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Indigenous Plant Species Establishment during Rehabilitation of an Opencast Coal Mine, South-East Otago, New Zealand

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Abstract

Establishment of nursery-raised seedlings was investigated at an opencast coal mine site near Kaitangata, south-east Otago, New Zealand. The mine was developed in quartz conglomerate interlayered with siltstones and multiple coal seams. The survival and growth of seven indigenous species were examined in two substrate types, minimally amended mine waste and loess (for comparison). Three different categories of waste were defined: quartz-rich, silt-rich, and coal-rich waste rock. Two different categories of loess were defined based on different levels of pre-planting earthworks but each with no natural soil layer.

Survival of seedlings three years after planting was low (35-55%) on all substrates, but seedling deaths were particularly acute on coal-rich waste rock. Plant height growth was generally minimal on waste rock. Height growth after three years on loess was twice that on any category of waste rock. Broad nutrient and trace element profiles were generated for the different substrate categories but no specific factor could be related to better growth on loess. Poor survival on waste rock is discussed in terms of substrate acidity and potential boron toxicity in the coal. Substrate disturbance history had little influence on seedling survival or growth in the loess but potentially so on waste rock.

Neither substrate type precluded indigenous species establishment *per se*, as was evidenced in widespread regeneration from natural seed dispersal. Research into the physical properties of the different substrates is required to isolate primary factors limiting nursery-raised seedling performance, with a focus on soil moisture stress.

Keywords: mine rehabilitation; coal; indigenous plant species; waste rock; loess; substrate chemistry; revegetation

Introduction

Re-establishing vegetation is a vital component of the physical and functional restoration of degraded landscapes (Wong & Bradshaw, 2002). At mine sites, the presence of plants can also control short and long-term environmental problems generated from the mining process, largely by reducing the interaction of water and oxygen with the underlying substrate (Munshower, 1994). Opencast mining is a common technique for ore extraction in New Zealand and generates large piles of waste rock. Historically, many mine sites were abandoned after mining ceased, and the disturbed land ‘left to nature’ to recover. Natural regeneration at such sites has been noted to be generally slow and dominated by weed species, particularly gorse (Gregg et al., 1998). Under the Resource Management Act 1991, rehabilitation is a

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mandatory part of a mining licence in New Zealand. Consequently, mining companies are investing in determining successful techniques for returning plant communities to the disturbed mined lands, and the use of indigenous forest species has been an increasing trend in this process (Ross et al., 2000).

One of the greatest problems encountered during mine site revegetation is that the main growing medium (usually crushed rock) has not supported plant life previously, and tends to inhibit soil-forming processes (Wong, 2003). At modern mine sites, original topsoil is stored for re-use on mine waste but for old sites or sites where the natural soil cover is thin, this option is not available. Consequently, the use of amendments aimed at ameliorating waste rock limitations for plant growth have been widely investigated in the rehabilitation literature (e.g. Holmes, 2001; Mercuri et al., 2005). An alternative, more economical and, arguably, more sustainable approach is to encourage establishment of vegetation directly on to mine wastes with minimal amendment (Prach & Pyšek, 2001). In New Zealand, it has recently been shown to be possible for indigenous forest species to grow well on unamended mine waste but Rufaut et al. (2006) and Craw et al. (2007a) studied naturally-established species in naturally ameliorated situations, rather than species planted during technical rehabilitation. For the latter, Gregg et al. (2000) determined that indigenous species ((kanuka, *Kunzea ericoides* (A.Rich.) Joy Thomps., cabbage tree, *Cordyline australis* (G.Forst.) Endl., flax, *Phormium tenax* J.R.Forst. & G.Forst., kohuhu (*Pittosporum tenuifolium* Sol. exGaertn.)) could be planted directly into tailings if required at the Waihi gold mine in the north-east of the North Island. Yet on the West Coast of the South Island, nursery-raised forest species planted directly into glacial gravel waste rock showed reasonable survival but poor vigour in one trial (Davis et al., 1997) and poor survival and slow growth in another (Langer et al., 1999).

By comparison, there is a lack of information on revegetation success using indigenous species at opencast mines in drier parts of the South Island, and rehabilitation methods developed for mesic sites may not be appropriate for more arid sites. While there has been some research into coal mine rehabilitation in Southland, the focus has been on re-establishing pasture (e.g. Widdowson & McQueen, 1990), rather than woody seedlings. Additionally, site-specific research is required into land rehabilitation because of the unique combination of environmental variables that define different mine sites around New Zealand (Gregg et al., 1998). In the present paper, we compare the survival, growth, and nutrition of nursery-raised indigenous forest species planted in a unique setting, a coal mine site on the south-eastern coast of Otago. The mine site has been undergoing final rehabilitation since 2001 by Solid Energy NZ Ltd, and has involved the planting of over 100,000 seedlings into a range of minimally amended substrates. The nutrient and trace element content of the two main substrate types, waste rock and loess, at the mine site is described and discussed in relation to the early performance of planted stock. We specifically use the term ‘substrate’ in this paper to refer to the planting medium because there is no natural soil left on any of the areas undergoing rehabilitation at the mine site.

Methods

Study Site Description

The Wangaloa opencast coal mine (252 ha) was developed near Kaitangata in South Otago, New Zealand ca. 65 km south-west of Dunedin. The site occurs 2.5 km from the coast, and is surrounded by rolling hills with locally steep relief (ca. 120 m). The area has a cool temperate maritime climate with a mean annual temperature of around 12 °C and 700-1000 mm of rainfall per year. The site is affected by frost during winter months and locally dry conditions on north-facing slopes during summer. The landscape surrounding the mine site is dominated by agriculture and plantation forestry, with small areas of indigenous forest at various stages of natural regeneration. The site is confined to a single stream catchment, with several smaller ancillary streams entering upstream. All water from the site discharges to the east through a wetland that drains into a small lake on an adjacent property.

Coal mining operated at Wangaloa for 45 years, between 1945 and 1989. The coal-bearing strata are part of the Late Cretaceous Taratu Formation, which extends from south to north Otago. The Taratu Formation is >500 m thick around Wangaloa, and includes quartz conglomerate, interlayered siltstones, and multiple coal seams. Tertiary marine sediments that overlay some parts of the Taratu Formation in South Otago have been eroded from the Wangaloa mine area. The hills around the mine area have a veneer of Quaternary loess, up to 4 m thick, which consists of immature silty material derived from the schist and greywacke basement. Loess still exists in the mine site at locations that have not been disturbed by mining activities, mainly on the slopes south of the coal seam (Figure 1). Excavation of coal at Wangaloa involved stripping off the topsoil, loess, and underlying Taratu Formation, which was dumped as waste rock at various locations around the mine site (Figure 1). The waste rock stacks consist predominantly of a poorly consolidated mixture of quartz pebbles, quartz sand, coal, and siltstone, yet there are fine-scale horizontal and vertical variations in the proportions of these components. In particular, the surface layers of the waste rock stacks are highly variable yet contain none of the original topsoil or loess, which are instead buried 10 m or so below (Craw et al., 2007b).

