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TECHNICAL ARTICLE

Mitigation of Acid Mine Drainage via a Revegetation Programme in a Closed Coal Mine in Southern New Zealand

C. G. Rufaut · D. Craw · Andrea Foley

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Abstract Acid mine waters (pH 3–5) at the closed Wangaloa coal mine have resulted from surface runoff and groundwater seepage in contact with pyrite-bearing waste rock piles. The low nutrient content, physical factors, and elevated boron levels, all combined with the low pH (down to pH 2) of most waste rocks have limited early planned revegetation and natural plant colonisation. A renewed programme of site rehabilitation, started in 2000, focussed on establishment of near-complete ground cover and functioning ecosystems. Small patches (tens of m^2) of low-pH, boron-rich, unvegetated substrates persist after more than 10 years of rehabilitation and introduction of a wide variety of species, but natural colonisation is slowly advancing on these remnants. The rehabilitation has coincided with and contributed to a rise in runoff water pH from $\approx$4.5 to $\approx$5.6. This decrease in severity of acid mine drainage (AMD) has apparently become sustainable without further intervention. Near-complete vegetative cover occurred by a combination of a major planting programme and natural colonisation from nearby islands of established native species. Both processes were accompanied by development of functioning ecosystems, and supported by increasing invertebrate diversity and abundance, which are ensuring the persistence of the ameliorative effects on AMD at the site. Vegetation established via natural processes can function ecologically at a higher level than comparable planted vegetation but may not lead to the desired plant cover on some substrates.

C. G. Rufaut · D. Craw (✉) · A. Foley
Geology Department, University of Otago,
PO Box 56, Dunedin 9054, New Zealand
e-mail: dave.craw@otago.ac.nz

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Introduction

Rehabilitation of a mine site after closure is an important component of modern mine planning, and there are strong expectations from the surrounding population that this be done promptly and completely (Cristescu et al. 2012; Vymazal and Sklenicka 2012). There is a long history of mine sites left unremediated, and these have had a negative impact on public perception of mining, to the detriment of the industry at large (Bradshaw and Hüttl 2001; Cooke and Johnson 2002). As part of mine site rehabilitation, revegetation of the today's mine excavations and waste rock piles is now typical. To this end, modern mines usually stockpile topsoil for later redistribution to allow rapid plant establishment (Bell 2001; Boyer et al. 2011; Bradshaw and Hüttl 2001). This approach limits erosion of bare rock piles, and generally yields a uniform vegetation cover with a predictable flora component that can be engineered to fit the perceived needs of the end use of the post-mining landscape (Hodačová and Prach 2003; Holmes 2001; Prach and Hobbs 2008; Voeller et al. 1998).

Rehabilitation of abandoned mine sites is more difficult because of the lack of stockpiled topsoil with which to establish revegetation, unless very expensive importation of topsoil is undertaken. Instead, plant establishment must occur in the various substrates left after the mining process, and this can present challenges if the substrates have low nutrient contents or contain components that are toxic for incoming flora (Prach and Hobbs 2008). In these cases, revegetation results can be incomplete and patchy unless appropriate tolerant species or substrate treatments are used

(Craw et al. 2007; dos Santos et al. 2008; Lottermoser et al. 2011). A further complication is the degree to which natural plant colonization can be relied on, instead of direct planting of imported species. Natural colonization can be effective at providing revegetation by suitable and tolerant local species, provided sufficient nearby seed sources exist, and is a lower cost option than direct planting (Borden and Black 2005; Hodacová and Prach 2003; Novák and Konvicka 2006; Valente et al. 2012). However, natural colonisation takes longer than direct planting, leaving bare ground exposed to erosional processes, with associated undesirable visual and water quality issues (Bradshaw 2000; Prach and Hobbs 2008).

