Plant and invertebrate assemblages on waste rock at Wangaloa coal mine, Otago, New Zealand

C. G. Rufaut[1*], S. Hammit[2], D. Craw[1], S. G. Clearwater[1]
[1]Department of Geology, University of Otago, P.O. Box 56, Dunedin, New Zealand
[2]Department of Geosciences, Princeton University, Princeton, New Jersey 08544, U.S.A
*Author for correspondence (E-mail: cathy.rufaut@stonebow.otago.ac.nz)

Published on-line: 20 November 2006

Abstract: Natural regeneration on waste rock was investigated at the old Wangaloa coal mine, south-east Otago. A 450-m long waste rock stack had been created 40–50 years ago, and has had little anthropogenic intervention since. The stack is made up of a gradient of three main waste rock types, defined as 'silt-rich', 'mixed', and 'quartz-rich', which reflect different proportions of loess siltstone and quartz gravel conglomerate. Plant species assemblages were quantified in four 5-m^2 quadrats in each waste rock type. Invertebrates were heat extracted from substrate cores (7 cm diameter; depth 5 cm) collected from quadrats over an eight-week period in spring 2003. Ordination analysis showed statistically distinct plant and invertebrate assemblages had arisen on each waste rock type. Revegetation patterns were dominated by native, woody individuals on all waste rock types, particularly manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*). Plant cover on 'silt-rich' waste rock was four-fold that on 'quartz-rich' waste rock. Total numbers of invertebrates were highest on 'quartz-rich' waste rock, but richness greatest on 'silt-rich' waste rock. Collembola dominated the fauna but their numbers were proportionally greatest in poorly vegetated areas. Further work is required to explain the absence of plants and invertebrates from local areas of waste rock.

Keywords: natural regeneration; coal mine; waste rock; siltstone; quartz pebbles; plants; invertebrates.

Introduction

In opencast coal mining, large amounts of waste rock are removed and stockpiled nearby. When mining ceases, site rehabilitation is necessary, and now mandatory in New Zealand (under the Resource Management Act 1991). Early stages of modern mine site rehabilitation typically focus on stabilising waste rock piles, followed by revegetation (Munshower 1994). Revegetation options include natural regeneration from nearby seed sources, planting nursery-grown stock, and translocating clumps of previously intact soil and vegetation. The latter two techniques have gained significant research attention on the South Island's West Coast, where coal and gold mine sites have been developed on or adjacent to conservation land (Davis and Langer 1997; Davis *et al.*, 1997; Ross *et al.*, 1995; Ross *et al.*, 2000; Simcock *et al.*, 2004). In comparison, little has been published on the composition and structure of vegetation that has naturally regenerated on mined lands in New Zealand, although it has been investigated for some time overseas (e.g. Bramble and Ashley, 1955; Roberts *et al.*, 1981; Johnson *et al.*, 1982; Russell and La Roi, 1986; Titlyanova and Mironycheva-Tokareva, 1990). Similarly, there is a scarcity of published information on invertebrate communities that occupy national mine sites.

This study presents distribution data for plant species and invertebrates found to naturally occur on three different types of waste rock at Wangaloa coal mine in south-east Otago. The waste rock stacks were created 40–50 years ago, and have been left to naturally revegetate in a surrounding landscape of regenerating kamahi (*Weimannia racemosa**) forest, *Pinus radiata* plantations, manuka/kanuka (*Leptospermum scoparium/Kunzea ericoides*) shrublands, and pasture. It was found that native woody species dominated revegetation patterns, and that invertebrates tracked plant cover development.

Methods

Study site

The study was conducted at Wangaloa coal mine (46° 17' S, 169° 54' E), *c.* 2 km east from the township of

* Nomenclature follows Allan (1961), Connor and Edgar (1987), Webb *et al.* (1988).

Kaitangata in south-east Otago. Waste rock stacks at the site consist of excavated rock from above the Barclay coal seam, and overlying colluvium (loess siltstone and quartz pebbles). The rock (late Cretaceous Taratu Formation) is dominated by a quartz pebble conglomerate with subordinate quartz-rich sandstone, siltstones, mudstones, and coal (Harrington, 1958). Individual quartz pebble size is up to 1–1.5 cm.

Mining operated at Wangaloa between 1945 and 1989. Aerial photographs taken in 1946 and 1962 show the waste rock examined in this study was created some time between these years. Many dumped truck loads of rock had coalesced into a single, continuous bench *c*. 450 m long, with steep northerly slopes around the angle of repose. These slopes have had little anthropogenic intervention since they were created. Until 2001, when the rehabilitation of Wangaloa coal mine was initiated, the entire bench had remained unmodified and left to revegetate naturally. Physical impacts from the recent rehabilitation programme have been extensive on the top of the bench yet minimal on the slopes. On the latter, one or two wilding pine trees were felled, and hydroseeding was attempted on some poorly vegetated sections, but was of limited success.