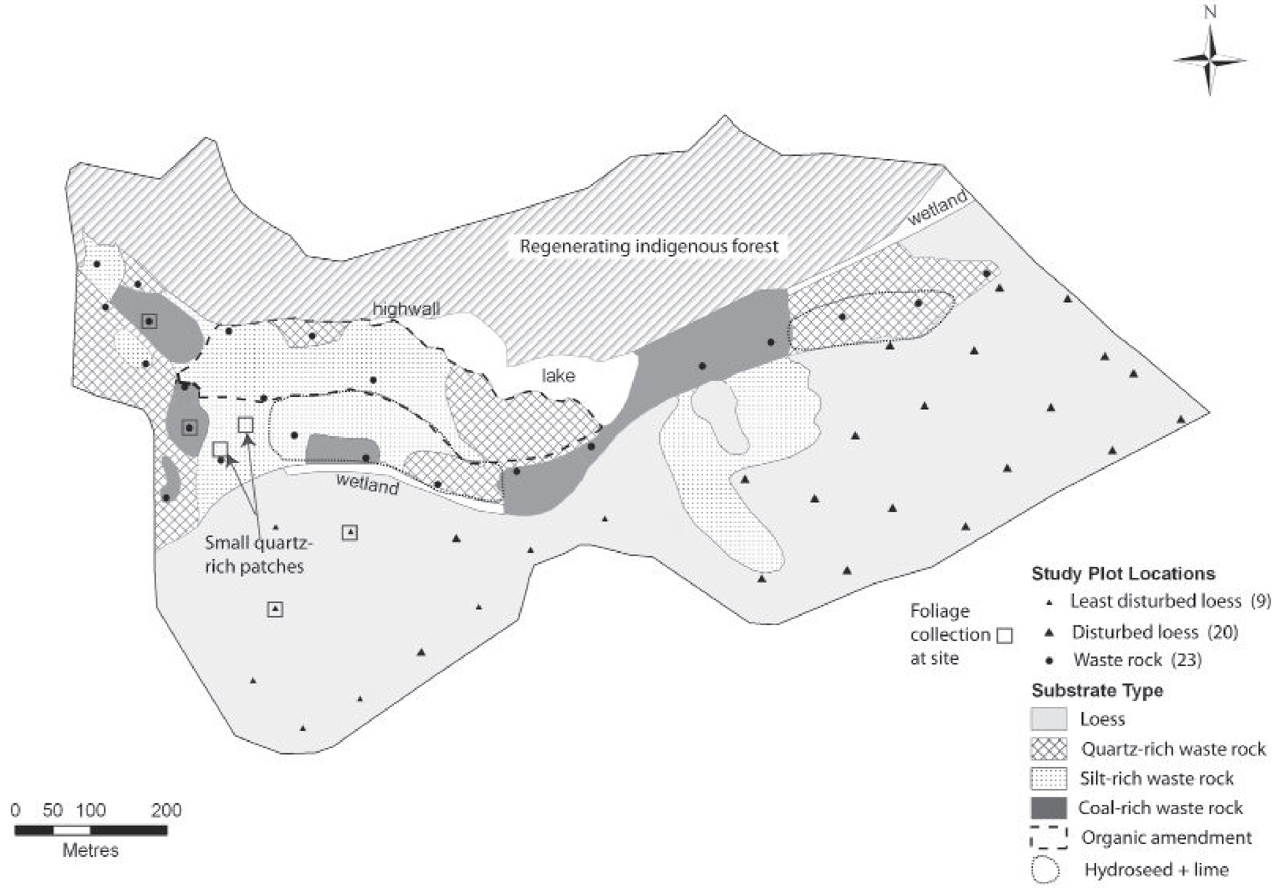

FIGURE 1: Map of the Wangaloa Coal Mine, showing the locations of the different substrate categories, studied planting plots, and foliage collection sites. Refer Table 1 for substrate category descriptions.

The Rehabilitation Project

Initial rehabilitation of the Wangaloa coal mine after mining ceased was minimal. A small area was planted in *Pinus radiata* D.Don (radiata pine) but the trees showed poor form and poor growth. In October 2001 a final rehabilitation project for the site was initiated, and is ongoing. With input from the local community, the objective of the project is to provide a public recreation area, while retaining historic mining features with some open areas. To achieve this outcome, the project also aims to enhance the indigenous ecological aspects and aesthetic values of the site via nursery-raised plantings, and to improve water quality (C. Evans & C. Glasson, pers. comm. 2002). Species selected for the planting project were chosen to reflect the natural vegetation of the local area, as well as exhibiting some tolerance to low pH and substrate infertility (C. Evans & C. Glasson, pers. comm. 2002). Seedlings were grown from seeds sourced in southern South Island but not from the Wangaloa mine site. Before planting, some waste rock piles had to be re-graded and terraced to achieve stability and reduce surface water erosion. The use of amendments was minimal. Some of the waste rock was hydroseeded with an exotic mix of grasses and legumes supplemented by a low level of lime (Figure 1). An imported organic mix of soil-cow manure-rotted sawdust was spread approximately 150 mm thick over the surface of part of the site. The organic amendment area is shown in Figure 1. Additional physical modifications were undertaken before planting commenced which involved the clearance of all adventive vegetation, mainly gorse and radiata pine trees. The latter were buried on site in large excavation pits located predominantly on the loess slopes at the eastern end of the mine site. Gorse biomass was retained *in situ* and bulldozed into windrows to provide organic matter and some wind protection to planted seedlings. Root-raking to a depth of 30 cm was undertaken in areas where the gorse cover had been dense, mainly on the loess slopes and old waste rock piles. The root-raking process caused disturbance and removal of the upper layers of substrate, but these were not quantified.

[1] *Covering a one-year period*

Planting at the mine site began in autumn 2003 and continues to the present day. Dead seedlings are replaced on an annual basis as part of a maintenance programme. This study includes only those seedlings planted during the original phase of planting at the site, which was completed at the end of 2003. Seedlings were planted with individual peat-rich root blocks. They were spaced approximately 1.5 m apart, between gorse windrows. Management strategies protecting planted stock have involved building a fence around the perimeter of the site to exclude browsing and grazing mammals. Rabbits, hares, and possums have also been regularly controlled using both ground-based and aerial bait operations. In general, this pest control strategy appeared successful, with little visual sign of damage to seedlings during the study period. At the time of planting, each seedling was supplied with Scott's slow-release[1] Agroblen fertiliser (20 g in sachet form) that contained salts with elemental equivalents of nitrogen, phosphorus, potassium and magnesium in the ratio 15% N : 3.9% P : 7.5% K : 1.8% Mg respectively. Seedlings planted in areas cleared from gorse received a wool mulch mat (350 mm diameter) around their base, to assist with suppressing weed growth. Weed control (using herbicides and scrub-cutting) has also been used on a regular basis to control gorse and weed re-growth in a 2 m^2 area around most of the planted seedlings.

Study Design

This study was conducted using a research-by-management approach with the focus on species-substrate interactions. Although a variety of techniques were used to prepare the site for planting (see above), we did not measure the effects of these *per se* on planted seedlings. More specifically, we documented the performance of kohuhu (*Pittosporum tenuifolium*), lemonwood (*Pittosporum eugenioides* A. Cunn.), broadleaf (*Griselinia littoralis* Raoul Choix 1846), wineberry (*Aristotelia serrata* J.R. et G.Forst), koromiko (*Hebe salicifolia* (Forst.f.), manuka (*Leptospermum scoparium* J.R. et G.Forst), and toetoe (*Cortaderia richardii* (Endl.) Zotov) in the first three years after planting occurred in June 2003. Seedling survival and growth were assessed initially in 39 study plots located across the site at random at a scale of 1 plot : 100 m. Six months later in December 2003, after a delay in the planting process, an additional 15 plots were established on waste rock to increase the number of plots occurring on this type of substrate compared to the loess. The locations of the plots are shown in Figure 1. In total, 23 plots occurred on waste rock and 29 plots on loess. The centre of each study plot was labelled and permanently marked using steel warratahs, the location of which was recorded using a Trimble GeoXT

TABLE 1: The five main categories of substrate undergoing rehabilitation at Wangaloa Coal Mine, south-east Otago.

Substrate type	Substrate category	Number of study plots	Description
Waste rock	Quartz-rich	7	>35% quartz pebbles, fines dominantly sand with minor silt, clay & widely dispersed coal.
	Silt-rich	7	<15% quartz pebbles, fines dominantly silt and clay with some widely dispersed coal.
	Coal-rich	9	>35% coarse & fine coal fragments, mixed with some quartz pebbles and/or silt.
Loess	Disturbed	20	Quaternary loess made up of immature silty material with no natural soil development. Disturbed by vegetation clearance, deep-ripping, and pine tree burial pits, with substantial mixing of surface and sub-layers.
	Least-disturbed	9	Quaternary loess as above but without burial pits and substrate mixing.

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[1] *covering a one-year period*

differential global positioning system. Of the 54 plots established, 52 were monitored because 1 plot was excluded due to absence of planted seedlings and the other plot became overgown with gorse after the first year. Each plot contained 8-9 seedlings in an area that measured approximately 25 m^2 (5 x 5 m).

Individual seedlings included in the study were initially tagged and numbered with pink tape, replaced later by coloured plastic sheep ear-clips. The first assessment of seedling status was made in September 2003, approximately three months after planting. Repeat measurements were made every three months thereafter for one year (i.e. December 2003, and March, June and September 2004). The 2003-2004 measurements were collected and presented by Todd (2005) as part of a Master of Science project at the University of Otago. Follow-up measurements were made on an annual basis in July/August 2005 by Solid Energy NZ Ltd and in September 2006 by the University of Otago. In total, the performance of 436 seedlings was assessed in this study.