Mine site revegetation is an approach to land management that is growing in importance, and results are not visible for many years, so the long-term advantages and disadvantages of different approaches are as yet sparsely documented in the scientific literature (e.g. Baasch et al. 2012; Tropek et al. 2010). In this paper, we present observations and inferences on the successes and limitations of a recent long-term (>10 years) programme of rehabilitation of an abandoned coal mine site which had localized but significant acid mine drainage (AMD) issues. Previous attempts in the 1980s at plantation revegetation had failed to ameliorate AMD effects, partly because complete ground cover was not achieved and water infiltration persisted. We outline the key limitations to development of a protective organic ground cover and evaluate the relative benefits of natural colonization versus planned plantings. Then we document the rates and extents of development of more complete and sustainable ecosystems involving colonization of a wide range of invertebrate faunal elements. These natural and anthropogenic rehabilitation processes have been strongly affected by the underlying geological, geochemical, and mineralogical properties of the various substrates. Establishment of ground cover has had a significantly positive, long-term, and sustainable effect on AMD from the site.

General Setting

The Wangaloa coal mine site in southern New Zealand (Fig. 1 inset; 169°54′E; 46°17′S) is located in rolling hills (≈120 m) with locally steep relief, ≈3 km from the Pacific Ocean. The site has a cool temperate climate, with a mean annual temperature of 12 °C and rainfall (≈800 mm/year) distributed evenly through the year. The hill slopes are coated with a thin veneer (up to 5 m thick) of wind-blown siltstone (loess) that was blown inland from the exposed continental shelf during Quaternary low sea levels. This loess is the principal substrate for the original vegetation in the area, and thin organic soil horizons have developed on that substrate. The loess contains quartz, albite, muscovite, and chlorite derived from the regional metamorphic basement.

The Wangaloa mine was developed in a Late Cretaceous fluvial sedimentary sequence, the Taratu Formation, which consists mainly of conglomerate with minor sandstone, siltstone, and mudstone, and numerous coal seams ca 10 m thick (Harrington 1958). The mined coal seam at Wangaloa dips gently in a valley that drains eastwards (Fig. 1a). Surficial loess and underlying Cretaceous fluvial sediments were removed to gain access to the coal seam, and were deposited in waste dumps on site.

The mine was active from the 1940s until 1989 (Fig. 2a), resulting in a depression partially filled with waste rock piles, and flanked by cliffs (high walls) of overburden (Fig. 1a). Low points in the site became lakes, with the lowest part of the mine forming the largest lake (Main lake; Fig. 1a). Waste rock dumps and excavation surfaces formed in the earlier stages of mining were partially revegetated by natural colonisation (Fig. 1b; Craw et al. 2007). Some of the site and surrounds were planted as pine plantation forest (*Pinus radiata*) in the 1980s (Figs. 1b, 2a), but this species failed to thrive on acid, boron-rich substrates (Craw et al. 2006). Large parts of the site, especially the loess substrate, became colonised by exotic species dominated by gorse (*Ulex europaeus*), but even this latter species failed to become established on many surfaces of waste rock piles. Consequently, AMD had developed by the late 1990s, resulting in Main lake having water with pH between 4 and 5 (Fig. 2b; Black and Craw 2001). This lake is fed by surface water runoff and groundwater passing through the waste rock piles, and is the principal source for site discharge waters (Fig. 2a, b). The mine water contained significant dissolved boron and commonly had a pH below 3 (Begbie et al. 2007; Craw et al. 2006). These environmental issues prompted an organised programme of site rehabilitation to establish a better, more native vegetative cover, aimed at limiting surface water runoff and infiltration of water into the acid-generating waste piles.

