VEGETATION AND SOIL FACTORS ON A HEAVY METAL MINE SPOIL HEAP

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SUMMARY

The vegetation of a small Scottish metal-mine spoil heap was sampled by means of 70 0.25-m² quadrats and classified into three groups. The most common species were Agrostis capillaris and Festuca rubra which were important constituents of all three groups. Soil samples were collected from each quadrat and analysed for pH, loss-on-ignition, heavy metal and nutrient elements in the soil solution and for several physical properties. The mine spoil was physically and chemically heterogenous with many of the soil solution samples having potentially toxic concentrations of copper, lead and zinc. The vegetation data were ordinated: axis 1 of the ordination was significantly correlated (positively) with all three heavy metal concentrations, silt and sand, and (negatively) with loss-on-ignition and potassium concentration; axis 2 was significantly negatively correlated with pH and calcium, nitrate and phosphate concentrations. Consideration of this ordination and comparisons between soil parameters associated with each of the three vegetation groups and with non-vegetated quadrats, suggest that lead and zinc may be the major determining factors of the spoil-heap vegetation. Low nutrients (except phosphate) and in some cases adverse soil physical factors might be important also. The apparently small influence of copper is discussed. Above-ground parts of five plant species were collected from the mine spoil and were shown often to have high heavy metal concentrations which differed between species. Finally we discuss some implications of interspecific differences in metal-mine occurrence within the genera Agrostis and Festuca.

INTRODUCTION

It has been recognized for some time that plant distribution on soils rich in heavy metals is influenced by many physical and chemical factors (Antonovics, Bradshaw and Turner, 1971). The overriding influence of heavy metals is usually assumed but a number of recent studies (Alvarez, Ludwig and Harper, 1974; Smith and Bradshaw, 1979; Clark and Clark, 1981) have suggested the importance of major nutrient elements in determining vegetation distribution on metal mines. The importance of soil physical factors for plants has been shown on colliery spoil (which is similar in particle-size composition to that of many metalliferous mines) by Richardson and Greenwood (1967). However there is a shortage of studies which give detailed vegetation descriptions, estimates of soil solution (rather than total or extractable) elements in the soil and which quantify physical parameters at the same site. The present paper reports an intensive investigation on the vegetation and the factors affecting its distribution on the Burn of Sorrow mine, Scotland. The site is small and has substantial quantities of copper, lead and zinc (Proctor and Bacon, 1978).

We chose analyses of soil solutions as the measure of elements that are influencing plants. It is known that soil-solution concentrations will vary with season (Williams and Chadwick, 1977) and, particularly in the case of nitrate ions,
with the pretreatment of the samples. In spite of this, analyses of the soil solution will give a closer approximation to the root environment than those of the usual (e.g. acetic acid, ammonium acetate, nitric acid) soil extractants, which bring a range of fractions into solution. Johnston and Proctor (1981) and Rothwell (1980) found that plants grown in water-culture media based on soil solutions extracted (by similar methods to those described in the present paper) from Scottish metalliferous soils were broadly similar in appearance and chemical composition to those of soil-grown plants.

There are few published analyses of metal concentrations in higher plants from copper-rich soils and we report here analyses for a number of species from the Burn of Sorrow mine.

**The Study Site**

The Burn of Sorrow mine is at an altitude of 305 m (National Grid Reference NN 946002) near Dollar, Scotland. It was worked for copper and lead in the eighteenth century until 1795 (Dickie and Forster, 1974) and hand-picked ore was washed and dressed at the site. A spoil heap some 100 m long and 15 m maximum width remains. The spoil is, in many places, a distinctive orange colour from a mixture of pink and white barytes, pyrite, chalcopyrite and galena with traces of malachite, azurite, limonite and chrysolla (Francis et al., 1970). The site has a patchy vegetation; much of it is barren, some is sparsely colonized mainly by *Agrostis capillaris* and *Festuca rubra*, in other places there is a more substantial species-rich plant cover. Proctor and Bacon (1978) made a preliminary description of the site and their soil analyses showed that high concentrations of copper, lead and zinc were extractable by acidified ammonium acetate solutions.