Data collection

Seedlings

The survival status and height of individual seedlings were quantified during each survey. The proportion of seedlings alive in each species in each substrate category were then calculated for each year (i.e. number alive in year XX / number planted in 2003). Seedling height data were used to analyse trends in species growth on the two different substrate types, waste rock and loess. Three different categories of waste rock were considered, based on their physical composition in the top 20 cm, as defined in Table 1. Two categories of loess were defined based on their relative level of recent earthworks disturbance. The number of study plots within each substrate category was not equal because the latter varied in their degree of spatial coverage (Figure 1). For waste rock, 7 plots were on quartz-rich and silt-rich material respectively, and 9 plots on coal-rich material. For loess, 20 were on disturbed and 9 on least disturbed substrate respectively. Similarly, the total number of seedlings assessed in the species-substrate data matrix varied because species distribution and clustering were at the discretion of the seedling supplier, not the authors.

Substrate

To identify nutrient and trace elements levels in the different substrate categories, we collected cores (7 cm diameter) from the middle of each study plot. Cores were taken from 5 cm below surface (to reduce the confounding effect of hydroseeding and organic amendment) to a depth of 20 cm, which well encompassed the zone of planted seedling root blocks (*ca* 10 cm length x 6 cm width). Cores were collected in June and December 2003 from the initial set of planted plots and in December 2003 only from the plots with delayed planting, as mentioned above.

Foliage

Six months into the sampling programme, it was apparent that differences were arising in the condition of seedlings on quartz-rich and coal-rich waste rock. In particular, seedlings appeared wilted, showed loss of leaves as well as leaf discolouration. To investigate possible reasons for this, foliage samples were collected in March 2004 from a number of seedlings growing at the affected sites, around some of the study plots on the western waste rock stacks (Figure 1). Seedlings growing on least-disturbed loess nearby were also included for comparison. No samples were collected from seedlings growing where the organic amendment had been spread over waste rock. Leaves were picked from seedlings that had shown sufficient growth since 2003 to survive a degree of harvesting. A mix of old and new leaves were selected from each seedling. Depending on the availability of biomass, 3-5 composite samples of around 50 g (green weight) were collected per species present on each of the three substrate categories, at two different test sites. Test sites extended beyond individual study plots, by a 5 m radius approximately, in order to obtain enough plant biomass for analyses. Dead plants were not included in the foliage collection.

Chemical analysis

Substrate Samples

The chemical analysis of each core was carried out by M.B. and A.T. in the Geography Department of the University of Otago, the full results of which are presented in Baker (2005) and Todd (2005). All analyses were carried out on the 2 mm sieved fraction of each substrate sample, which was <65% of quartz-rich and coal-rich waste rock samples, and 80-95% of silt-rich waste rock samples (Craw et al., 2007). In this paper, we present mean values for a sub-set of tested elements. This is because some of the standard New Zealand soil testing procedures we used were deemed to produce spurious results for the waste rock samples that contained negligible classical, aggregated soil material. The problems occurred mainly for potassium chloride (KCl) extraction for ammonium and nitrate ions, sodium bicarbonate extraction for phosphorus ions (Olsen P method), and loss on ignition for organic matter. Also the presence of coal in samples influenced measurements for total carbon (C), determined by a Carlo-Erba Elemental Analyser, but it is not known how available nutrients in coal are to plants (Vetterlein et al., 1999). We conservatively focus here on reporting values for total nitrogen, phosphorus, silicon, cation exchange capacity (CEC), and pH, determined in duplicate following Blakemore et al. (1987). The trace elements boron (B), iron (Fe), arsenic (As), copper (Cu), and zinc (Zn) were extracted using 5 g of sample in 10 mL concentrated nitric acid and 15 minutes microwave digestion followed by inductively coupled plasma optical emission spectroscopy (ICP-OES; Thermo Jarrell Ash Atomscan 25). Detection limits used were: boron (10 mg/kg), iron (20 mg/kg), arsenic (1 mg/kg), copper (1 mg/kg), and zinc (2 mg/kg).

Foliage Samples

Foliage samples were sent to Hill Laboratories, Hamilton, for analysis by the same methods as for Craw et al., 2006. The samples were oven-dried at 62 ºC, powdered with a steel grinder to pass a 1 mm screen, digested overnight with concentrated nitric and hydrochloric acids and analysed for phosphorus, zinc, copper and boron by ICP-MS (Perkin-Elmer Sciex Elan-6100 DRC Plus). These trace elements were chosen because previous work had shown they were readily mobilised at the mine site (Black & Craw, 2001).

Data Analysis

Point data characterised by multiple environmental variables can be usefully analysed by multivariate statistical techniques. In this paper, we used Principal Component Analysis (PCA) in the program PRIMER-5 to identify which of the tested elements accounted for the greatest variability in the substrate chemical data set. By assigning Factors in the analysis, we were able to assess the distribution of this variability in terms of the different substrate categories. (Clarke & Gorley, 2001). Results from the PCA analysis were also used to quantify the relationship between substrate chemistry and species growth at the mine site via correlation analysis.

Results

Substrate chemistry

Average values for the chemical profile of different substrate categories at the mine site are shown in Table 2. The two loess categories, disturbed and least-disturbed loess, were chemically similar and are hence

TABLE 2: Nutrient and trace element values for five different substrate categories at Wangaloa Coal Mine. Values represent mean ± standard deviation (S.D). Values shown in italics are individual values in test groups where the majority of samples were below detection limits.

Substrate type	**Waste rock**			***In situ* substrate**	
Substrate category	**Quartz-rich**	**Coal-rich**	**Silt-rich**	**Disturbed loess**	**Least-disturbed loess**
No. of sites	**6**	**9**	**7**	**20**	**10**
total N (%)[1]	0.08 ± 0.09	0.17 ± 0.12	0.12 ± 0.03	0.22 ± 0.09	0.25 ± 0.09
total P(%)[1]	0.01 ± 0.01	0.03 ± 0.01	0.02 ± 0.00	0.04 ± 0.01	0.04 ± 0.01
total Si (%)[2]	*1.79; 0.22*	2.0 ± 1.3	0.8 ± 0.6	*0.4*	< 0.1[3]
B mg/kg)[2]	< 20[3]	34.8 ± 7.7	*25*	< 20[3]	< 20[3]
Fe (mg/kg)[2]	3395.7 ± 696.6	3915.6 ± 2346.2	5088.6 ± 1068.5	11523 ± 2428.7	10987.8 ± 4022.75
CEC [1] (me/100g)[2]	5.3 ± 4.3	10.1 ± 4.4	4.6 ± 1.9	8.0 ± 1.9	8.0 ± 1.9
pH[1]	4.3 ± 0.5	4.1 ± 0.8	4.4 ± 0.5	4.5 ± 0.2	4.5 ± 0.3
As (mg/kg)[2]	*2.0*	*2.0*	*2; 2*	3.2 ± 0.6	2.9 ± 0.7
Cu (mg/kg)[2]	4.6 ± 1.7	15.2 ± 11.9	9.6 ± 6.7	3.4 ± 1.4	3.9 ± 2.2
Zn mg/kg)[2]	5.8 ± 2.0	9.6 ± 2.5	12.0 ± 6.0	15.4 ± 4.0	17.6 ± 6.7

[1] from two sampling periods (June 2003 and December 2003);

[2] one sampling period only (December 2003).