Vegetation Substrates

No topsoil was saved during mine development, so all vegetation has developed on substrates exposed by mining. Most of the slopes on the southern side of the mine (Fig. 1a, b) are still coated with loess, with localized remnants of organic soil, and these slopes have presented few problems for revegetation. However, waste rock piles have a wide variety of substrates on their upper surfaces, and these have presented greater revegetation challenges. The principal substrate types are summarized in Table 1,

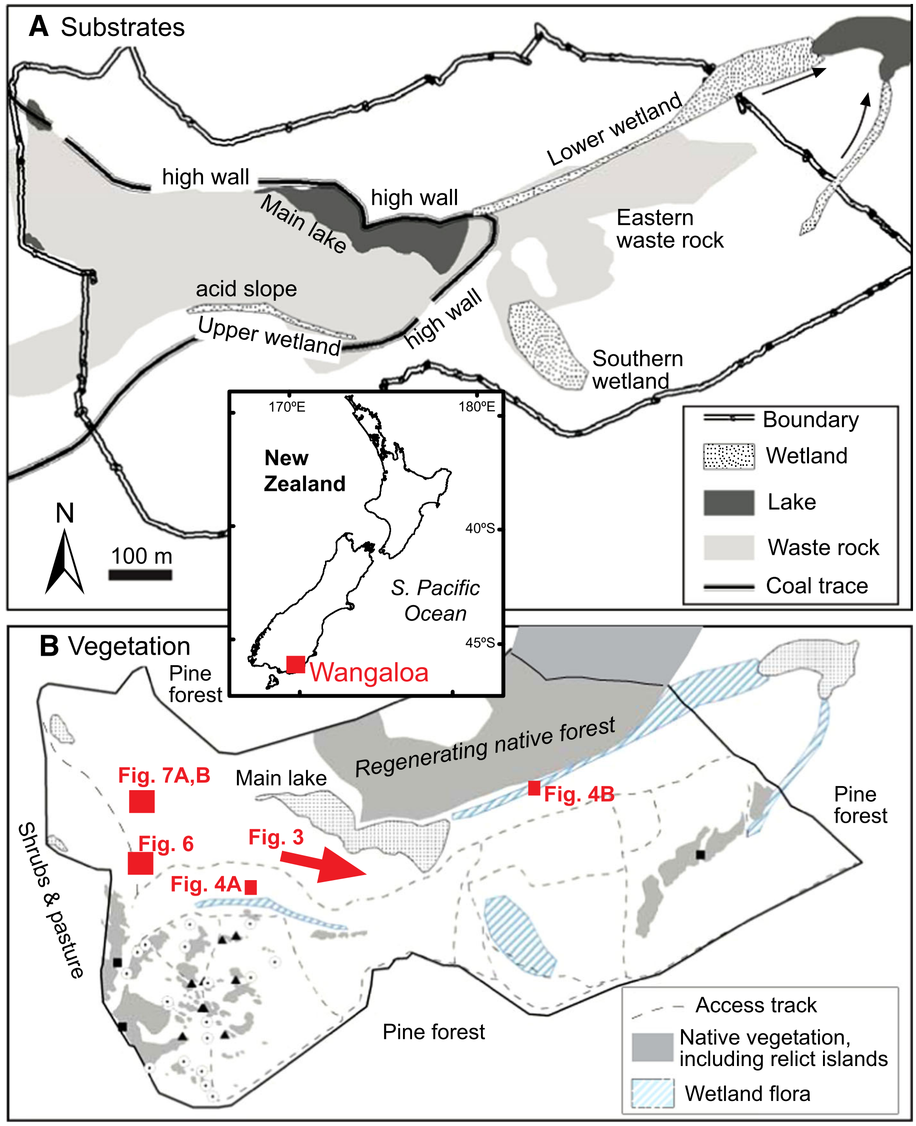

Fig. 1 Location maps for the Wangaloa coal mine (see *inset* for regional location). **a** Principal substrate features of the mine site. **b** Principal vegetation types. The *uncoloured area* within the mine site boundary was revegetated with introduced plantings

with the main physical and chemical features that affect revegetation success.