Three main types of waste rock can be defined along the length of the bench on a west-east gradient that represents reversed stratigraphy of the site (Craw *et al.*, 2006). 'Silt-rich' waste rock at the western end of the bench was deposited first, and contained abundant fine-grained siltstone from near the surface. 'Quartz-rich' waste rock at the eastern end of the bench was deposited last, and contained abundant quartz pebble conglomerate from deeper down the mine. 'Mixed' waste rock was a heterogenous mix of predominantly quartz pebble conglomerate but with minor sand, siltstone, and coal, located in the middle of the bench between 'silt-rich' and 'quartz-rich' waste rock.

Plant and invertebrate sampling

Sampling plots (measuring 10 × 50 m) were located in each of the three waste rock types described above. Individual plots were orientated to the north and positioned in line with each other from the top of the slope. Neighbouring plots were separated by a distance of 30–40 m. Each plot was further subdivided into four 5-m^2 replicate quadrats spaced *c*. 5 m apart. The slope of each quadrat was between 30–40º. Extensive erosion in the 'quartz-rich' waste rock had created steep (60–90º) rills, up to 3 m deep at their head walls, and adjacent ridges. In this waste rock type, quadrats were located only on the ridges because of rill instability and inaccessibility.

Plant species present in each quadrat were identified, and their origin (native or adventive) determined. The presence of mosses and lichens were noted but not identified to species level. Plant abundance (number of individuals) was recorded for woody plants only (< 30 cm height).

Invertebrates occupying each quadrat were sampled weekly using a randomly located stainless steel corer (7 cm diameter, depth 5 cm) during October and November 2003. An earlier pilot study had shown the majority of invertebrates collected from waste rock using this technique were found in the top 5 cm, rather than at greater depths (C. Rufaut, unpubl. data). Sampling points alternated each week between vegetated and bare waste rock in quadrats with incomplete plant cover. All samples were collected on the same day within a 2 hour time frame to reduce temporal variation among samples.

It was determined from the pilot study above that invertebrate numbers at the study sites were limited. Consequently, a technique of processing and counting live specimens was trialed, using Order-level identifications, as follows. Substrate cores were first carefully broken up by hand and the larger invertebrates (> 2 mm body length) removed and counted. The core material was then placed in individual funnels (22 cm diameter), on top of a mesh screen (2 mm mesh size), located 20 cm beneath a 60 W light bulb, for 48 hours to heat extract the smaller invertebrates. Invertebrates moving out of the core material collected on top of white, plastic discs (5 cm diameter) floating in water that ¾ filled plastic collection jars (6 cm diameter, 10 cm height). The discs acted as 'counting rafts' and were found to accumulate the majority of extracted invertebrates. The bottom of the collection jars, and the water, were also checked for individuals. Four samples were processed at a time, with the remaining samples stored intact in paper bags in cool, damp conditions.

Data analysis

Mean (±95% confidence intervals) values summarised the numerical distribution of plant species and invertebrate orders among quadrats on different waste rock types. Variations in the composition of plant and invertebrate assemblages were quantified by calculating average similarity values using the SIMPER function in the multivariate program PRIMER-5 (Clarke and Gorley, 2001). Comparisons of assemblage structure were made using NMDS ordination and one-way Analysis of Similarity (ANOSIM), with the Bray-Curtis dissimilarity distance measure, also in PRIMER-5. Similarity matrices were generated using both presence/absence and log $(x + 1)$ transformed abundance data for comparison. Invertebrate relative abundance data on vegetated and bare waste rock were compared using two sample *t*-tests in Minitab 13.

Table 1. Mean (± 95% C.I.) abundance for woody plant species growing naturally on different types of waste rock at Wangaloa coal mine. In brackets, frequency of occurrence in four replicate quadrats.