**Spoil-heap Vegetation**

The vegetation of the spoil heap was sampled in June 1979 by means of 70 50 x 50-cm quadrats which were regularly positioned. Two quadrats had a sharp vegetation boundary at their mid-point and were each divided into two sub-quadrats of 25 x 50 cm which were subsequently treated as full quadrats. For each quadrat the overall slope and aspect were noted and all vascular plants and bryophytes were recorded on the Domin scale. The Domin values were transformed using the method of Bannister (1966) for subsequent calculations.

Of the 72 quadrats, 19 had no vascular plants or bryophytes and one had a small cover of a single species of bryophyte (*Hylocomium splendens*) which was not recorded elsewhere on the mine. The vegetation data for the other 52 quadrats were classified by TWINSPAN, a polythetic divisive classification method based on reciprocal averaging (Hill, 1973, 1979a). This gave three interpreted vegetation groups of which some details are given in Table 1 and which can be briefly characterized: group 1 has a high plant cover and includes the following constants (frequency \( \geq 60\% \)), *Anthoxanthum odoratum*, *Deschampsia flexuosa*, *Festuca ovina*, *Rhacomitrium lanuginosum* and *Thymus praecox* ssp. *arcticus* as well as *Agrostis capillaris* and *F. rubra*; group 2 has a high cover of *Agrostis capillaris* and *F. rubra* but no other constants; group 3 has a sparse but constant presence of *Agrostis capillaris* of which the most frequent associate (in 13 out of 24 quadrats) is the rare liverwort, *Cephalozia stellulifera* Tayl. M.S. Schiffn.

* Species names are from Clapham, Tutin and Warburg (1981) or from Watson (1968) unless the authorities are given.
Table 1. The species frequency in three interpreted vegetation groups based on a *twin*span classification of 52 quadrats from the Burn of Sorrow Mine, Scotland

| Species                          | Group 1 \((n = 10)\) | Group 2 \((n = 18)\) | Group 3 \((n = 24)\) |
|----------------------------------|-----------------------|-----------------------|-----------------------|
| Hypnum cupressiforme             | 2                     | —                     | 1                     |
| Anthoxanthum odoratum            | 6                     | 1                     | 1                     |
| Dicranum scoparium                | 5                     | 2                     | —                     |
| Carex sp.                        | 2                     | —                     | —                     |
| Hypochaeris radicata             | 2                     | —                     | —                     |
| Luzula campestris                | 1                     | —                     | —                     |
| Festuca ovina                    | 7                     | 2                     | —                     |
| Hieracium pilosella              | 3                     | 1                     | —                     |
| Trifolium repens                 | 2                     | 1                     | —                     |
| Thymus praecox ssp. arcticus     | 9                     | 1                     | —                     |
| Deschampsia flexuosa             | 7                     | 2                     | —                     |
| Dryopteris filix-mas             | 1                     | —                     | —                     |
| Oxalis acetosella                | 1                     | —                     | —                     |
| Rhacomitrium fasciculare         | 1                     | —                     | —                     |
| Vaccinium myrtillus              | 2                     | —                     | —                     |
| Galium verum                     | 1                     | —                     | —                     |
| Diplophyllum albicans            | 1                     | —                     | —                     |
| Polytrichum piliferum            | 1                     | —                     | —                     |
| Nardus stricta                   | 4                     | 3                     | —                     |
| Galium saxatile                  | 2                     | 3                     | —                     |
| Rhacomitrium canescens           | 2                     | 1                     | 1                     |
| Campanula rotundifolia           | 3                     | 4                     | —                     |
| Urtica dioica                    | —                     | 2                     | —                     |
| Equisetum arvense                | —                     | 1                     | —                     |
| Plantago lanceolata              | —                     | 1                     | —                     |
| Rhytidiadelphus squarrosum       | 1                     | 3                     | —                     |
| Taraxacum officinale             | —                     | 1                     | —                     |
| Grimmia apocarpa                 | 1                     | 2                     | —                     |
| Rhacomitrium lanuginosum         | 6                     | 6                     | 3                     |
| Agrostis capillaris              | 7                     | 17                    | 21                    |
| Festuca rubra                    | 9                     | 14                    | 10                    |
| Rumex acetosa                    | 1                     | 4                     | 2                     |
| Bryum sp.                        | —                     | 3                     | 2                     |
| Pohlia nutans                    | 2                     | 10                    | 12                    |
| Pleurozium schreberi             | 2                     | 1                     | 4                     |
| Ceratodon purpureus              | 1                     | 1                     | 4                     |
| Brachythecium rutabulum          | —                     | 1                     | 1                     |
| Cerastium fontanum ssp. glabrescens | 1           | 2                     | 2                     |
| Cephaloziaella stellulifera      | —                     | 2                     | 3                     |
| Barbula tophacea                 | —                     | 2                     | 3                     |
| Bryum inclinatum                 | —                     | 1                     | 3                     |
| Dicranella varia                 | —                     | 1                     | 1                     |