Most waste rock consists of Taratu Formation conglomerate, which is made up of quartz pebbles (up to 2 cm) with a matrix of finer-grained quartz, muscovite, and kaolinite (Fig. 3a). Thin beds of fluvial siltstone and mudstone, which were locally interlayered with the conglomerate, have been variably mixed with the conglomerate during excavation and dumping. These finer grained sediments have high kaolinite contents, with subordinate quartz and muscovite, and some contain carbonaceous material, especially near the coal seams. The finer sediments allow vegetation establishment readily, but the dominant quartz conglomerate is less amenable to colonisation because of development of a surface armour layer (hardpan) of quartz pebbles (Table 1; Craw et al. 2007). Direct planting through the armour layer into the underlying sediment is more successful for plant establishment but the underlying ratio of coarse and fine grains remains influential for long term survival and reproductivity.

The coal that was mined at Wangaloa is rich in sulfur, with S contents ranging up to 5 wt%. The S is partially dispersed through the organic matter, and is partially present as pyrite (FeS_2). Oxidation of the pyrite dispersed through the coal leads to acidification of the coal-bearing substrates. Pyrite oxidation products include gypsum, jarosite, and iron oxyhydroxide, and these minerals commonly occur as surface coatings on coal fragments. In addition, the coal contains abundant boron (up to 450 mg/kg; Craw et al. 2006). This boron is readily mobilised by weathering of coal fragments in the waste rock piles (Craw et al. 2006). Boron-rich efflorescence, including boric acid and/or colemanite ($Ca_2B_6O_{11}.5H_2O$), can develop on coal

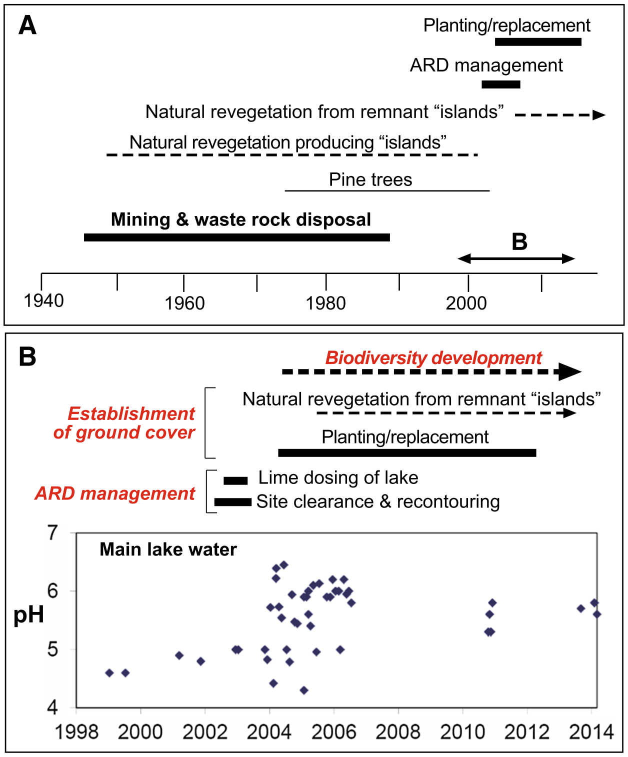

Fig. 2 Mining and rehabilitation time-line for the Wangaloa coal mine site. **a** Full history of the site. **b** History of the rehabilitation programme, with the Main lake water pH measured over the rehabilitation period. Principal rehabilitation stages (in *red text*) are described in the text

fragment surfaces during dry periods (Craw et al. 2006). Hence, coal-bearing substrates are typically acidic and B-rich, hindering establishment of non-local plant species ill-adapted to the conditions (Table 1).

Pyrite is most abundant near the top of the mined coal seam, and pyrite cements the quartz conglomerate immediately above the coal seam. This S-rich zone was removed during mining and disposed of in waste dumps. This pyrite readily oxidises at the surface of the waste dumps, yielding sulphuric acid runoff in surface and ground waters. Hence, pyrite-bearing quartz conglomerate constitutes one of the most problematic substrates for vegetation establishment at the site (Table 1).