		Waste rock type					
Species		'Quartz-rich'		'Mixed'		'Silt rich'	
Woody plants							
Cassinia vauvilliersii[+]		0.3±0.5	(1)	5.5±1.3	(4)		
Coprosma spp.[+,a]		2.8±4.3	(2)	2.8±2.8	(3)	3.5±1.9	(4)
Erica lusitanica	spanish heath*	1.8±2.9	(2)	51.5±58.5	(4)[s]	8.0±4.1	(4)[s]
Gaultheria spp.[b]	snowberry[+]	0.5±0.5	(1)	7.0±6.3	(4)	0.5±0.6	(2)[s]
Griselinia littoralis	broadleaf[+]	0.5±1.0	(1)[s]	0.3±0.5	(1)[s]		
Hebe salicifolia	koromiko[+]					0.3±0.5±	(1)[s]
Leptospermum scoparium	manuka	3.0±3.2	(3)	82.3±26.0	(4)[s]	16.5±16.4	(3)[s]
Kunzea ericoides	kanuka	2.8±3.5	(4)	19.8±16.6	(4)[s]	3.5±4.4	(3)[s]
Muehlenbeckia australis	pohuehue[+]					0.3±0.5	(1)
Myrsine australis	red mapou	0.3±0.5	(1)				
Pinus radiata	radiata pine*	0.3±0.5	(1)				
Pittosporum eugenoides	kohuhu					0.3±0.5	(1)[s]
Pseudopanax colensoi	three finger[+]					0.8±0.5	(4)
Ulex europaeus	gorse*	0.3±0.5	(1)	1.8±1.5	(3)[s]	6.3±7.2	(4)
Weimannia racemosa	kamahi+			1.8±3.5	(1)[s]	5.0±2.2	(4)[s]
Herbaceous species							
Agrostis capillaris	browntop*				(4)		
Anthoxanthum odoratum	sweet vernal*				(1)		
Blechnum minus	hard fern		(2)		(1)		(2)
Polystichum vestichum	prickly shield fern						(1)
Histiopteris incisa	water fern		(1)				
Cortaderia richardii	toetoe		(1)		(3)		(1)
Phormium tenax	flax						(1)
Pteridium esculentum	bracken						(4)
Hypochoeris radicata	catsear*				(4)		(2)
Thelymitra sp.	sun orchid		(1)		(3)		
Mosses and lichens[+]		uncommon		common & dense		uncommon	

* adventive species; [+] species present in nearby old kamahi forest; [a] represented by 5 species (*C. foetidissima*, *C. propinqua, C. rigida, C. rubra* & *C.* sp.), [b] represented by 2 species (*G. antipoda* and *G.* sp); [s] present as seedlings.

Results

'Quartz-rich' waste rock

Plant abundance (Table 1) and cover on 'quartz-rich' waste rock was low. The vegetation consisted mainly of highly spaced, woody individuals, separated by up to 2 m of bare waste rock. Seven native woody species were present, of which manuka and kanuka were most common (Table 1). Herbaceous species were a minor component (Table 1), and their degree of ground cover was minimal (< 1%). Adventive species, moss and lichen were also uncommon (Table 1). Of the total plant species recorded, 64% occurred in only one of four quadrats. A low level of spatial similarity in plant assemblage composition existed (Table 2; Fig. 1a).

Invertebrates on 'quartz-rich' waste rock were dominated numerically by Collembola. They accounted for 96% of individuals collected (Table 3). Members of the Onychiuridae were particularly abundant, and Sminthuridae were also more common than on the other waste rock types (Table 3). Spatial similarity in assemblage composition reduced when the numerical influence of Collembola was omitted (Fig. 1b). High average similarity values in Table 2 also lowered to 33% when Collembola were omitted from the analysis. Numbers of the seven other orders present were generally low (Table 3). Acari were an exception, although 80% of individuals were collected from one quadrat. Numbers of invertebrates on vegetated 'quartz-rich' waste rock were significantly higher than on respective bare waste rock (Fig. 2). Twenty-two percent of 'quartz-rich' samples contained no invertebrates, all collected from bare rock.