The vegetation has a number of species in common with similar sites elsewhere in Northern Britain (Ernst, 1974) including *Agrostis capillaris, Anthoxanthum odoratum, Campanula rotundifolia, F. ovina, Galium saxatile, Rumex acetosa, T. praecox ssp. arcticus* and *Pohlia nutans*. The abundance of *F. rubra* (omitted from Ernst’s tables of metal-mine species) on the Burn of Sorrow mine is discussed later. *Cephaloziaella* spp. are recorded from metalliferous soils (Antonovics et al.,
Cephaloziella stellulifera is known from metal-mine sites in Cornwall (J. S. Paton pers. comm.).

**SOIL ANALYSES**

*Sampling and particle-size analysis*

During the vegetation description (in June 1979) four 5-cm deep soil cores were taken, using a 42-mm diameter steel auger, from as close as possible to the points mid-way between the centre and the corners of each 50 × 50-cm quadrat. The four cores (two cores in the case of the sub-quadrats described earlier) were lumped, air-dried, lightly ground and sieved through a 2-mm mesh. A second series of samples were collected and treated in the same way in June 1980 for further analyses.

For quantification of stones, a representative 25 × 25-cm area was chosen within each quadrat. Large (> 15 cm along the longest axis) stones were noted and left whilst smaller stones and soil to a depth of 5 cm were collected. Stones of which the greater proportion lay outside the delimited area or below 5-cm depth were not collected. The samples were sieved through a 17-mm mesh in the field and stones retained on the sieve weighed on a spring balance. In the laboratory the sieved soil was then passed through a 2-mm mesh and the weight of stones of diameter 2 to 17 mm recorded. Sub-samples of the 2-mm sieved soil were subjected to mechanical analyses by Buoyucos hydrometry.

*Soil chemical analysis*

*Samples collected in 1979.* pH was measured, using a Corning-Eel meter, on a freshly stirred mix, that had stood for at least 2 h, of 10 g soil with 30 ml deionized water. Loss-on-ignition was measured after heating 1 g soil at 400 °C for 12 h.

The air-dried samples from which soil solutions were to be extracted were placed in pots stood in saucers, thoroughly moistened with deionized water and maintained wet for 48 h. They were then centrifuged at 12000 g for 20 min at 0 °C and the supernatants were filtered through Whatman’s no. 42 filter paper and frozen until required. The solutions were analysed for calcium, copper, lead, magnesium, potassium and zinc by a Perkin-Elmer 373 atomic absorption spectrophotometer.

*Samples collected in 1980.* Soil solutions were extracted as above and analysed for phosphate by a method based on Allen (1940) and nitrate by a colorimetric method described by Allen *et al.* (1974) (save that concentrated sulphuric acid was substituted for fuming sulphuric acid). Magnesium and potassium analyses, using the methods of the previous year, were carried out for a few sub-samples from quadrats for which there had been insufficient solution extracted for complete analysis in 1979.

*Results of soil analyses.* A summary of the analytical results for the soils of the three vegetation groups and for those with no recorded plants, is given in Table 2. The soils are often stony and after sieving have a preponderance of sand particles. The concentrations of copper, lead and zinc in many of the soil solutions exceeded those known to be toxic to non-tolerant plants. Wong and Bradshaw (1982) reported a 50% reduction of root growth of *Lolium perenne* by 0.02 mg l⁻¹ copper or 1.7 mg l⁻¹ lead or 1.6 mg l⁻¹ zinc. The concentrations of nutrients, with the exception of phosphorus were relatively low. Epstein (1972) summarized a number of element concentrations in solutions from many soils and the following were the most frequent ranges (in mg l⁻¹): nitrogen (as nitrate), 101 to 150; phosphorus (as phosphate), 0 to 0.03; potassium, 21 to 40; calcium, 51 to 100;
Table 2. The means and ranges of soil pH, loss-on-ignition, nitrate, phosphate and metal concentrations in soil solutions, weights of stones, percentage sand, silt and clay and the slope of quadrats in three TWINSPIR vegetation groups and in quadrats with no recorded vegetation.