Rehabilitation Programme

The active rehabilitation programme for the Wangaloa site was initiated in 2000, and progressively implemented over the following 10 years (Fig. 2a, b). The pine trees were removed and buried in large holes dug across the site. Adventive shrubs deemed to be problematic weeds were removed by bulldozing across the hillsides, and the substrate was prepared for planting native species by deep ripping to a depth of 30 cm (Fig. 3a). The rehabilitation programme incorporated three main stages that overlapped in time: acid mine drainage management, establishment of new vegetation ground cover, and development of faunal and floral biodiversity (Fig. 2a, b). The last stage was mainly a passive follower of the earlier two stages via species recovery and colonisation, but was influenced by site management procedures.

Acid Mine Drainage Management

The AMD at the site was generated by oxidation of pyrite, most of which occurred in the vadose zone of the waste rock piles. The AMD management strategy initially involved recontouring of most of the waste rock piles to limit erosion and associated progressive exposure of fresh pyrite. This was done at the same time as removal of the pre-existing scattered vegetation, leading to large areas of bare ground (Fig. 3a). Groundwater wells were drilled in waste rock and surrounding undisturbed rocks to monitor and model water table depths, flow rates, flow directions, and evolving water compositions (Begbie et al. 2007). Waters on site evolved rapidly to become sulfate-rich and acid (pH down to 2) with locally elevated boron contents (up to 6 mg/L) (Begbie et al. 2007; Craw et al. 2006).

The water monitoring and modeling showed that the surface water runoff and groundwater in the waste rock piles mostly flow to Main lake, from which the waters discharge through a wetland into a natural stream course east of the site (Fig. 1a). The Main lake therefore acts as a useful sink for mine water, and provides a useful water sampling point to determine the average water compositions at the site (Begbie et al. 2007). The pH of the water in the lake over time (Fig. 2b) gives an indication of the effectiveness of AMD management of the site through the rehabilitation programme. Minor additional AMD enters the wetland downstream of Main Lake (Craw et al. 2006), but this is diluted before the waters leave the site.

To obtain a rapid increase in pH of site discharge waters during the early stages of the rehabilitation programme, Main lake was dosed with 300 kg of hydrated lime in 2002. Acid neutralization by this lime raised the pH over the following $\approx$3 years, but the effects waned as the lime was consumed and the lake water was progressively replaced with incoming acid waters. However, the lake pH did not return to its original low levels after 2006, and the lake pH has since remained between 5 and 6 (Fig. 2b).

Extremely acid quartz–pyrite waste rock occurs on a slope in the centre of the mine (Figs. 1a, 4a), and this attracted additional procedures in an attempt to raise substrate pH and reduce the mortality of plantings (Leckie et al. 2008). Various amounts of alkaline coal fly ash or crushed limestone were added to different parts of the upper portions of the slope and mechanically mixed into

Table 1 Comparison of the physical and chemical properties of the principal substrate types at the Wangaloa mine (20 cm depth), with the resulting effectiveness of establishment of a vegetation cover

	Loess	Quartz-rich	Quartz-pyrite	Coal-rich
Physical properties				
Erodability	Low	High	High	Moderate
Surface armouring	Low	High	High	Moderate
Moisture retention	High	Low	Low	Moderate/low?
Bulk density	Low	High	High	Moderate
Chemical properties				
pH	4–5	3–4	2–4	3–4
Boron	<5 mg/kg	<5 mg/kg	1–8 mg/kg	10–400 mg/kg
Total P	Low	Very low	Very low	Low
Nutrients	Adequate (both natural colonisation and plantings)	Adequate (natural colonisation)-low (plantings)	Adequate (natural colonisation)-low (plantings)	Adequate (natural colonisation)-low (plantings)
Revegetation success				
Natural colonisation	Rapid, effective (years)	Slow, patchy (decades)	Negligible over decades	Slow, patchy, (years to decades)
Plantings	Effective	Moderate	Ineffective	Poor-ineffective

the substrate with an excavator. These treatments were experimental, and involved separate treatment plots totalling ≈ 100 m^2. The fly ash contained additional boron, so fly ash treatment plots had B levels locally exceeding 6 mg/kg, at the upper end of the range for these substrates. The experimental treatments were temporarily effective, but have had limited benefit after 8 years and no more general application of such treatments has been pursued.