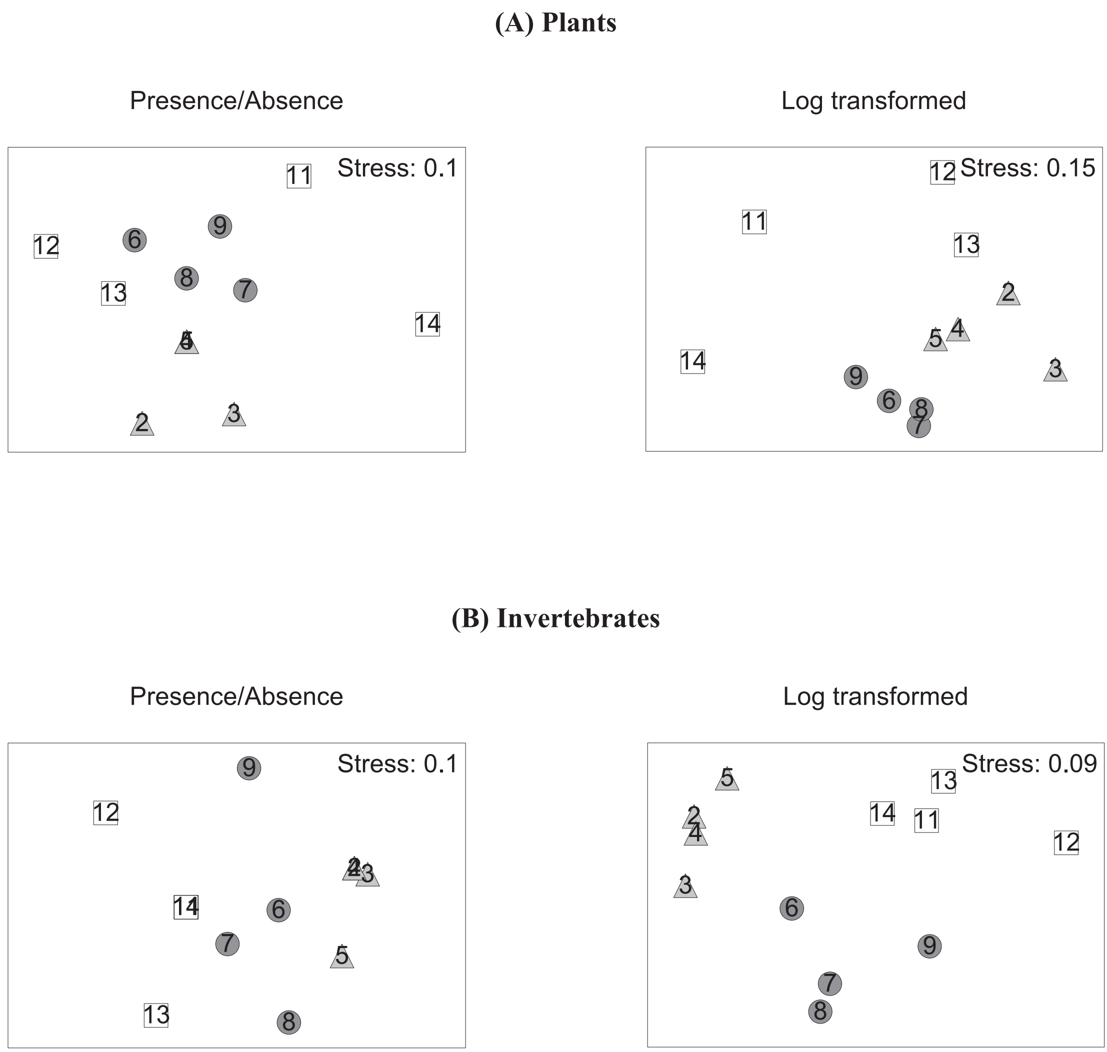

Figure 1: Non-metric multidimensional scaling ordination plots for (A) plant and (B) invertebrate assemblages, using presence/absence and log (χ + 1) transformed abundance data, on different types of waste rock at Wangaloa coal mine. *Plot symbols*: **'quartz-rich' waste rock** = open squares (Q), **'mixed' waste rock** = grey circles (M), and **'silt-rich' waste rock** = grey triangles (S). Quadrat field number displayed within symbols. One-way ANOSIM pairwise comparisons for plants quantify clear differences between only M & S (R = 0.7, *P* = 0.03) in each plot, with R < 0.4, *P* > 0.06 for remaining pairs. For invertebrates, large differences exist between each pair combination in the log plot and between Q & S in the presence/absence plot (R > 0.75, *P* = 0.03), with R = 0.5-0.6, *P* = 0.03 for M & Q and S & M in the latter plot.

Table 2. Average similarity values quantifying variation in woody plant and invertebrate assemblages within different types of waste rock at Wangaloa coal mine. Values are percentage similarity (a similarity value of 100% would infer all replicates within the same waste rock type contained identical species assemblages) for presence/absence data (P/A) and log (χ + 1) transformed abundance data (Log).

Taxa	Similarity within waste rock type (%)		
	'Quartz-rich'	'Mixed'	'Silt-rich'
Woody plants			
P/A	48.5	81.8	85.6
Log	33.1	73.5	69.6
Invertebrates			
P/A	77.5	70.8	88.2
Log	78.9	73.8	81.5

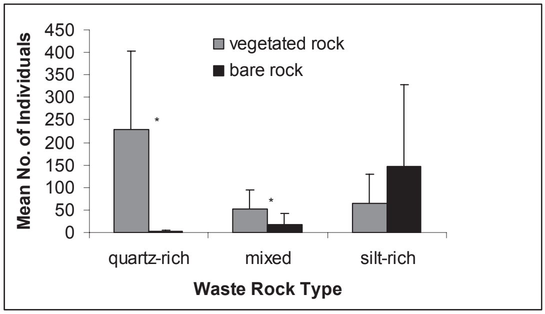

Figure 2: Mean (95% C. I) invertebrate relative abundance on vegetated and bare rock within different waste rock types at Wangaloa coal mine. N = 16 cores for each group within 'quartz-rich' and 'mixed', * indicate t-test significant differences ($P < 0.01$). T-test not performed on 'silt-rich' data because of uneven sample distribution, n = 12 vegetated and n = 4 bare rock cores respectively.

'Mixed' waste rock

Plant cover on 'mixed' waste rock was highly patchy. The vegetation consisted of multi-species patches of dense, small-stemmed woody individuals (*c*. 1 m high) separated by variably sized areas of bare waste rock. Seven native woody species were present, of which manuka was particularly abundant (Table 1). The adventive Spanish heath also occurred in high numbers (Table 1). Adventive grass species and catsear occurred frequently (Table 1), but their ground cover was low (< 1% in each quadrat). Moss, lichen and seedlings were common components of woody plant patches (Table 1). Moss and lichen also grew in isolation from vascular plant species. Spatial similarity in plant assemblage composition was high (Table 2; Fig. 1a).