[3] below detection

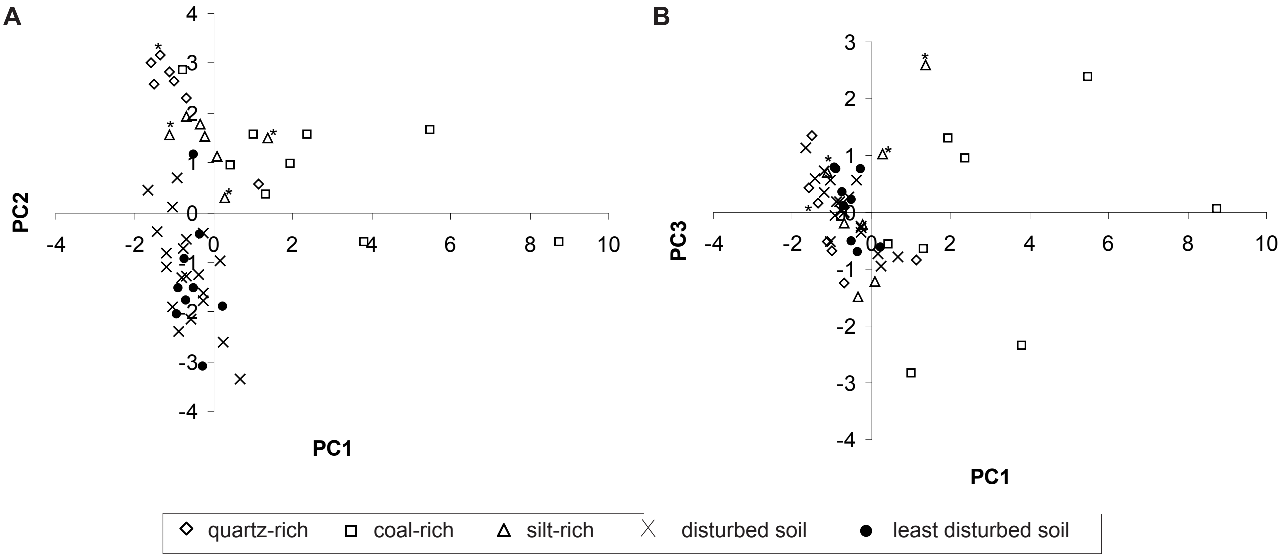

FIGURE 2: Plot showing the separation of different substrate categories at Wangaloa Coal Mine along the first two axes of the Principal Component Analysis. See Table 3 for variables considered. Open symbols correspond to different categories of waste rock. Asteriks show individual samples taken from the organic-amendment area.

referred to simply as 'loess' in this section. Across all substrate categories, total nitrogen, phosphorus, and the CEC were rated as low to very low compared with typical New Zealand soils (Blakemore et al., 1987), but total nitrogen and phosphorus were on average higher on loess than waste rock, although values were locally elevated in four of the coal-rich plots. Coal-rich waste rock contained higher and more variable nitrogen, phosphorus, and CEC than either quartz- or silt-rich waste rock. Overall, substrate pH ranged from extremely (< 4.5) to strongly (4.5 – 5.2) acid, with average values between 4 and 5. The lowest pH values (2.5-3.1) were recorded on coal-rich waste rock. Predictably, total silicon (Si) and boron were elevated specifically on coal-rich waste rock (up to 5% and 43 mg/kg respectively) because coal at Wangaloa contains between ca. 1-5% silicon and 50-450 mg/kg boron (Craw et al., 2006). Arsenic levels were low overall, yet were elevated in the loess compared with any category of waste rock (up to 4 mg/kg and <2 mg/kg respectively), as was zinc. Otago schist, from which the loess was derived, has typical background metal concentrations of arsenic (10-15 mg/kg), zinc (80-100 mg/kg) and copper (15-30 mg/kg) (Craw, 2002). Copper levels were greater in some of the coal- and silt-rich waste rock samples specifically (up to 35 mg/kg), raising mean values to more than twice that of the loess or quartz-rich waste rock.

The PCA analysis identified three linear combinations of variables that accounted for a high proportion of variability (81%) in the substrate data (Table 3). Plotting the values for PC1, PC2 and PC3 provides an illustration of how that variability is partitioned between replicate samples. For PC1 (a coal gradient dominated by total silicon and boron), the coal-rich waste rock samples showed the greatest deviation and variation in values compared with samples from substrate with low coal content (Figure 2A). For PC2 (a nutrient gradient) dominated by total nitrogen and phosphorus as well as iron and zinc (Table 3), replicate sample clusters corresponding to a general gradient of increasing values were identified in the following order: quartz-rich → silt-rich → coal-rich waste rock → loess (Figure 2A). For PC3 (a pH gradient), there was a high degree of overlap between waste rock and loess, illustrating that the majority of samples had a similar pH range (Figure 2B).

One quartz-rich plot and three silt-rich plots occurred within the organic amendment area. Of these, two of the silt-rich plots were shown to have a different chemistry to other silt-rich plots, which accounts for some of the variation in element values for this substrate category (Figure 2A & 2B; Table 2). In particular, the latter plots formed a loose group with some of the coal-rich samples along PC1 and PC3, showing relatively high pH and total silicon content.

TABLE 3: Results from the Principal Component Analysis on substrate data at Wangaloa Coal Mine. Arsenic was excluded due to the majority of samples being below detection.

PC	% Variation	Cummulative % Variation
1	36.4	36.4
2	33.9	70.3
3	10.5	80.8
4	9.6	90.4
5	3.6	94.0

	Eigenvectors		
Variable	**PC 1**	**PC 2**	**PC 3**
total N (%)	0.22	-0.44	-0.22
total P (%)	0.12	-0.52	-0.06
total Si (%)	0.51	0.11	-0.03
B (mg/kg)	0.50	0.07	0.32
Fe (mg/kg)	-0.22	-0.45	0.07
CEC (me.100g^{-1})	0.32	-0.33	-0.01
pH	-0.25	0.01	0.81
Cu (mg/kg)	0.48	0.11	0.29
Zn (mg/kg	-0.03	-0.46	0.33

Seedling survival

At the time of first assessment in 2003, all seedlings in study plots were alive. Mortality of the 8-9 seedlings per plot increased each year until 45% of the overall stock were alive in 2006 (Figure 3A). By the last survey (September 2006), most study plots contained 3-5 surviving seedlings (Figure 3B). Seedlings planted into coal-rich waste rock had the lowest survival (overall 35%; Table 4), and four of the five study plots recording 100% mortality also occurred on coal-rich waste rock, data not shown. Proportions of surviving seedlings on quartz- and silt-rich waste rock (43% and 39% respectively) were also lower than on least-disturbed loess (55%) but similar to disturbed loess (48%). Seedlings growing on quartz- and silt-rich waste rock covered with a layer of organic material showed both good and poor survival (Table 4).

Wineberry and manuka had widespread losses across all substrate categories, with between 20 - 30% and 18 - 47.5% of original seedlings surviving respectively (Table 4). Wineberry deaths occurred consistently from year to year whereas manuka loss was greatest in the second year (2004). Other species showed more substrate-specific survival patterns (Table 4). For the *Pittosporum* species, kohuhu and lemonwood, survival rates were highest on the loess. Kohuhu was also the

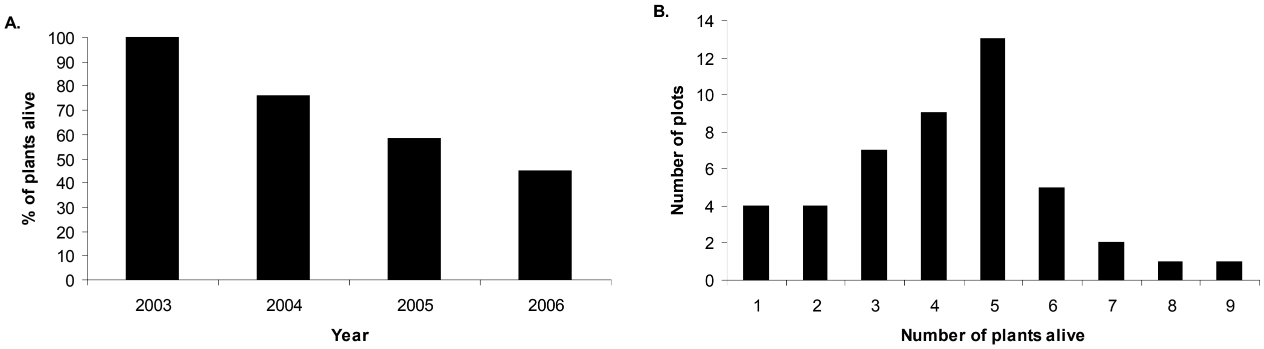

FIGURE 3: (A) Survival of indigenous seedlings three years after planting at Wangaloa Coal Mine, and (B) Frequency distribution for seedling survival among individual study plots (n = 48) at the time of final measurement in 2006. Five additional plots recorded 100% seedling mortality. Plots were initially planted with either 8 or 9 seedlings.