Establishment of Vegetation Ground Cover

Natural regeneration of native vegetation occurred during the mining period on parts of the unmined loess slopes on the southern side of the mine site (Figs. 1b, 2a). Principal species involved were manuka, *Leptospermum scoparium*, and kanuka, *Kunzea ericoides* (Rufaut and Craw 2010). The seed sources for native shrub colonisation lay in semi-natural forest remnants bordering the mine site (Fig. 1b), and in relict seed banks in organic soil remnants on those slopes. Gorse developed alongside the manuka and kanuka, becoming more dominant with increasing distance from the forest remnants. Likewise, manuka, kanuka, and gorse colonisation occurred on waste rock piles at the eastern and western ends of the mine site after they were left inactive during the latter stages of the mining period (from 1962–1989). This initial waste rock plant colonisation was strongly affected by the nature of the exposed substrate (Craw et al. 2007; Rufaut et al. 2006). Armouring by pebbles on quartz conglomerate substrates was one of the principal barriers to natural colonisation, producing a dry, cement-like matrix that was a barrier for seed and moisture retention (Table 1; Craw et al. 2007). In contrast, admixed Cretaceous siltstone and mudstone within the quartz-rich waste rocks strongly supported natural colonisation and new forest establishment, even on steep slopes (Craw et al. 2007).

Adventive shrubby weed species that colonised large parts of the mine during and immediately after mining were removed in the first phase of rehabilitation (above; Fig. 3a). Unfortunately, this activity also removed regenerating native species that had become established beneath the gorse canopy, especially on the loess substrate. However, some patches of naturally regenerated native vegetation were retained during this preparation process, including single specimen trees (Fig. 1b). Substrate surfaces were ploughed to a depth of 30 cm to facilitate the introduction of new plantings. Over 100,000 native New Zealand plants were emplaced across the unvegetated parts of the site, with half emplaced in the first 2 years from 2003 and the other half added progressively to replace mortalities over the subsequent 7 years. Plants were introduced in individual peat-rich blocks (≈ 10 cm^2) containing slow-release fertilizer. Weeds were physically controlled with some herbicides where necessary, to limit competition with the new plants. Localised addition of a grass–legume seed mix was emplaced on the waste stack through the centre of the mine, mixed with lime, cellulose, and water (hydroseeding).

Plantings on the loess substrate have been more successful than on the quartz conglomerate. The canopy cover of plantings in plots monitored since 2003 ranged between 50 and 100 % on loess compared to an average of 20 % on waste rock (Fig. 5a). Low cover by plantings on waste rock is due to poor survival and lower growth rates than on the loess (Fig. 5b).