| Vegetation group | n  | pH     | Loss-on-ignition (%) | Nitrogen as nitrate (mg l⁻¹) | Phosphorus as phosphate (mg l⁻¹) | Potassium (mg l⁻¹) | Calcium (mg l⁻¹) | Magnesium (mg l⁻¹) | Copper (mg l⁻¹) | Lead (mg l⁻¹) |
|------------------|----|--------|----------------------|-----------------------------|--------------------------------|--------------------|-----------------|------------------|-----------------|---------------|
| 1                | 10 | 5.4    | 22.1                 | 9.2                         | 3.3                            | 8.3                | 11.6            | 3.1              | 0.69            | 0.22          |
|                  |    | (3.9-7.0) | (4.8-37.0)           | (0.07-31.0)                 | (0.0-64)                       | (2.1-18.0)         | (20-49.0)       | (0.9-9.4)        | (0.0-3.2)       | (0.0-0.8)     |
| 2                | 18 | 5.5    | 12.6                 | 8.7                         | 3.1                            | 5.6                | 12.8            | 1.3              | 0.11            | 1.1           |
|                  |    | (4.1-7.0) | (3.3-23.0)           | (1.1-30.0)                  | (0.0-9.5)                      | (2.0-9.1)          | (2.1-40.0)      | (0.1-1.5)        | (0.0-5.6)       | (0.0-5.6)     |
| 3                | 24 | 5.8    | 9.7                  | 13.1                        | 3.1                            | 3.6                | 13.2            | 2.1              | 1.0             | 1.2           |
|                  |    | (4.2-6.5) | (4.4-31.0)           | (0.0-33.0)                  | (0.2-10.3)                     | (1.0-7.7)          | (3.4-31.0)      | (0.95-4.7)       | (0.15-2.8)      | (0.20-4.8)    |
| Non-vegetated quadrats | 19 | 5.6    | 5.2                  | 7.4                         | 1.5                            | 7.6                | 1.3             | 1.0              | 50              | 50            |
|                  |    | (4.7-6.7) | (1.8-12.0)           | (0.5-38.0)                  | (0.2-9.5)                      | (1.2-18.0)         | (2.9-22.0)      | (0.7-2.2)        | (0.29-2.7)      | (0.7-15.0)    |

| Vegetation group | n  | pH     | Loss-on-ignition (%) | Zinc (mg l⁻¹) | Large stones (kg 625 cm⁻²) | Small stones (kg 625 cm⁻²) | Clay (%) | Sand* (%) | Silt (%) | Slope (°) |
|------------------|----|--------|----------------------|---------------|-----------------------------|-----------------------------|----------|-----------|----------|-----------|
| 1                | 10 | 5.4    | 22.1                 | 0.15          | 0.84                        | 0.53                        | 1.6      | 72        | 3.8      | 9.6       |
|                  |    | (3.9-7.0) | (4.8-37.0)           | (0.04-0.28)   | (0.24-2.5)                  | (0.02-2.4)                  | (54.0-85.0) | (0.0-11.0) | (0.20-0.0) |           |
| 2                | 18 | 5.5    | 12.6                 | 0.59          | 0.89                        | 0.45                        | 1.1      | 81        | 5.2      | 5.6       |
|                  |    | (4.1-7.0) | (3.3-23.0)           | (0.2-21)      | (0.0-2.8)                   | (0.01-1.5)                 | (6.0-93.0) | (0.1-20.0) | (0.15-0.0) |           |
| 3                | 24 | 5.8    | 9.7                  | 0.67          | 1.4                         | 0.78                        | 1.4      | 81        | 7.1      | 5.3       |
|                  |    | (4.2-6.5) | (4.4-31.0)           | (0.08-3.6)    | (0.02-3.5)                  | (0.04-3.0)                 | (5.0-94.0) | (2.0-16.0) | (0.20-0.0) |           |
| Non-vegetated quadrats | 19 | 5.6    | 5.2                  | 3.5           | 0.78                        | 1.5                         | 2.1      | 85        | 8.3      | 9.7       |
|                  |    | (4.7-6.7) | (1.8-12.0)           | (0.22-0.0)    | (0.14-2.3)                  | (0.44-2.6)                 | (75.0-95.0) | (3.0-15.0) | (0.2-5.0) |           |