TABLE 4: Survival data (% of seedlings alive) for indigenous species in different categories of substrate at Wangaloa Coal Mine, up to three years after planting. The initial number of seedlings initially planted is shown in parentheses. * Values with asterisk relate to seedlings planted in an organic amendment area.

Substrate type	**Waste Rock**					***In situ* substrate**		**TOTAL number of specimens**
Substrate category	**Quartz-rich**		**Coal-rich**	**Silt-rich**		**Disturbed loess**	**Least-disturbed loess**	
Species								
Kohuhu	*(15)*		*(19)*	*(0)*	*(6)**	*(39)*	*(17)*	*96*
2003	100		100	n/a	100*	100	100	
2004	66.7		94.7	n/a	100*	84.6	94.1	
2005	66.7		73.7	n/a	50*	82.1	91.1	
2006	40		63.2	n/a	50*	79.5	88.2	
Lemonwood	*(6)*		*(5)*	*(0)*	*(1)**	*(8)*	*(12)*	*32*
2003	100		100	n/a	100*	100	100	
2004	66.7		60	n/a	0*	87.5	83.3	
2005	66.7		40	n/a	0*	87.5	83.3	
2006	50		0	n/a	0*	87.5	66.7	
Broadleaf	*(3)*		*(18)*	*(8)*	*(4)**	*(11)*	*(0)*	*44*
2003	100		100	100	100*	100	n/a	
2004	66.7		100	87	100*	72.7	n/a	
2005	66.7		38.9	50	50*	54.5	n/a	
2006	66.7		22	12	25*	54.5	n/a	
Wineberry	*(5)*		*(1)*	*(10)*		*(40)*	*(10)*	*66*
2003	100		100	100		100	100	
2004	60		0	50		45	90	
2005	No record		0	20		27.5	30	
2006	20		0	20		25	30	
Koromiko	*(3)*	*(7)**	*(6)*	*(13)*	*(3)**	*(26)*	*(13)*	*71*
2003	100	100*	100	100	100*	100	100	
2004	0	100*	50	100	100*	80.8	84.7	
2005	0	100*	0	77	100*	80.8	53.8	
2006	0	100*	0	69	100*	73.1	46.2	
Manuka	*(10)*	*(1)**	*(13)*	*(0)*	*(10)**	*(48)*	*(19)*	*101*
2003	100	100*	100	n/a	100*	100	100	
2004	80	100*	84.6	n/a	90*	72.9	100	
2005	60	100*	53.8	n/a	30*	43.8	89.5	
2006	10	100*	30.8	n/a	0*	18.8	47.5	
Toetoe	*(3)*		*(16)*	*(4)*		*(0)*	*(3)*	*26*
2003	100		100	100		n/a	100	
2004	66.7		43.8	100		n/a	100	
2005	66.7		43.8	100		n/a	100	
2006	66.7		43.8	75		n/a	100	

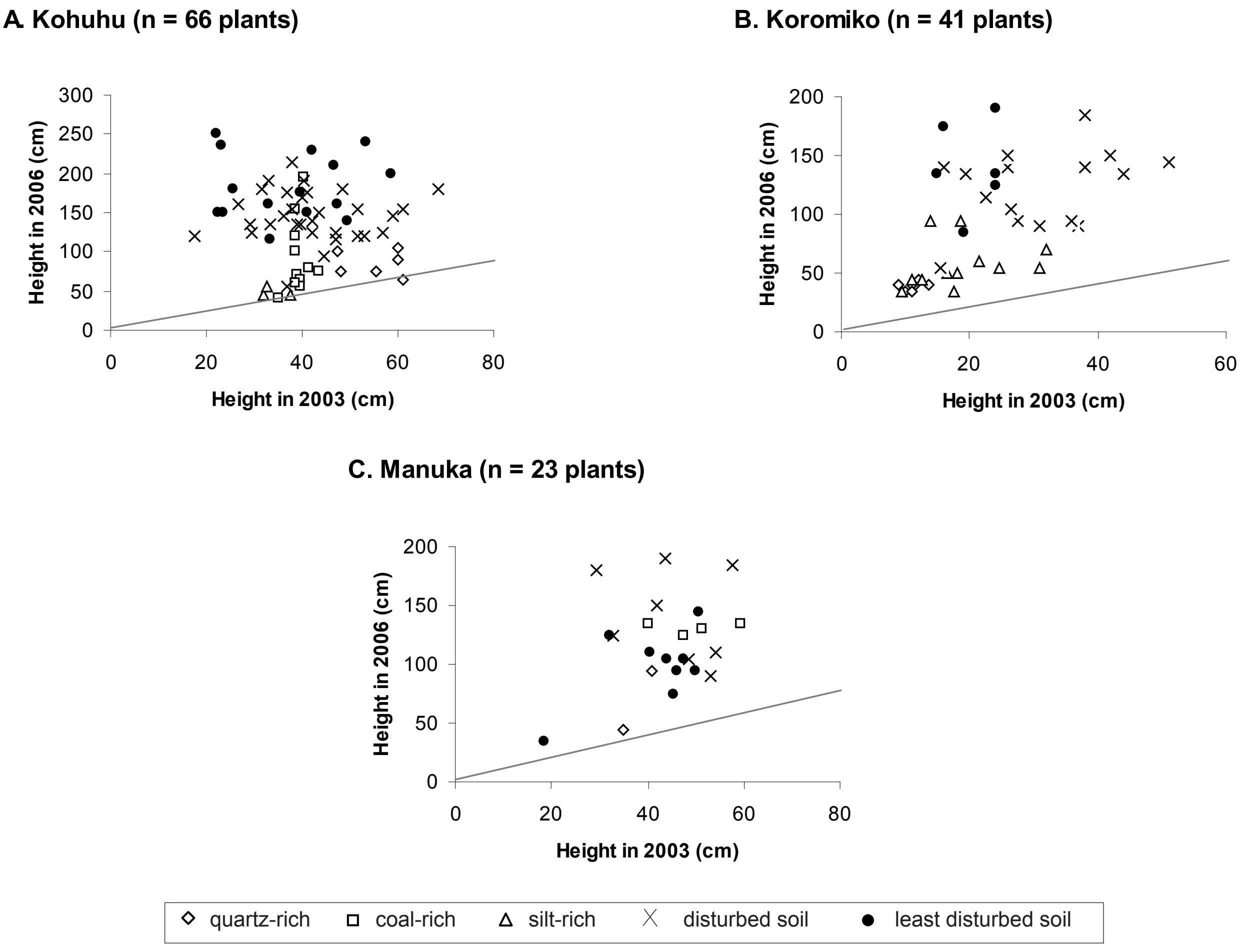

FIGURE 4: Scatterplots showing growth of three indigenous species planted in different types of substrate at Wangaloa Coal Mine. Data are height measurements for individual seedlings taken soon after planting (in 2003) and three years later (in 2006). Diagonal line represents a 1:1 ratio, i.e. no growth between the years. Open symbols correlate to different categories of waste rock. N.B. not all substrate categories represented for each species either because of seedling mortality or absence (see Table 4).

best surviving species on coal-rich waste rock. For broadleaf, a similar number of seedlings was planted into coal- and silt-rich waste rock as well as disturbed loess, with the latter showing greatest survival by 2006. For koromiko, seedling survival was comparably lower on least-disturbed loess in 2005 and 2006 than on either quartz- or silt-rich waste rock or disturbed loess. For toetoe, numbers planted were too few to compare survival trends between substrate categories.

Seedling growth

Plant growth in the different substrates was compared only for those species with an adequate number of survivors, i.e. kohuhu, koromiko, and manuka. The height of each individual seedling at the time of first measurement in 2003 was plotted against height attained in 2006 to assess relative growth during the study period (Figure 4). A 1 : 1 growth line on each plot in Figure 4 showed that most seedlings had grown since planting but that there were differences between substrate categories. For kohuhu and koromiko, the main differences in growth rates occurred between the two general types of substrate (i.e. waste rock *versus* loess). Mean height growth for kohuhu was 85 cm on quartz-rich, 92 cm on coal-rich, 48 cm on silt-rich waste rock, and 146 cm and 183 cm on disturbed and least-disturbed loess respectively. For koromiko, mean height growth was 39 cm on quartz-rich and 58 cm on silt rich waste rock, and 123 cm and 141 cm on disturbed and least-disturbed loess respectively. Within waste rock categories, kohuhu grew faster on quartz-rich and koromiko in silt-rich plots respectively (Figures 4A and B). There were also two coal-rich plots that produced good kohuhu and manuka seedling growth (Figures 4A and 4C). For manuka, the differences in seedling height showed no clear

TABLE 5: Pearson correlation coefficients (and *p* values) for PC1, PC2, and PC3 versus height growth of three species, three years after being planted.

