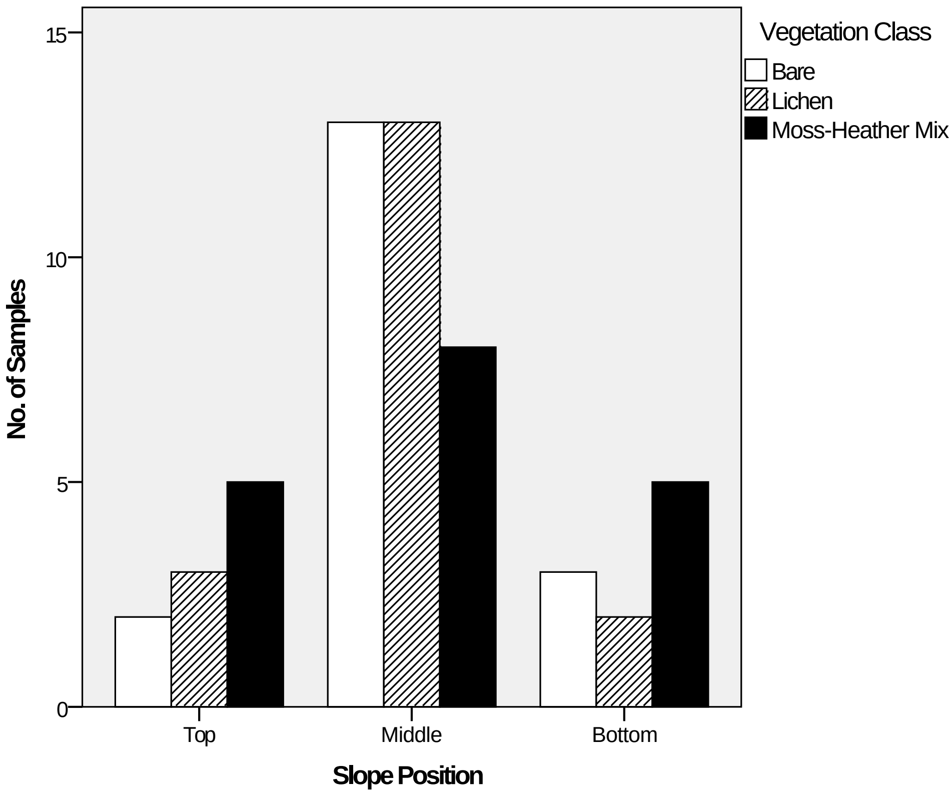

Figure 4 Number of samples found in each position on the spoil tip

The Fisher's exact test identified a significant relationship between slope form and vegetation class ($p = 0.01$). Figure 5 shows the distribution of samples across the three slope forms. All three vegetation classes favoured linear slopes; however, moss-heather mix was limited to only linear and convex slopes.