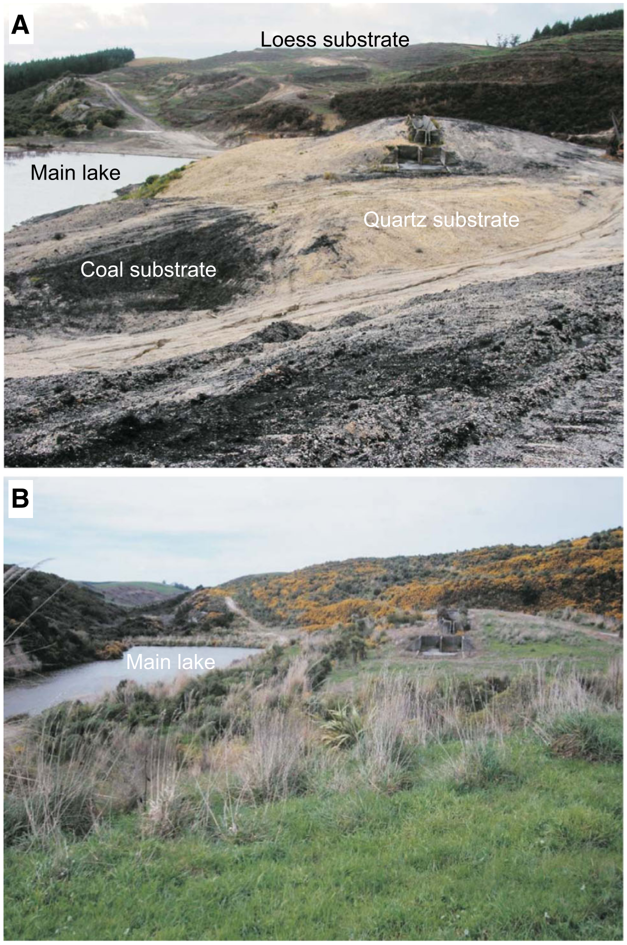

Fig. 3 General views of the Wangaloa mine site, looking eastwards from the centre of the site, with Main lake on left (see Fig. 1B). **a** Site at the time of weed clearance and recontouring prior to localised spreading of some organic amendment in the foreground (2002). Waste rock in the foreground is coal-rich substrate (*black*) and quartz conglomerate (*pale brown*). Rows of cleared vegetation are stacked on loess-covered hillsides in the background along slope contours. **b** Same view in 2013, with established vegetation, and most prolific growth of planted shrubs on the loess hillsides amongst regenerated gorse (*yellow*). Grass in foreground was introduced by hydroseeding

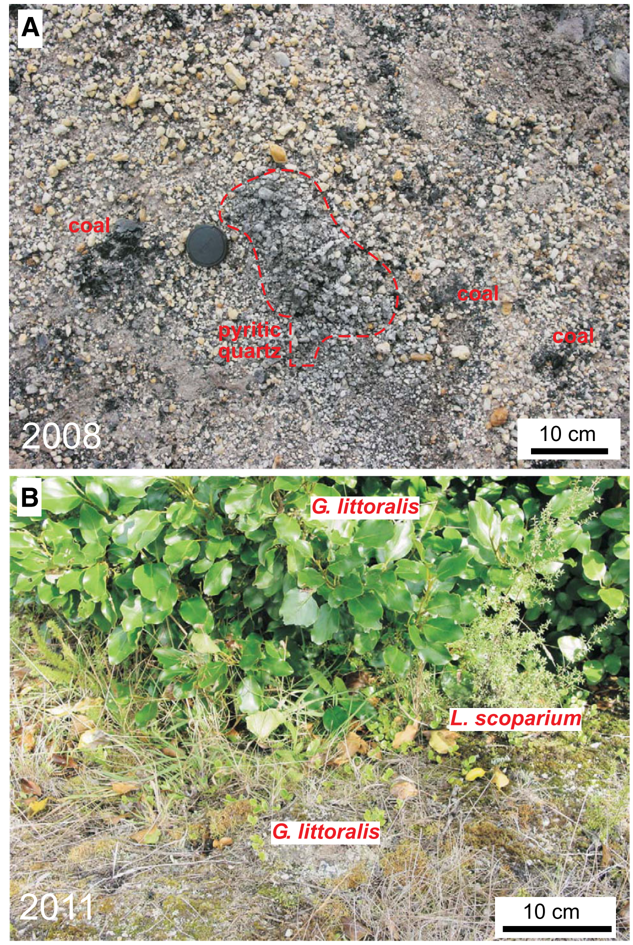

Fig. 4 Contrasting vegetation success on quartz conglomerate on a slope with pyrite (**a**) and on a flat surface without pyrite (**b**). Substrate surface in A is partly armoured with quartz pebbles. Acidification by oxidation of the large patch of pyrite (outlined with *red dashed line*) has resulted in dissolution of Fe oxyhydroxide stains on quartz pebbles, so pebbles near the pyrite are white, not brown. Substrate surface in B is coated with moss, in which seeds from a planted *G. littoralis* shrub (background) have germinated (foreground). Several naturally colonising *L. scoparium* seedlings have also established