Species	Number of seedlings	PC1	PC2	PC3
Kohuhu	66	-0.19 $p = 0.12$	-0.66 $p < 0.01$*	-0.20 $p = 0.11$
Koromiko	41	0.34 $p = 0.03$	-0.83 $p < 0.01$*	0.06 $p = 0.72$
Manuka	23	0.25 $p = 0.26$	-0.19 $p = 0.37$	-0.21 $p = 0.33$

* significant results

pattern in relation to substrate type or category. In the plots amended with organic material, average heights in 2006 were lower than in the unamended waste rock plots for kohuhu (60 cm and 96 cm respectively) and koromiko (40 cm and 63 cm respectively), but there were too few manuka to compare.

Simple correlation coefficients between species growth and the component scores for substrate PC1 (the coal gradient), PC2 (the nutrient gradient), and PC3 (the pH gradient) showed mostly weak associations (Table 5). Only the correlation between kohuhu and koromiko maximum height and PC2 was significant (r>60, p<0.01).

Foliar chemistry

The foliage chemistry of species sampled from selected substrate categories (quartz-rich and coal-rich waste rock, and least-disturbed loess) is displayed in Table 6. Levels of phosphorus were within the range of 0.1-0.3% dry weight. Copper levels were consistent on all substrate categories (from 3-15 mg/kg dry weights). Zinc was more variable (10-180 mg/kg dry weight) and showed a trend of greatest concentrations in koromiko, kohuhu, and toetoe growing on least-disturbed loess but not in manuka or broadleaf. Zinc solubility is common in areas of low pH at Wangaloa (Black & Craw, 2001), which may account for the variation in mean concentration levels in seedlings on waste rock compared with least-disturbed loess. Foliar boron levels were also more variable on waste rock (7-228 mg/kg dry weight) than on least-disturbed loess (6-36 mg/kg dry weight). For coal-rich waste rock at Site 1 (see Figure 1), boron values in each species strongly exceeded other values, despite containing a similar level of boron in the substrate as to coal-rich Site 2 (43 mg/kg compared with 32 mg/kg). There were no apparent species-specific patterns in boron uptake but the highest level of 228 mg/kg was found in broadleaf.

Discussion

Two main results have arisen from our investigation into the performance of indigenous forest species planted on two different types of minimally amended substrate at an east coast coal mine site in southern New Zealand. First, seedling mortality was higher and more rapid on all categories of waste rock than on either category of loess. Secondly, seedling growth rates were slower on waste rock than on loess. For both these results we identified some species-specific trends, which are discussed below in relation to the chemical environment of the mine site.

Plant survival on waste rock

Only around one third of seedlings originally planted into coal-rich waste rock survived the first three years in the mine site environment. Seedling survival was also low on quartz-rich and silt-rich waste rock (<50%) but seedling deaths did not occur over such spatially extensive areas as on the coal-rich substrate. The chemical profiles for the different substrates are not complete but highlight a generally higher nutritional status in coal-rich waste rock than either quartz-rich or silt-rich waste rock. The presence of coal in substrates may provide a potential source of plant nutrients (nitrogen, phosphorus, silicon, boron). However, the degree of their availability to plants is not yet well understood although is likely to be less than organic sources (Vetterlein et al., 1999). For example, most nitrogen released from weathering fossil sources is in the form of ammonium (NH_4^+) ions, which is unavailable to most dicotyledons due to an absence of nitrifying bacteria in mine waste (Kent, 1982). Countering potential geogenic nutrients in the coal-rich plots at Wangaloa was a potentially more acidic growing medium compared to the other substrate types considered. Local areas of substrate acidity at the mine site arises from the seasonal oxidation of pyrite (Black & Craw, 2001) and any positive impacts from the limited liming associated with hydroseeding

TABLE 6: Analyses of foliage for phosphorus (P; wt.% dry weight) and zinc (Zn), copper (Cu) and boron (B) (mg/kg dry weight) from affected specimens of indigenous species planted at four waste rock sites and two control loess sites (from Craw et al., 2006).

Substrate type	**Waste rock**				**Loess (control)**	
Substrate Category	**Quartz-rich**		**Coal-rich**		**Least-disturbed**	
Site[1]	**1**	**2**	**1**	**2**	**1**	**2**
Species						
Manuka						
P	nc	0.1	0.2	0.2	0.1	0.1
Zn	nc	57	180	70	14	20
Cu	nc	6	12	6	6	5
B	nc	28	113	44	20	23
Koromiko						
P	0.1	0.1	0.2	0.2	0.2	0.3
Zn	11	29	24	22	100	59
Cu	5	4	6	3	6	15
B	13	17	96	20	28	33
Broadleaf						
P	nc	0.1	0.2	0.1	0.2	nc
Zn	nc	160	86	74	76	nc
Cu	nc	4	4	4	8	nc
B	nc	41	228	78	30	nc
Kohuhu						
P	0.3	0.2	nc	0.2	0.2	0.3
Zn	15	93	nc	63	130	105
Cu	6	5	nc	4	6	9
B	23	51	nc	44	27	36
Toetoe						
P	0.1	0.1	0.1	0.2	0.2	nc
Zn	17	29	11	10	130	nc
Cu	6	6	5	5	6	nc
B	7	12	71	11	27	nc

nc = sample not collected either because of limited amount of foliage or species absent from the test area.

[1] Sites extended beyond individual study plots by approximately a 5 m radius, as shown in Figure 1.

were negated in less than a year. Pyrite in the coal at Wangaloa can also be locally elevated in arsenic (up to 100 mg/kg; Black & Craw, 2001) although there was no arsenic enrichment in any of the study plots examined here (As<2 mg/kg). It is well known that acidic environments can limit revegetation success by interfering with the solubility of chemicals, including nutrients and toxic metals (Wong, 2003). In particular, phosphorus can be immobilised in low pH environments (Kent, 1982). The current study found that plots with 90-100% seedling mortality occurred on coal-rich waste rock that had been disturbed by earthworks for recent rehabilitation purposes. Such technical operations have brought previously buried pyrite to the surface for decomposition by atmospheric oxygen, causing local areas of acid mine drainage. At a gold mine site near Waihi, (North Island, New Zealand) pit walls containing areas of unoxidised pyritic rock developed acidity of around pH 2.5 within 6-8 months, and plant death occurred soon after (in Gregg et al., 1998) but the exact mechanisms causing plant death were not clear, as at Wangaloa.

Overall, the effect of acidic mine water drainage on indigenous species is not well understood in New Zealand, and more research is needed into this issue to assist with mine site rehabilitation projects. At an old uranium mine in north-east Washington State USA, Voeller et al. (1998) found native shrub species differed significantly in acidic soil tolerance, and in their potential for subsequent growth. For some species, tolerance to low pH also seems to interact with nutrient availability, highlighting the complex nature of stress tolerance in plants at acid sites (Voeller et al., 1998). Of the species planted in coal-rich plots at Wangaloa, kohuhu was the best survivor, and although low overall, manuka survival was also comparably better than on quartz-rich or silt-rich waste rock. In contrast, koromiko was an exceptionally poor survivor on coal-rich waste rock. Both manuka and kohuhu may, therefore, have a degree of natural tolerance to chemical limitations associated with substrate high in coal content. It is widely known that manuka, and to a lesser degree, kohuhu have a good ecological tolerance of low soil fertility but elevated boron and fluctuating acidity are also characteristic of coal waste at the mine site (see below).