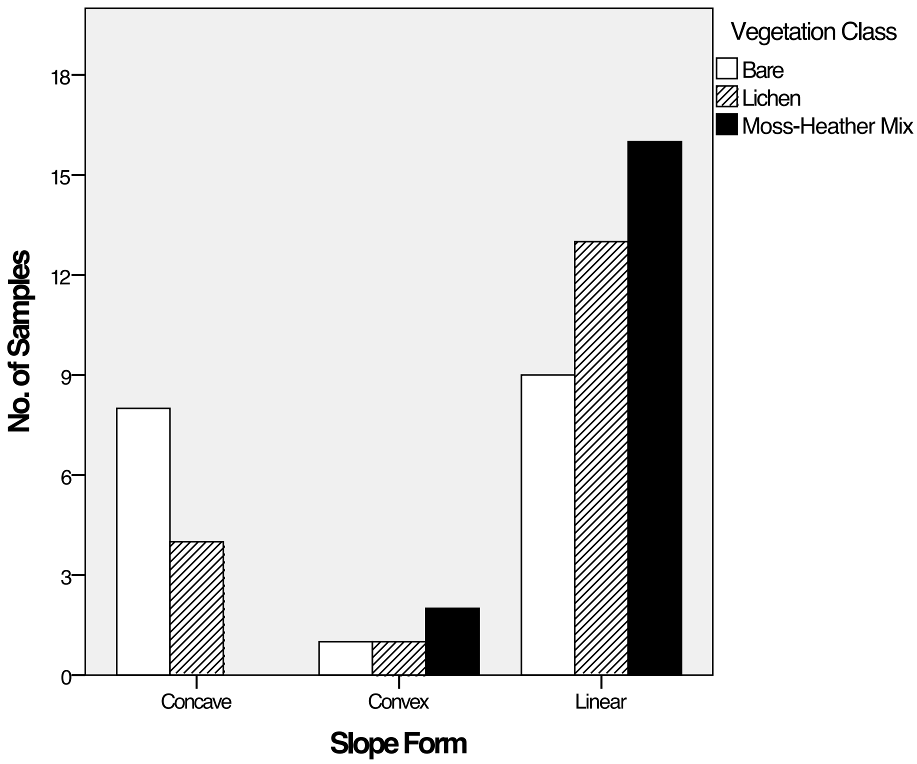

Figure 5 Number of samples across the three different slope forms

3.2 Laboratory analysis

Before determining whether the erodibility of the slope-forming material found at the study site had a significant influence on lichen spatial distribution, a normality test identified that the erodibility data generated by the rainfall simulations was skewed; therefore, it was $\log_{10}$ transformed to make the dataset normally distributed. This ensured a more robust parametric statistical test could be conducted. Figure 6 illustrates that the distribution of vegetation was affected by the erodibility values of the slope-forming materials (p = 0.00).

Figure 6 Box and whisker plot (median, interquartile range, range) of erodibility data across the three vegetation classes

To determine if the PSD of the material had a significant influence on lichen spatial distribution, the data generated by the PSD analysis were first tested for normality. However, two samples were removed, as they skewed the data (an anomalous lichen material sample from spoil tip 56 and an outlier from a bare material sample on spoil tip 71). Figure 7 indicates the PSD samples were clustered, with the majority of samples containing a high silt fraction percentage. However, the factorial ANOVA detected a significant difference between PSD values for all three vegetation classes. Material samples with the lowest abundance of sand fractions were associated with lichen. The lowest silt fractions were found for bare ground, and the lowest clay fractions were associated with moss-heather samples.

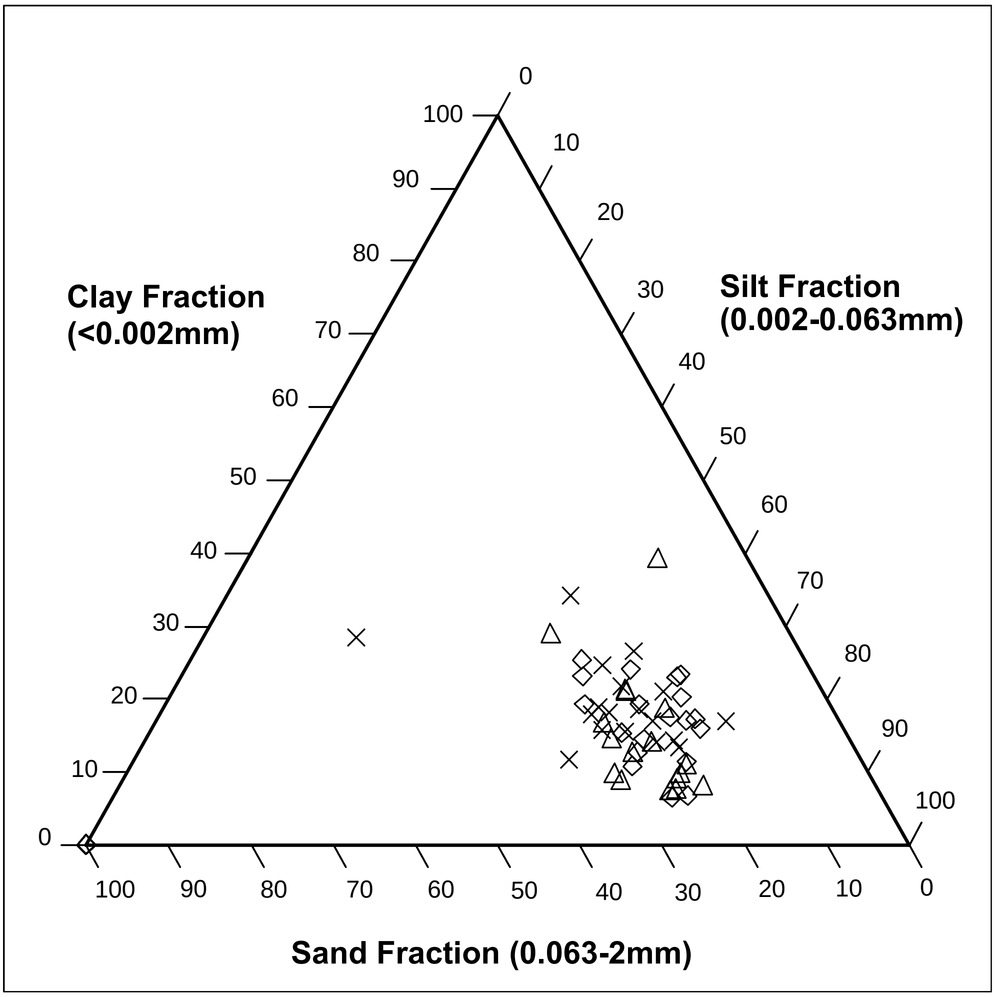

Figure 7 Ternary plot of particle-size distribution of samples split by vegetation class (X =bare ground, △ lichen-dominant and ◇ = moss-heather mix)