Collembola accounted for 79% of invertebrate individuals collected from 'mixed' waste rock. Members of the Onychiuridae were abundant (Table 3). Spatial similarity in assemblage composition was high (Fig. 1b), but average similarity values in Table 2 were reduced to 52% when Collembola were omitted from the analysis. Numbers and frequency of occurrence for

Table 3: Mean (± 95% C.I.) number of individuals for invertebrate Orders on different types of waste rock at Wangaloa coal mine. The number of quadrats in which each order was found on each of the waste rock types is given in brackets.

Overall Community	Waste rock type		
	'Quartz-rich'	'Mixed'	'Silt-rich'
Collembola +	895 ± 419.7 (4)	215.5 ± 115.5 (4)	358.3 ± 223.2 (4)
Coleoptera +	1.3 ± 1.3 (3)	0.8 ± 1.5 (1)	7.3 ± 5.3 (4)
Diptera +	0.3 ± 0.5 (1)	0.3 ± 0.5 (1)	0.3 ± 0.5 (1)
Hemiptera		11.3 ± 13.7 (3)	3.0 ± 1.6 (4)
Heteroptera +		1.5 ± 1.3 (3)	8.3 ± 5.9 (4)
Hymenoptera +	1.8 ± 1.3 (3)	9.3 ± 13.3(3)	
Lepidoptera +	2.0 ± 1.4 (3)		2.3 ± 2.6 (3)
Thysanoptera +	0.5 ± 0.6 (2)		
Annelid +			1.3 ± 1.3 (3)
Chilopoda+			0.3 ± 0.5 (1)
Diplopoda +		0.8 ± 1.5 (1)	0.5 ± 1.0 (1)
Amphipod +			2.3 ± 2.1 (3)
Araneae +	2.8 ± 2.5 (3)	2.0 ± 1.6 (3)	9.0 ± 7.9 (4)
Acari +	24.0 ± 36.2 (3)	32.3 ± 13.7 (4)	116.3 ± 54.6 (4)
Opiliones +		0.5 ± 0.6 (2)	2.8 ± 1.5 (4)

+ present in nearby old kamahi forest

the nine other orders present varied (Table 3). Acari, Hemiptera and Hymenoptera (Formicidae, ants) were the most abundant non-Collembola groups (Table 3). Acari were evenly distributed among quadrats, but for Hemiptera and Formicidae, 67% and 78% respectively of individuals were collected from one quadrat. Numbers of invertebrates on vegetated 'mixed' waste rock were significantly higher than corresponding bare waste rock (Fig. 2). Three percent of mixed samples contained no invertebrates, all from bare rock.

'Silt-rich' waste rock

Plant cover on 'silt-rich' waste rock was high. Area coverage was 100% for three of four quadrats. A small area of bare waste rock occurred in the fourth quadrat (85% plant cover). The vegetation consisted mainly of multilayered shrubs up to 4–5 m high. Nine native woody species were present, of which manuka was most common (Table 1). Kamahi, small-leaved *Coprosma* spp., gorse and Spanish heath also occurred frequently (Table 1). Small ferns, seedlings and locally dense areas of bracken formed much of the ground cover (Table 1). Leaf litter on top of waste rock was spread throughout. Spatial similarity in plant assemblage composition was relatively high (Table 2; Fig. 1a).

Collembola accounted for 70% of invertebrate individuals from 'silt-rich' waste rock. Forty-eight percent of Collembola individuals were collected from the one quadrat with incomplete plant cover. Members of the Onychiuridae were most abundant, and the Entomobryiidae were also more common than on the other waste rock types (Table 3). Spatial similarity in assemblage composition was high (Fig. 1b). Average similarity values in Table 2 were reduced to 73% when Collembola were omitted from the analysis. The numbers and frequency of occurrence for 12 other orders are shown in Table 3. Acari, Araneae, Heteroptera and Coleoptera were the most abundant non-Collembola groups. Earthworms, Amphipods and Chilopods were only collected from this type of waste rock. Numbers of invertebrates on vegetated 'silt-rich' waste rock were lower than respective bare waste rock, but uneven sample sizes prevented statistical analysis of differences (Fig. 2). None of the 'silt-rich' samples contained zero invertebrates.

Discussion

Natural revegetation

This study has identified a number of native plant species that have naturally established on coarse grained, steeply sloping (30–40º) waste rock without any anthropogenic intervention. Inventories of natural plants are useful because they highlight tolerant species that may be selected for engineered rehabilitation projects (Munshower, 1994). In addition, studies of natural plants on mine waste can contribute towards understanding key ecological processes in derelict habitats, such as colonisation and regeneration (Bradshaw, 1983; Prach, 1994). At Wangaloa, the surface layers of waste rock stacks would not have contained any seeds or plant fragments, since they consist of excavated rock. Natural soil cover at the site is thin and would have been buried early in the mining process. Therefore, the plant species distribution patterns documented here represent rates at which natural colonisation and establishment are occurring at the site. However, mean differences in species abundance show that these processes occur at locally variable rates, and with variable degree of success, on different types of underlying waste rock.