Manuka along with kanuka also dominate the natural re-invasion of plants on waste rock at the site (Craw et al., 2007b). In the current study, we observed coal-rich plots recording 100% planted seedling mortality being rapidly colonised by self-established manuka and kanuka (Rufaut & Craw, unpubl. data). The poor performance of the planted stock compared with naturally colonised seedlings suggests that local ecotypes (which are better adapted to local conditions) interact with substrate chemistry to determine revegetation patterns in the short- to medium-term. In addition, the presence of other self-established forest species (Rufaut et al., 2006) highlights that the unamended waste rock chemical environment does not exclude indigenous species growth *per se* at Wangaloa but perhaps different transplantion mechanisms, such as hydroseeding rather than the system of seedlings in potting media used in this study, may be more successful for some indigenous species, (Simcock et al., 2004). Contrary to expectation, manuka survival on all study plots was poor even on the more favourable loess, despite seedlings being sourced regionally. At a coal mine site in Westland, New Zealand, Davis et al. (1997) suggested differences in mycorrhizal associations may explain why beech seedlings transplanted from nearby forest had a higher rate of survival than nursery-raised beech seedlings, and this may also be a factor contributing to planting mortality in our study.

A second environmental issue was identified from the foliage analysis. This is that boron toxicity may contribute to seedling deaths on waste rock. Boron is associated with the presence of coal and boron contents of the main coal seam have been found to be between 84 to 463 mg/kg, with lower boron associated with the upper part of the exposed seam specifically (Craw et al., 2006). As with substrate acidity, little is known about the relationship between boron uptake levels and the effect on indigenous species. A general plant toxicity threshold for boron of 200 mg/kg has been suggested by Foth and Ellis (1997) but levels below this (50-150 mg/kg boron) have been related to poor growth in *Pinus radiata* trees planted earlier in waste rock at Wangaloa (Craw et al., 2006). In the current study, boron levels in indigenous seedlings varied between species, substrate category and location (between sample sites) but some values on waste rock occurred within the range of poor growth for *Pinus radiata* trees, as mentioned above. In particular, one of the two coal-rich sites tested showed elevated levels of boron in foliage of each species analysed. At this site, broadleaf seedlings also contained levels of boron (228 mg/kg dry weight) that were above the potential boron toxicity threshold. Although our study could not relate high boron uptake in foliage to seedling death (because plants displayed enough vigour to be harvested), a later investigation by Slack et al. (2008) has found that boron toxicity was a survival issue for indigenous seedlings planted into waste rock at Wangaloa. The time-frame for investigating boron uptake and seedling death is clearly important, and ideally requires levels in foliage to be repeatedly measured during a seedling's life, rather than once-off as was used in the current study.

From our data, 50% of the assessed seedlings died in the first three years after planting. Although more seedlings survived, on average, in the loess (59.8%) than in waste rock (34.7%), survival rates in loess were expected to be higher than the measured values. This was because before rehabilitation, the loess supported a dense natural shrubland mixed with native and adventive species. The loss of planted stock on both the disturbed and least-disturbed loess emphasise that variables beyond substrate chemistry are also involved in successful seedling establishment at Wangaloa. The effect of substrate physical properties needs further investigation at the mine site to build on initial work by Todd (2005), and a focus on substrate moisture stress is also suggested. Drought stress from low water contents within the waste rock piles at Wangaloa in summer (Black & Craw, 2001) could pose a serious survival risk to seedlings before they extend roots to deeper layers. Also, for substrates with high coal content, high temperatures on black surfaces could also contribute to young plant die-back and dehydration (Kent, 1982). Organic amendments to mine waste are typically used to assist with moisture retention, as well as a source of slow releasing nutrients, but we are unable to provide any conclusive information for positive impacts on substrate characteristics from our study. Only 50% of the plots subsequently covered by an organic layer showed any chemical differences compared with non-amended plots, and these could feasibly be explained by underlying differences in coal fragment concentrations, as suggested by the PCA results (Figure 2).

Plant growth

The two species with the highest overall survival, kohuhu and koromiko, showed generally slower growth rates on all categories of waste rock than on loess. How representative this pattern is for the other species considered remains largely unquantified, owing to inadequate sample sizes, but slow growth of vegetation is notoriously typical of unmodified mine waste (Munshower, 1994). Our attempt to quantify relationships between species growth and substrate chemistry identified few significant associations, and provided little direction for future research. A strong correlation was found between koromiko, and to a lesser degree kohuhu, height growth and a combination of nitrogen, phosphorus, iron and zinc levels (from a nutrient gradient, PC2) in the substrate. It is possible that these associations reflect a cause and effect relationship, and that increasing the nutrient status of waste rock at Wangaloa could produce better growth rates (Davis et al., 1997), although not necessarily (Gregg et al., 2000). Increased values for PC2 were also overall signatures inevitably for the loess, so the aforementioned correlations may simply reflect better growth on loess *per se* rather than highlighting primary elements limiting plant growth.

Mean phosphorus foliar concentrations were similar in plants growing on waste rock (where growth was poor) to those growing on least-disturbed loess (where growth was good), suggesting that phosphorus is not a main factor limiting performance of species at Wangaloa. Most zinc levels were also within a ‘sufficient’ uptake range (Foth & Ellis, 1997). Mean foliar concentrations of the potentially toxic element, boron, on some coal-rich plots exceeded those on other plots (as discussed above), but it is not possible to determine from this study whether boron toxicity alone limits seedling growth in the species considered because other key components were also at levels that could limit plant growth, such as water and nitrogen. Nitrogen concentrations were not tested in the foliage analysis but substrate nitrogen levels were substantially lower in waste rock (<0.01-0.24 mg/kg) than least-disturbed loess (0.16-0.53 mg/kg). Nitrogen was tested in the foliage of pine trees planted in the initial rehabilitation attempt of the mine site, and showed some correlation between concentration levels and relative growth, i.e. <1.0 %N = poor growth and >1.2 %N = good growth (Craw et al., 2006). At a coal mine site in Westland, New Zealand, nitrogen deficiency was also suggested by Davis et al., (1997) and Langer et al., (1999) to account for poor growth in indigenous forest species on unamended waste rock. Nutrient availability to plants is generally maximised at around pH 6.5 (Harris et al., 1996). Although all pH values were below this at Wangaloa, it is possible that pH interacts with substrate nutrient levels to limit growth at some of the extremely acid sites, or seasonally. Measurements of available nitrogen (as NO_3^- and NH_4^+ ions) and phosphorus (using the Olsen P method) were obtained for the mine substrates but wide variability between analytical replicates indicated unreliable results from the waste rock samples. Consequently, relationships between total and plant available element values at the mine site remain unresolved.

Seedling persistence in combination with slow growth is characteristic of indigenous forest species planted on ‘poor’ sites in New Zealand (Bergin, 2003). It remains largely unclear from this study what defines ‘poor’ for the planted stock at Wangaloa. The nutrient status of the tested fraction of quartz-rich and silt-rich waste rock was inferior to that of the loess, and the presence of quartz pebbles dilutes nutrient concentrations even further in the field. Possibly coal-rich waste rock is also inferior to loess if elements in coal are not readily available to plantings. Yet as mentioned in the previous section, all categories of waste rock were capable of being naturally colonised by at least some of the species used in the technical revegetation project, such as manuka, kohuhu, and koromiko. On all categories of waste rock, seedling growth was observed to be better on weathered versus unweathered substrate. This is at least partly due to rapid acidification by freshly exposed pyrite in disturbed ground. One of the reasons why substrate chemical links with seedling growth remain unresolved at the mine site could be spatial incompatibility between the scale of our substrate sampling and that at which seedlings operate. This is a likely scenario for seedlings planted into the waste rock at Wangaloa. This is highly heterogenous over tens of centimetres, both horizontally and vertically, whereas loess has greater uniformity in chemical composition (Baker, 2005). Excavating dead and surviving seedlings at various stages and depths to examine root architecture and growth would provide an indication of the degree of seedling-substrate interaction beyond their peat root blocks (Gregg et al., 2000). Other studies in New Zealand suggest the physical effects of water balance and weed competition are also worthy of future research attention at the mine site (Langer et al., 1999; Bergin, 2003).

Heterogeneity within waste rock categories was illustrated in the growth pattern plots in Figure 4. That is, some study plots on coal-rich and silt-rich waste rock produced seedlings with growth rates at least equal to that on the loess. These particular plots need further investigation to define their physico-chemical differences in relation to other plots within the same general substrate type that produced poor species growth. Casual observation of each of these plots suggested that they were on waste rock that had been minimally disturbed since time of initial emplacement (around 50 years ago) and, as a result, the process of natural plant colonisation had begun. Although a certain amount of this natural cover was removed pre-planting, owing to the clearance of undesirable adventive species, there is some evidence at the mine site that self-established shrubs modify underlying waste rock properties (Craw et al., 2007b), from which the planted stock may have benefited. Elsewhere it has also been shown that early colonising species in the natural regeneration of severely disturbed ground can promote pedogenesis and improve survival conditions for later arriving species (Walton, 1993; Ross & Buxton 2005).