4 Discussion

4.1 Physical factors and vegetation distribution

The results of this research concur with several studies indicating that slope aspect has a significant effect on ground cover distribution. The northwest- to northeast-facing slopes were dominated by moss-heather mix and vascular plant classes. Spoil tip 56 had no northwest to east slope faces, explaining the concentration of moss-heather vegetation surveyed on the south-facing slopes. Although bare ground was observed on north faces of some spoil tips at the study site, this is probably due to animal track erosion and sheep scars across the landscape. Furthermore, incidence of sheep scars increased on the southerly slope faces, which might explain the predominant slope orientation of the bare ground patches. It is unclear why the sheep scars are in higher abundance on the south-facing slopes. However, this may be linked to selection in shelter, diet (as sheep are highly selective in feeding preferences), the south-facing slopes' exposure to the longest duration of direct sunlight or the location of the animals' winter feed (Armstrong, 2003). While no (bare soil) sheep scars were surveyed, one lichen-dominant sample was taken within a sheep scar because of the low occurrence of lichen-dominant vegetation elsewhere on the spoil tip (spoil 5). Overall, both bare ground and lichen-dominant vegetation favoured similar slope aspects (Figure 2) because lichen species were the primary colonisers of bare earth surfaces in this habitat.

Pentecost (1979), Armstrong (2002) and Johnson (2011) all confirm that species' slope aspect preferences are strongly associated with soil moisture content. With this in mind, moisture content can influence a slope material's susceptibility to erosion. Renner (1936) identified that north-facing slopes (in the northern hemisphere) were more stable than south-facing slopes owing to differences in moisture and temperature. This could explain the absence of lichen from north-facing slopes, as vascular species would outcompete lichen species where disturbance was absent or minimal. Further research is needed to understand the preferred requirements of individual lichen species and validate this relationship.

Furthermore, slope gradient is a proxy for soil erosion and slope stability processes. Therefore, it is unsurprising that the results identify all bare ground areas to exceed 12°; four bare ground samples exceeded a 30° slope gradient. Bare ground samples also had the highest degree of erodibility. Both bare ground and the moss-heather mix were found across a wide range of gradients. The bare ground areas that had lower slope gradients could have been influenced by previous disturbance events, including paths and sheep scars that had been subject to erosion and had consequently collapsed. Furthermore, some bare ground sections on sampled spoil tips could not be surveyed because of the steepness and instability of the material (spoils 61 and 71). Nonetheless, all but one of the samples taken on these slopes exceeded a 20° gradient, so this is unlikely to have significantly impacted the results. The small slope gradient range in which lichen-dominant patches were found (Figure 3) suggests they could have a slope gradient threshold in which they are less subject to competition from other vegetation types. All but two lichen-dominant samples were within a 10° gradient range (22–32°).

Slope morphology parameters (i.e. slope form and position on slope) were subjective. Slope position did not identify a relationship with the spatial distribution of the vegetation classes, despite physical differences observed when surveying; all vegetation classes were established across each of the slope positions. Perhaps if a more extensive survey of each spoil tip had been conducted, identifying all vegetation class patches on each spoil tip, the differences would have been detected.

Tang et al. (2010) split slopes into four sections, separating the summit from the rest of the slope. The four-section was not applied in this study because the spoil tips were not uniform in slope length or shape across each of the spoil tips. If the four-section method had been applied, the results would have been altered significantly because there were notable differences and similarities across the six spoil tips that were unable to be represented in the survey approach used. For example, all six spoil tips had flat spoil tip summits and four of the summits were dominated by moss-heather, while the other two summits were dominated by other vascular plant vegetation classes. Other studies identified the highest section on a slope to be most abundant in lichen vegetation (Cerdà, 1998), but in the present study, lichen vegetation was sparse in the upper sections of the slope (Figure 4). The lowest slope gradients at the study site were found on the summits and toeslopes, where higher succession vegetation classes dominated, and perhaps this is why lichen patches were not found in abundance on these sections. The two lichen-dominant patches positioned on the lower slopes of the spoil tips also had the lowest slope gradients.

The slope forms on each spoil tip exhibited discontinuities along singular slopes, as expected (Cerdà, 1998; Gray, 2013). All three slope forms were present across the landscape (Figure 5). Convex slopes were not abundant within the study. As no prior study has explored the spoil site's morphological characteristics, it is unclear whether there were too few convex slopes across the site, as they are often uncommon in less actively eroding landscapes, or whether the sampling technique limited the selection of convex slopes across the study. Two moss-heather mix patches were sampled and surveyed on convex summits (associated with higher rates of erosion, than are concave and linear slopes), despite vascular plants' association with more stable slope forms (Cantón et al., 2004). The most stable slope form, concave, did not host any moss-heather mix in this study. This was perhaps owing to the abundance of other vascular plant species classes dominating these stable slopes in the lower sections of the spoil tips. All vegetation classes favoured linear slopes. Although slope form needs to be addressed further, the fact that vegetation class patches are influenced by slope form demonstrates that another physical property influenced the spatial distribution of lichen-dominant patches.