'Silt-rich' waste rock, containing abundant siltstone, was found to be more conducive to vegetation development than either the 'mixed' or 'quartz-rich' waste rock. Plant species assemblages on 'silt-rich' rock formed a dense, diverse, multilayered cover, containing a number of natural forest species (Table 1). On 'mixed' waste rock, plant cover development was patchy, and consisted of simple assemblages dominated by early colonising, woody species. On 'quartz-rich' waste rock, plant abundance and cover was low. On the latter, *c*. 80% of the substrate remained bare after at least 40 years of immigration opportunities from surrounding seed sources. It is beyond the scope of this paper to identify reasons for hindered revegetation in the study plots, but in a companion paper we suggest surface quartz pebble abundance is a key geological control on seed retention and seedling establishment (Craw *et al*., 2006).

A lack of quadrat replication prevented statistical analysis of mean differences in revegetation parameters. Experimental design was compromised by the difficult topography in 'quartz-rich' waste rock. Nevertheless, multivariate ordination analysis showed distinct plant species assemblages had arisen on each type of waste rock (Table 2; Fig. 1a). Of native woody species, 38% occurred only on 'silt-rich' waste rock, and a number of these were shared with the natural remnant kamahi forest stand nearby (Table 1). Spatial heterogeneity in plant assemblages was particularly high on 'quartz-rich' waste rock, owing to a single occurrence in over half of the species. In contrast, more uniform assemblages existed on the 'mixed' and 'silt-rich' rock, determined from an increase in frequency of species occurrence. Plant abundance data defined more statistically distinct assemblages than presence/absence data because a number of species were shared among waste rock types. Manuka and kanuka were common components of all three floras.

Recently, some authors have recommended natural revegetation as a scientifically valid and preferable strategy for site rehabilitation in some situations (e.g.

Prach and Pyšek, 2001; Hodačová and Prach 2003; Pensa *et al.*, 2004). One criticism of the latter is the threat of weed invasion, and subsequent potential to slow down native species recovery (Holl, 2002). Indeed, other old mine sites in New Zealand have been noted to slowly revert to a scrubby weed cover (Ross *et al.*, 1995; Gregg *et al.*, 1998). However, this study has shown that unmodified waste rock stacks do not necessarily create weed problems for a mine site. On the contrary, native species were found to dominate the flora arising from natural revegetation. Gorse and adventive grasses, common weeds on disturbed land in New Zealand, occurred in low abundance despite being prominent on unmined slopes tens of meters away. It is possible that the dry nature of the waste rock slopes played a role in restricting weed species establishment, and favouring local native species instead. More studies are required to understand interactions between environmental parameters and waste rock stack construction on weed invasion processes at New Zealand mine sites.

Invertebrate recovery

The collection of live, order-level invertebrate data over a short period (2 months) was trialed, and found to identify major differences in invertebrate assemblages on the different types of waste rock. Like the plants, invertebrate distribution patterns represent rates of natural colonisation because the original biologically active layers were buried beneath 10–12 m of excavated rock. Given that the majority of invertebrate groups sampled feed either on plants or in the decomposer cycle, their populations are likely to be finely structured around the condition of the flora. Therefore, the invertebrate data patterns presented here are most likely to be linked to plant assemblage spatial patterns, rather than the underlying waste rock type *per se* (see also Pižl, 2001; Wanner and Dunger, 2002; Davis *et al.*, 2003). This was supported in Figure 2 where invertebrates from vegetated and bare substrate within the same waste rock type were compared. Numbers in bare waste rock increased along the revegetation gradient, from 'quartz-rich' to 'silt-rich' waste rock, which suggests distance to the nearest plant is an important factor influencing invertebrate colonisation of unvegetated substrate.

Numbers of individuals varied widely within and between replicate quadrats, and the sampling regime did not adequately measure their degree of spatial variation. Nevertheless, order-level invertebrate assemblages were found to be statistically more distinct than the species-level plant assemblages. Like the plants, invertebrate relative abundance data defined more distinct assemblages than presence/absence data (Table 2; Fig. 1b). Also like the plants, a number of forest-dwelling groups were recorded only from the 'silt-rich' waste rock. However, without species-level data we cannot comment on the status of invertebrates in the study. Assemblage complexity increased from 'quartz-rich' to 'mixed' to 'silt-rich' waste rock, but it is unknown how this is reflected in terms of native/adventive ratios, or functional group changes because some orders were multi-trophic (e.g. Collembola, Coleoptera). Without such information, it is not possible to fully consider natural recovery on waste rock at the ecosystem level.