* Calculated as 100% - % loss-on-ignition - % clay - % silt.
magnesium, 51 to 100. Except for phosphorus the Burn of Sorrow mine soil-solution concentrations are all below the lower end of these ranges.

**Plant Analyses**

Samples of shoots of *Agrostis capillaris* and *F. rubra*, leaves of *Cerastium fontanum* ssp. *glabrescens* and *Rumex acetosa* and leaves and stems of *T. praecox* ssp. *arcticus* were collected at widely-spaced intervals over the mine surface. All plant samples were 0-5-1 g after drying and were collected on 8 October 1979.

The plants were thoroughly washed three times in deionized water, dried at 60 °C and wet-ashed in concentrated nitric acid. The solutions were filtered through Whatman’s no. 42 paper, made up to a standard volume and analysed for metals by similar methods to those used for the soil solutions.

Table 3 shows that the plant-tissue concentrations of heavy metals in the Burn of Sorrow samples usually exceed, whilst those of potassium, calcium and magnesium are usually less than, concentrations on plants of non-metalliferous areas. The substantial interspecific differences in Table 3 probably reflect a variety of mechanisms of metal tolerance since different species collected from chemically similar parts of the mine showed large differences in chemical composition (Thompson, 1980). The high concentrations in the leaves of some plants of *Rumex acetosa* are noteworthy. The relatively low concentrations of copper and iron in shoots of *Agrostis capillaris* and *F. rubra* probably result from a retention of these elements in the roots. Analyses of these species grown in water cultures which simulated the chemical composition of soil solutions from the Burn of Sorrow, showed that copper was up to 33 times and iron up to 21 times more concentrated in roots than in shoots (Thompson, 1980). Thompson showed in the same experiments that zinc was usually about five times more concentrated in the shoots than in the roots.

**Causes of Vegetation Distribution**

The vegetation data for the 52 quadrats described earlier were ordinated by **DECORANA** (Hill, 1979b) (Fig. 1). Eigenvalues for the ordination were: axis 1, 0·657; axis 2, 0·368; axis 3, 0·236; axis 4, 0·166. The vegetation groups from the **TWINSPAN** classification are better separated on axis 1 than axis 2 of the ordination.

Correlation coefficients (Spearman’s non-parametric \( r_s \)) were calculated, for each quadrat, between the positions on each axis of the ordination and the soil parameters (Table 4). Several significant correlations emerged: axis 1 positively with heavy metals and silt and sand, negatively with potassium and loss-on-ignition; axis 2 negatively with pH, nitrate, phosphate and calcium; axis 4 negatively with lead and silt and clay. Before attempting to interpret these correlations in terms of causal factors it must be pointed out that soil factors are often themselves inter-correlated and there are difficulties in separating their effects on vegetation. Further light is shed on the importance of the different soil factors when they are related to the **TWINSPAN** vegetation groups 1 to 3 and the non-vegetated quadrats (Table 2). Mean soil-solution copper concentrations show less than a twofold difference between the groups in Table 2 and the ranges also overlap. The highest soil-solution copper values were found in vegetated rather than barren quadrats. Thus although copper is highly positively correlated with axis 1 of the ordination (Table 4) there is reason to believe that this results from its own high positive
Table 3. Mean concentrations and their ranges (in parentheses) of mineral-elements (μg g⁻¹ dry matter) in plants collected from the Burn of Sorrow mine