4.2 Erodibility of slope material

Bare ground material was more susceptible to rainfall-induced erosion than was material associated with lichen and moss-heather vegetation classes, which concurs with previous research (Eldridge and Greene, 1994; Buxton et al., 2005; Lázaro et al., 2008; Malam Issa et al., 2011). While the material associated with lichen and moss-heather vegetation classes shared similar susceptibility to rainfall-induced erosion, the median erodibility for moss-heather mix was lower than that for material samples associated with lichen-dominant patches (Figure 6). This result reiterates the stability associated with the spoil tip summits and toeslopes where higher successional class species were most abundant, relegating lichen to the less stable slope gradients (Lázaro et al., 2000). Furthermore, disturbances such as animal trampling can strongly influence the materials' susceptibility to erosion through selective grazing choices that concentrate disturbance (Eldridge 1998).

Lázaro et al. (2008) outlined the importance of low-magnitude, low-intensity precipitation in enabling lichen species to thrive in semi-arid environments. Although the study site is much more stable than the study area explored by Lázaro et al. (2008), identifying the thresholds of disturbance lichen species can survive will promote lichen distribution across coal mine spoil habitats. The impacts of a range of rainfall simulation events (intensities and durations) were not explored in this study. However, the relatively high-intensity rainfall event used in this study generated such small amounts of erosion across all vegetation classes (0.09–0.5 g) that it is unlikely that a further study exploring a combination of rainfall intensities would add to the findings of the present study. Instead, the relationship between erosion processes and lichen spatial distribution should be investigated further by exploring the materials' erodibility in terms of infiltration capacity and resistance to detachment. This would enhance the understanding of the results found.

The PSD results identify significant differences across spoil tips and vegetation classes, even though most samples were classified as silty clay loam (UK ADAS Textural Triangle). It was expected that bare ground samples would have the largest silt fraction percentages, because silt particles are more susceptible to erosion (Wischmeier and Mannering, 1969). Seventy-five per cent of the samples contained high silt content (54–70%). Both lichen-dominant and moss-heather mix classes contained higher silt fractions than the bare ground samples. The comparatively lower silt fraction found in bare ground samples is likely to be linked to the increased mobility of the silt in this vegetation class, especially for bare ground, as there is no vegetation cover protecting the material. None of the sampled material contained clay fractions below 10%, thus improving the materials' cohesive nature, which may have contributed to the three vegetation classes' low susceptibility to erosion. Material associated with lichen contained the smallest sand particle fractions. Lalley and Viles (2008) suggest that sand particles help reduce the impact of disturbance and positively influence the recovery rate of lichen recovery. Again, this raises the question of what degree of disturbance is required to encourage lichen populations while preventing higher successional vegetation from establishing.

5 Conclusions

The findings of this study demonstrate that several physical properties of a coal mine spoil have significant influence on the spatial distribution of vegetation classes at the study site near Llwydcoed, South Wales. The results show that lichen species were present across east- to northwest-facing slopes; however, lichen was only abundant on southwest-facing slopes within a refined range of slope gradients (22–32°). Aspect plays an important role in the spatial distribution of lichen; however, this relationship could be dependent on the lichen species across the site, as species preferences could vary on a site-by-site basis. The roles of slope morphology, material susceptibility to erosion and PSD need to be explored further to increase understanding of the relationships that could exist both at the study site and across other coal mine spoil sites. Nonetheless, knowing the influence of physical parameters on vegetation spatial distributions at the study site will aid future management decisions if the site is reworked for coal in the future. Prioritising slope aspect, gradient, material erodibility and PSD would be fundamental to encourage the re-establishment of lichen communities in the future. For example, loose tipping methods could be used to create as many southwest-facing large bare linear slope surfaces with gradients between 22 and 32° as possible.

This study has clarified the importance of identifying the optimal conditions required to encourage lichen-dominant vegetation to establish in coal mine spoil habitats in South Wales. Important physical properties have been identified that could be explored across other coal mine spoil sites to develop an expansive collection of optimal conditions for lichen species to thrive in rare and unique coal mine spoil habitats. Further work is required if the application of a rule-based approach is to be established. Ultimately, research should concentrate on understanding how micro-habitats change across multiple coal mine spoils as a function of the physical characteristics of the site. This can be achieved by replicating and further developing the methodology applied in this study.

Acknowledgements

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