Invertebrate abundance did not follow the same pattern as richness because the numerically dominant group, Collembola, was particularly abundant on 'quartz-rich' substrate (Table 2). One reason for this may have been the hydroseed applied to previously bare slopes of 'quartz-rich' waste rock six months prior to sampling. Our data recorded high Collembola numbers (average 229.5 individuals per core sample) in struck hydroseed compared to very low numbers (2.8 individuals respectively) in adjacent bare waste rock. This finding indicates firstly, that Collembola colonisation and rise in density can be quite rapid on waste rock, and secondly, that rehabilitation strategies have an impact on invertebrate communities at mine sites.

Because of their relatively high numbers, Collembola strongly influenced invertebrate abundance patterns at the assemblage-level. For example, they determined the contrasting pattern of higher invertebrate numbers on bare rather than vegetated waste rock in the 'silt-rich' plot (Fig. 2). The effect of Collembola on statistical analyses reduced from 'quartz-rich to 'mixed' to 'silt-rich' waste rock because numbers of other invertebrates increased (Table 2). Proportionally high numbers of Collembola have been attributed to rapidly expanding adventive populations (Hutson, 1980; Geenslade and Majer, 1993) and/or lack of inter-species relationships in simple assemblages (Hutson, 1980; Yeates, 1991). In New Zealand, information about the status of Collembola at disturbed sites is scarce (Keesing and Wratten, 1998), and to our knowledge their populations have not been investigated at a mine site setting before. In fact overall, there is a general paucity of published information on invertebrate communities at national mine sites, which makes it difficult to put the current study into perspective.

Conclusions

The patterns of revegetation we have described provide a temporal scale for natural restoration attempts on different types of waste rock, and indicate that with time any potential environmental toxicity may be ameliorated to allow natural colonisation by surrounding native plant species. Native plant communities are an important goal for restoration projects, and this study has shown that they can develop on mine substrates without any anthropogenic intervention. Native plant cover development was greatest on waste rock containing the highest proportion of fine to coarse material. 'Silt-rich' waste rock had reached near 100% cover in *c*. 50 years, which could be within the time period of a mine site life. Mine site owners should consider making use of the 'free' process of natural revegetation in rehabilitation strategies. The current study has highlighted that natural revegetation of mine waste can be extremely patchy at small spatial scales, which is not an ideal outcome for site restoration. Further work is required to define variables that influence the success of natural plant establishment on different types of waste rock.

The invertebrate component of this study highlighted plant presence as a key factor structuring the substrate/litter dwelling component of the community examined. The effects of plant spatial patterns appeared to over-ride any underlying differences in waste rock composition. Invertebrate numbers were very low in bare waste rock separated from plants over a distance of >1 m. Groups of multi-species plants contained more complex assemblages than either single species or isolated plants ('quartz-rich' waste rock). At another level, tall multi-layered, native plant assemblages ('silt-rich' waste rock) contained more complex invertebrate assemblages than low statured, uni-layered plant assemblages ('mixed' waste rock). The introduction of fast-growing, adventive plant species could quickly increase invertebrate numbers on predominantly bare waste rock, but further work is required to determine the status of such an assemblage. Consideration of links between plants and invertebrates should be given when planning mine site restoration to aid the return of functional processes on mine waste, which are paramount for re-establishing sustainable ecosystems.

Acknowledgements

We are grateful for the support of Solid Energy N.Z. Ltd and Tim Preston. Many thanks also to Simon Clearwater, Andrea Todd, Hamish Barrons, Jenny Rufaut, Michelle Baker, and Denise Fastier for assistance in the field and lab.

References

Allan, H.H. 1961. *Flora of New Zealand, Volume 1.* Government Printer, Wellington, N.Z.

Bradshaw, A.D. 1983. The reconstruction of ecosystems. *Journal of Applied Ecology 20:* 1-17.

Bramble, W.C.; Ashley, R.H. 1955. Natural revegetation of spoil banks in Central Pennslyvania. *Ecology 36:* 417-423.

Clarke, K.R.; Gorley, R.N. 2001. *PRIMER v5: User Manual/Tutorial.* PRIMER-E Ltd, Plymouth Marine Laboratory, Plymouth, United Kingdom.

Connor, H.E.; Edgar, E. 1987. Name changes in the indigenous New Zealand flora 1960-1986 and Nomina Nova IV, 1983-1986. *New Zealand Journal of Botany 25:* 115-170.

Craw, D.; Rufaut, C.G.; Hammit, S.; Clearwater, S.G.; Smith, C.M. 2006. Geological controls on natural ecosystem recovery on mine waste in southern New Zealand. *Environmental Geology* (in press).

Davis, M.R.; Langer, E.R. 1997. Part 2 & 3: Giles Creek – Fertiliser response of *Coprosma robusta* and *Nothofagus fusca* seedlings. *Science for Conservation 54.* Department of Conservation, Wellington, New Zealand.