| Species             | n  | Plant part | Potassium     | Calcium       | Magnesium    | Copper       | Iron      | Lead     | Zinc     |
|---------------------|----|------------|---------------|---------------|--------------|--------------|-----------|----------|----------|
| *Agrostis capillaris* | 9  | Shoots     | 17000         | 3300          | 1500         | 33           | 140       | 190      | 180      |
|                     |    |            | (11000–27000) | (1900–4800)   | (810–2400)   | (< 10–85)    | (100–190) | (100–500) | (90–270) |
| *Cerastium fontanum* ssp. *glabrescens* | 5  | Leaves     | 27000         | 13000         | 6200         | 87          | 540       | 290      | 210      |
|                     |    |            | (21000–40000) | (7500–19000)  | (3700–10000) | (36–180)    | (170–1400) | (120–420) | (160–310) |
| *Festuca rubra*     | 10 | Shoots     | 12000         | 4400          | 1400         | 12          | 110       | 100      | 67       |
|                     |    |            | (8500–16000)  | (3800–5900)   | (910–1800)   | (< 10–30)   | (70–140)  | (< 10–150) | (50–86)  |
| *Rumex acetosa*     | 6  | Leaves     | 26000         | 7700          | 4000         | 170         | 1400      | 870      | 170      |
|                     |    |            | (19000–33000) | (3600–13000)  | (2400–5700)  | (< 10–540)  | (230–6000) | (< 10–3600) | (< 10–320) |
| *Thymus praecox* ssp. *arcticus* | 6  | Leaves     | 9700          | 13000         | 3800         | 16          | 250       | 100      | 190      |
|                     |    |            | (5200–14000)  | (9500–17000)  | (1900–5700)  | (< 10–32)   | (83–680)  | (41–160) | (< 10–460) |
| *Thymus praecox* ssp. *arcticus* | 6  | Stems      | 11000         | 7400          | 3600         | 82          | 700       | 600      | 130      |
|                     |    |            | (9800–14000)  | (6000–8400)   | (2200–4900)  | (19–230)    | (150–1900) | (69–1100) | (56–320) |
| Typical concentrations in plants of non-metalliferous soils |
|                     |    | Leaves     | 15000–50000*  | 10000–50000*  | 2500–10000*  | 5–15*       | 50–300*   | 0–05–3†  | 15–75*   |

* Hewitt and Smith (1975).
† Allen et al. (1974).
Data for plants of non-metalliferous soils are included for comparison.
Fig. 1. A DECORANA ordination on the vegetation data from 52 quadrats from the Burn of Sorrow mine. The numbers 1 to 3 refer to the TWINSPAN vegetation group into which the quadrat has been classified (x denotes a point for five group-3 quadrats with the same position).

Table 4. Correlation coefficients (Spearman’s $r_s$) between the positions of quadrats on axes 1 to 4 of the DECORANA vegetation ordination (Fig. 1) and soil parameters for each quadrat (n = 52)

| Soil parameter   | 1       | 2       | 3       | 4       |
|------------------|---------|---------|---------|---------|
| pH               | 0.169   | -0.498*** | -0.130  | 0.166   |
| Loss-on-ignition | -0.355** | 0.085   | 0.001   | 0.193   |
| Nitrate          | 0.1542  | -0.241*  | -0.227  | -0.017  |
| Phosphate        | -0.178  | -0.462*** | -0.121  | 0.080   |
| Potassium        | -0.321** | 0.100   | 0.082   | 0.226   |
| Calcium          | 0.088   | -0.433*** | -0.174  | 0.214   |
| Magnesium        | 0.051   | -0.069   | 0.016   | 0.108   |
| Copper           | 0.395** | -0.045   | -0.054  | -0.040  |
| Lead             | 0.351** | 0.223    | -0.191  | -0.361** |
| Zinc             | 0.262*  | 0.220    | -0.092  | -0.167  |
| Large stones     | 0.074   | -0.084   | -0.187  | 0.177   |
| Small stones     | 0.131   | -0.185   | -0.204  | 0.025   |
| Clay             | 0.063   | -0.002   | -0.166  | -0.249* |
| Sand             | 0.287*  | 0.032    | -0.130  | -0.017  |
| Silt             | 0.262*  | 0.038    | 0.005   | -0.294* |
| Slope            | -0.203  | 0.030    | 0.230   | -0.179  |