Seedling growth rates were higher on unamended waste rock and loess than in the areas of waste rock covered with an organic layer and/or hydroseeded. This may reflect a greater pressure of sward competition from imported seed types rather than *in-situ* weeds (gorse and broom). The effects of the aforementioned rehabilitation practices were not part of our original study design, given that they were conducted after our study plots had been established. However, repeat monitoring over time may compensate for the low level of spatial replication within some substrate categories, and provide more robust evidence for any differences in indigenous species performance associated with adding organic material to, and/or hydroseeding waste rock at the site. Certainly, elsewhere in New Zealand, the benefits of stockpiling and respreading original topsoil have been repeatedly demonstrated for mine site rehabilitation (Gregg et al., 1998; Simcock et al., 2004).

The contribution of natural revegetation

We have reported here on the technical revegetatation process at Wangaloa in the first three years. Clearly, this is a very short time period in the development of new indigenous plant ecosystems, and future monitoring of the seedlings is essential in providing a long term perspective on rehabilitation success. Although there has been a relatively high initial mortality rate, as discussed above, it is predicted that the planted seedlings will eventually become part of a self-sustaining indigenous shrub or forest community if the mine site managers allow natural colonisation to proceed alongside the plantings. Rufaut et al., (2006) showed that indigenous shrubs dominated natural revegetation processes on waste rock stacks at Wangaloa, and that canopy closure could naturally occur within a 50-year time frame. The process takes longer on waste rock stacks that are steep and have a high quartz gravel content (Craw et al., 2007b), and perhaps also in local areas with high boron and low acidity (Craw et al., 2006), but it does not appear fully retarded. Unfortunately, the introduction of foreign grasses and legumes (via hydroseeding and organic matter importation) will also impair the natural re-invasion of indigenous species on central waste stacks. On loess, natural regeneration is vigorous and dominated initially by gorse, but an abundant indigenous seed bank is also present. Owing to several decades with little anthropogenic disturbance, and the presence of indigenous seed sources in surrounding farmland, the Wangaloa coal mine was already on the way to naturally evolving a new indigenous ecosystem, and the final rehabilitation programme has probably ‘fast-tracked’ this process at large.

Species performances in comparison to Westland coal mines

Information on the establishment of indigenous forest species is lacking for mined sites in New Zealand where there has been catastrophic soil disturbance. To date, a considerable amount of research has been undertaken at Giles Creek opencast coal mine in North Westland, where rehabilitation using indigenous species is a consent requirement (Davis et al., 1997; Langer et al., 1999). In this section, we briefly assess our findings with the aforementioned studies, using common species to provide an east-west coast comparison for the South Island (manuka, wineberry, koromiko, and broadleaf). Comparisons of natural regeneration on unamended waste rock are also included.

Unlike the quartz gravel waste rock at Wangaloa, waste rock at Giles Creek consists of alluvial gravels overlaying coal seams associated with mudstone and sandstone layers. Substrate chemical data available for comparisons are limited, yet show higher waste rock pH (5.4-5.6) at Giles Creek than at Wangaloa, as well as a lower range of total nitrogen (0.01-0.15%), and CEC (3.1-7.3 me/100 g) respectively. Elevation of the mine at Giles Creek is 200 m (cf. 120 m at Wangaloa) and annual rainfall 2900 mm (cf. up to 1000 mm at Wangaloa).

Numbers of seedlings surviving for the species above were generally higher on waste rock at Giles Creek than any of the substrate categories examined at Wangaloa, including the loess, except for broadleaf, which was heavily browsed at Giles Creek. After 4-4.5 years, around 75% of manuka, 60% wineberry, and 95% koromiko were alive at Giles Creek. In contrast, average seedling height growth at Giles Creek was within the ranges identified for species in common with Wangaloa. For mean foliar nutrient concentrations, similar levels of phosphorus were found at Giles Creek (0.15%) to plants growing on the silt-rich and quartz-rich material at Wangaloa (1.4%). Similar levels were also found for copper (5 mg/kg vs. 3.5 ppm) and boron (24 mg/kg vs. 27 ppm) respectively, whereas zinc at Wangaloa was higher (51 mg/kg) than at Giles Creek (18 ppm). Natural plant invasions of unamended waste rock at Giles Creek were reported to be negligible whereas at Wangaloa, manuka seedling densities of around 20 seedlings/m^2 have been recorded in some waste rock areas (Rufaut & Craw, unpubl. data).

In summary, the much better seedling survival at Giles Creek than either substrate type at Wangaloa may be due to: (i) better water balance from high rainfall in Westland; and (ii) absence of any substrate toxicities in the glacial outwash gravels – both of which are key east-west coast differences. The disparity in levels of natural plant invasions on waste rock could be related to differences in substrate particle size and natural seed source, i.e. coarse boulders surrounded by mature beech forest at Giles Creek Mine compared with quartz gravels surrounded by regenerating manuka/kanuka shrubland at the Wangaloa site.

Conclusions

Minimally amended waste rock after mining of coal in south-eastern Otago has not been easily revegetated, at least in the short term, by planting nursery-raised indigenous tree and shrub species. Waste rock with high coal content has been a particularly challenging substrate category and the low rate of seedling survival on this substrate is not completely accounted for. Boron toxicity cannot be discounted but drought and nitrogen deficiency, as well as local acidic mine water drainage (pH < 3), may also play contributing roles. Growth of species in surrounding loess was substantially better than on any of the three categories of waste rock studied here. Possibly this is because of greater substrate fertility of loess, but physical factors, particularly those related to water storage and weed competition, still require quantification. Waste rock containing high proportions of siltstone, which is chemically and structurally similar to loess, produced some of the fastest growth rates in the planted stock. We suggest that had the waste rock been covered by conserved soil or soil-like material from the site, including loess, the revegetation results would probably have been better. However, a surface distribution of imported organic material does not appear to have been particularly beneficial to the planted stock, at least in the short-term, but more research is required because of the uncontrolled nature of this treatment in our study.

On all categories of waste rock, seedling growth was casually observed to be better on weathered versus unweathered substrate. For Wangaloa there appears to be a period of time (at least 5 years) after re-grading operations when we suggest indigenous forest species could be more successfully established as plantings. The variable vegetation cover introduced via plantings is probably adequate for forming a long-term cover on the loess but remains questionable on some waste rock piles, even with replacement plantings. However, the technical revegetation programme has been greatly enhanced by natural invasions of indigenous species from surrounding seed sources, and it is predicted that these will ‘fill in the gaps’ between plantings to eventually form a continuous indigenous cover in the desired areas. The presence of self-established indigenous trees and shrubs highlights two main points: (i) the potential of unamended waste rock at the site to act as a growing medium for indigenous species; and (ii) the value of conserving adjacent native vegetation to enhance natural regeneration processes in drastically disturbed landscapes. Natural regeneration from surrounding seed sources is a ‘free’, and as has been outlined here, successful, revegetation process that mine site managers should consider in their plans for rehabilitation. As has been shown in this paper, most of the Wangaloa coal mine site is not affected by high substrate toxicity, a problem identified from only some local areas of waste rock. Our findings at large are, therefore, also relevant to the reafforestation of other highly disturbed sites, where the natural soil cover is thin or absent, and naturally acid.

This paper reports on an initial snap-shot in the development of new indigenous vegetation. Distinct differences in the ability of individual species to be initially introduced to the mine site were clearly identified. Kohuhu has been one of the most successful species whereas wineberry and manuka have been among the least. Ongoing temporal replication of the study is vital to follow the longer term evolution of the new ecosystem, as is wider scale substrate sampling as root systems expand. More detailed species-specific studies are also required to balance the broad-scale study described here and to understand better reasons for poor performances of nursery stock in some waste rock areas. Resolving the inaccuracies in analysing rock material by standard soil testing techniques would greatly increase the understanding of plant-nutrient interactions at mine sites.

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