Davis, M.R.; Langer, E.R.; Ross, C.W. 1997. Rehabilitation of native forest species after mining. *New Zealand Journal of Forestry Science 27(1):* 51-68.

Davis, A.L.V.; van Aarde, R.J.; Scholtz, C.H.; Delport, J.H. 2003. Convergence between dung beetle assemblages of a post-mining vegetational chronosequence and unmined dune forest. *Restoration Ecology 11:* 29-42.

Greenslade, P.; Majer, J.D. 1993. Recolonization by Collembola of rehabilitated bauxite mines in Western Australia. *Australian Journal of Ecology 18:* 385-394.

Gregg, P.E.H.; Stewart, R.B.; Ross, C.W. 1998. Land reclamation practices and research in New Zealand. *In:* Fox, Moore and McIntosh (Editors), *Land Reclamation: Achieving Sustainable Benefits,* pp 365-372. Balkema, Rotterdam.

Harrington, H.H. 1958. *Geology of the Kaitangata Coalfield*. New Zealand Department of Scientific and Industrial Research, Wellington. Geological Survey Bulletin n.s. 59. 131 p.

Hodačová, D.; Prach, K. 2003. Spoil heaps from brown coal mining: Technical reclamation versus spontaneous revegetation. *Restoration Ecology 11:* 385-391.

Holl, K.D. 2002. Long-term vegetation recovery on reclaimed coal surface mines in the eastern USA. *Journal of Applied Ecology 39:* 960-970.

Hutson, B.R. 1980. Colonization of industrial reclamation sites by Acari, Collembola and other invertebrates. *Journal of Applied Ecology 17:* 225-275.

Johnson, F.L; Gibson, D.J.; Risser, P.G. 1982. Revegetation of unreclaimed coal strip-mines in Oklahoma. *Journal of Applied Ecology 19:* 453-463.

Keesing, V; Wratten, S.D. 1998. Indigenous invertebrate components in ecological restoration in agricultural landscapes. *New Zealand Journal of Ecology 22:* 99-104.

Munshower, F. F. 1994. *Disturbed Land Revegetation.*

Lewis Publishers, CRC Press, Inc., Florida.

Pensa, M.; Sellin, A.; Luud, A.; Valgma, I. 2004. An analysis of vegetation restoration on opencast soil shale mines in Estonia. *Restoration Ecology 12:* 200-206.

Pižl, V. 2001. Earthworm succession in afforested colliery spoil heaps in the Sokolov Region, Czech Republic. *Restoration Ecology 9:* 359-364.

Prach, K. 1994. Succession of woody species in derelict sites in Central Europe. *Ecological Engineering 3:* 49-56.

Prach, K.; Pyšek, P. 2001. Using spontaneous succession for restoration of human-disturbed habitats: Experience from Central Europe. *Ecological Engineering 17:* 55-62.

Roberts, R.D.; Marrs, R.H.; Skeefington, R.A.; Bradshaw, A.D. 1981. Ecosystem development on naturally colonized china clay wastes. *Journal of Ecology 69:* 153-161.

Ross, C.W.; Mew, G.; Jackson, R.J.; Payne, J.J. 1995. *Land rehabilitation to indigenous forest species.* Science for Conservation 17. Department of Conservation, Wellington, New Zealand.

Ross, C.; Simcock, R.; Williams, P.; Toft, R.; Flynn, S.; Birchfield, R.; Comesky, P. 2000. Salvage and direct transfer for accelerating restoration of native ecosystems on mine sites in New Zealand. *New Zealand Minerals & Mining Conference Proceedings, 29-31 October, 2000.*

Editorial Board member: David Wardle

Russell, W.B.; La Roi, G.H. 1986. Natural vegetation and ecology of abandoned coal-mined land, Rocky Mountain Foothills, Alberta, Canada. *Canadian Journal of Botany 64:* 1286-1298.

Simcock, R.; Ross, C.; Pizey, M. 2004. Rehabilitation of alluvial gold and open-cast coal mines from 1904-2004. *Proceedings of the 37th Annual Conference of the Australian Institute of Mining and Metallurgy,* Nelson, 29 August – 1 September 2004: 77-82.

Titlynova, A.A.; Mironycheva-Tokareva, N.P. 1990. Vegetation succession and biological turnover on coal-mining spoils. *Journal of Vegetation Science 1:* 643-652.

Wanner, M.; W. Dunger. 2002. Primary immigration and succession of soil organisms on reclaimed opencast coal mining areas in eastern Germany. *European Journal of Soil Biology 38:* 137-143.

Webb, C.J.; Sykes, W.R.; Garnock-Jones, P.J. 1988. *Flora of New Zealand. Volume 4.* Botany Division, Department of Scientific and Industrial Research, Christchurch, New Zealand.

Yeates, G.W. 1991. Impact of historical changes in land use on the soil fauna. *New Zealand Journal of Ecology 15:* 99-106.