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

correlation with another factor, probably lead (Table 5). Mean lead concentrations are least under vegetation group 1 (with the highest cover and most species) and often very high under non-vegetated quadrats. Zinc (significantly correlated with lead but not copper in the soil) is also low under vegetation group 1 and often high in the non-vegetated quadrats. The soil pH and nutrient elements show relatively small differences between the groups (Table 2). Nevertheless, all nutrient elements, except phosphorus, have low soil-solution concentrations and are potentially limiting for plant growth.
Table 5. Correlation coefficients (Spearman’s \( r_s \)) between soil parameters from samples from vegetated quadrats from the Burn of Sorrow mine (\( n = 52 \))

| Soil parameter       | Loss-on-ignition | NO\(_3\) | PO\(_4\) | K    | Ca   | Mg   | Cu   | Pb   | Zn    | Large stones | Small stones | Clay    | Sand    | Silt    | Slope |
|----------------------|------------------|---------|---------|------|------|------|------|------|-------|-----------|-------------|----------|---------|---------|--------|
| pH                   | -0.372**         | 0.424***| 0.357** | -0.149| 0.749***| 0.361**| 0.277* | -0.137| -0.359**| 0.047     | 0.252*     | 0.162    | 0.243*  | 0.083   | -0.138 |
| Nitrate              | -0.089           | 0.108   | 0.557***| -0.179| 0.003 | -0.071| -0.232*| -0.182| -0.209 | -0.450***| -0.317*    | -0.641***| -0.235* | -0.051  |        |
| Phosphate            | 0.094            | -0.226  | 0.306*  | 0.172 | 0.183 | -0.037| -0.181| -0.003| 0.053  | 0.065     | -0.104     | 0.293*   | 0.045   |         |        |
| Potassium            | 0.277*           | 0.429***| 0.326** | 0.371**| 0.054 | -0.262*| -0.114| -0.172| -0.134| 0.0089    | -0.291*    | -0.082   |         |         |        |
| Calcium              | 0.205            | 0.423***| 0.142   | -0.041| 0.121 | -0.042| -0.310*| -0.305*| -0.216| -0.416***| 0.028      |         |         |         |        |
| Magnesium            | 0.501***         | 0.447***| -0.075  | -0.212| 0.082 | 0.064 | 0.064 | 0.020 | 0.068 | -0.146    |           |         |         |         |        |
| Copper               | 0.403**          | 0.586***| 0.167   | 0.208 | 0.004 | -0.145| 0.087 | 0.027 | -0.335**|           |           |         |         |         |        |
| Lead                 | 0.182            | 0.230*  | 0.053   | -0.022| 0.175 | 0.175 | 0.175 | 0.071 | 0.071 | 0.175     |           |         |         |         |        |
| Zinc                 | 0.118            | 0.280*  | 0.024   | -0.210| 0.137 | 0.086 | 0.010 |       |       |           |           |         |         |         |        |
| Large stones         | 0.159            | -0.304* | 0.127   | -0.211| 0.273 | -0.192| 0.228 |       |       |           |           |         |         |         |        |
| Small stones         | 0.053            | 0.002   | 0.171   | 0.175 | 0.071 | 0.071 | 0.175 | 0.071 | 0.175 | 0.071     |           |         |         |         |        |
| Clay                 | 0.175            | 0.137   | 0.086   | 0.010 |       |       |       |       |       |           |           |         |         |         |        |
| Sand                 | 0.175            | 0.137   | 0.086   | 0.010 |       |       |       |       |       |           |           |         |         |         |        |
| Silt                 | 0.175            | 0.137   | 0.086   | 0.010 |       |       |       |       |       |           |           |         |         |         |        |

* \( P < 0.05, ** P < 0.01, *** P < 0.001. \)
Soil loss-on-ignition (roughly equivalent to soil organic matter) increases with the vegetation cover. Since the percentage of soil inorganic matter (clay, sand and silt) is negatively correlated with loss-on-ignition this may explain the positive correlations with both sand and silt on axis I of the ordination (Table 4). Nevertheless we expect some influence of physical factors and the non-vegetated quadrats have a higher mean percentage of small stones than those quadrats with vegetation although the ranges overlap. Vegetation is usually lacking from stones greater than 15 cm in length. We found no relationship between quadrat aspect and vegetation: there were well-vegetated, south-facing quadrats on the steepest slopes (the most xeric combination amongst the samples) whilst some quadrats on flat areas had no vegetation.

**Discussion**

**Evolution of metal tolerance**

The evidence that copper is of limited importance as a vegetation determinant on the Burn of Sorrow mine is intriguing in view of the reports of the extreme sensitivity of non-tolerant plants to copper. For example copper concentrations of 0.02 mg l⁻¹ have been shown to cause a 50% reduction of root growth rate of *L. perenne* whereas 1.7 mg l⁻¹ lead or 1.6 mg l⁻¹ zinc were needed to cause the same effect (Wong and Bradshaw, 1982).

At the Burn of Sorrow mine a large number of species, including *Anthoxanthum odoratum* and *Trifolium repens*, which have been reported as never occurring on copper contaminated soils (Gartside and McNeilly, 1974), occur in soils with solution copper concentrations up to 3.2 mg l⁻¹. We cannot discount the possibility that the soil-solution copper is in an innocuous chemical form but it seems just as likely that many species have evolved tolerance to copper alone. Thus the apparently greater influence of lead and zinc toxicity on the Burn of Sorrow mine may be a result of the difficulty of evolving tolerance to high concentrations of these elements. Walley, Khan and Bradshaw (1974) and Gartside and McNeilly (1974) found that copper-tolerant individuals of *Agrostis capillaris* could be selected from non-tolerant populations in one step whereas in the case of zinc, full tolerance was not achieved in one cycle of selection.

Evolution of metal tolerance at the Burn of Sorrow mine is probably complex because copper, lead and zinc occur frequently together, all in potentially toxic concentrations. There are impressive cases of probable multiple metal tolerance there, e.g. *Agrostis capillaris* grew in a quadrat which had soil-solution concentrations of 4.2 mg l⁻¹ copper, 5.6 mg l⁻¹ lead and 1.5 mg l⁻¹ zinc. Plant analyses (summarized in Table 4) showed a number of cases of high tissue concentrations of all three of these metals: for example one sample of *Rumex acetosa* had (in µg g⁻¹ dry matter): copper, 540; lead, 3600; zinc 220. The evolution of tolerance to lead and zinc may be difficult when the metals occur together and combined with other unfavourable soil factors such as high concentrations of copper and low ones of nutrient ions in the soil solutions. Karataglis (1980) showed that copper and zinc toxicities may be additive for *Agrostis capillaris*.

**Interspecific differences in occurrence on metal spoil**

Antonovics *et al.* (1971) reported that *F. rubra* is found on calcareous mines, whilst *F. ovina* is found on acid mines. The abundance of *F. rubra* on the Burn of Sorrow spoil which is acid and not calcareous is surprising. At the Burn of Sorrow, soils bearing *F. rubra* have higher mean soil-solution calcium concentration and a higher mean pH than those for *F. ovina* although there is a large degree of
overlap. Thompson (1980) showed no amelioration of copper toxicity by calcium in simulated-soil-solution culture experiments on *F. rubra* collected from a Burn of Sorrow soil with 0·63 mg l\(^{-1}\) soil-solution copper. If *F. rubra* does require relatively high soil calcium then its function is apparently unconnected with amelioration of copper toxicity.

In quadrats where both occur, *F. rubra* predominates over *F. ovina* where there are higher heavy-metal concentrations whilst the reverse is true at lower heavy-metal concentrations. The selection of races of *F. rubra* rather than *F. ovina* in the more extreme metalliferous soils at Burn of Sorrow raises questions about the importance of interspecific differences in the evolution of tolerance. Craig (1972) observed a Scottish mine at Tyndrum which had spoil with high lead and zinc and which was colonized by *Agrostis vinealis* but not *Agrostis capillaris* although both species were common on non-metalliferous soils in the same area. We did not record *Agrostis vinealis* on the Burn of Sorrow mine although it is in the surrounding hills. The soils on the Tyndrum spoil often have higher soil-solution lead and zinc concentrations than occur at Burn of Sorrow but lower copper (Rothwell, 1980). However, at each site there are soils in which the solution heavy-metal concentrations are similar to those under the *Agrostis* species at the other site. The precise selection of species on these mine sites implies that the evolution of metal tolerance in the field may not be so rapid and straightforward as is sometimes suggested from glasshouse investigations of tolerance to single metals at low effective concentrations.

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