Natural plant colonization of exposed substrate after site preparation was first apparent at locations that, because of chemical or physical effects, were not amenable to healthy growth of plantings (Rufaut and Craw 2010). The most prominent species that colonized at this time is *L. scoparium* and *K. ericoides,* particularly in planted areas adjacent to the retained bush patches (Fig. 4b; Rufaut and Craw 2010). These occurred on the in situ waste stacks in the west and east, with the more isolated restructured central stack showing a lower rate of manuka and kanuka invasion. Instead here, adventive weeds are the common natural colonisers; gorse, lupin, and broom. On average, natural shrub colonisation accounts for more canopy cover (35 %) of waste rock plots than planted specimens (20 %) but not on loess (Fig. 5a). Natural shrubs (up to 2 m height) have established on waste rock in micro-sites, initially in shallow rills (Rufaut and Craw 2010) and later around the base of plantings (Fig. 4b). Manuka and kanuka have been able to establish on all substrates within the range of the pH continuum, from 2 to 5. On loess, the natural plant cover is also recovering, mainly with tree fuchsia, manuka, and kanuka, and in combination with the plantings, has successfully displaced gorse at the western end of the site.

Remnant Unvegetated Patches

Some waste rock patches persistently resisted the introduction of plants, despite repeated replacement of dead specimens. These patches are typically 10–100 m across,

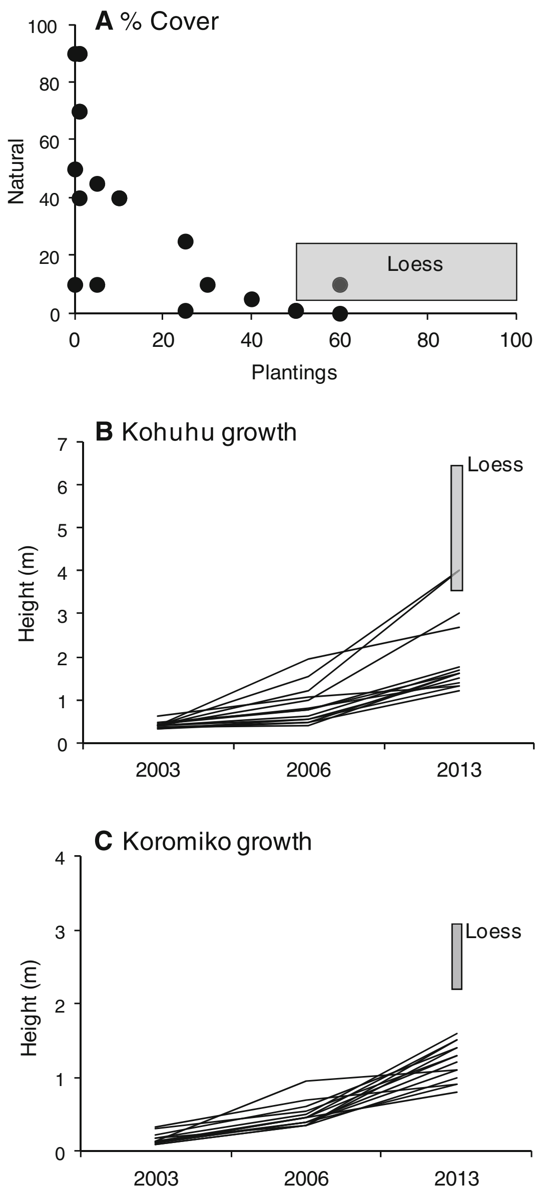

Fig. 5 **a** Increase in % canopy cover for plantings and natural colonisation on waste rock and loess (2013). Data are based on visual estimates of % of the ground covered by a shrub/tree canopy. **b**, **c** Annual vertical height growth (m) for planted tree species (**b**, kohuhu) and planted shrub species (**c**, koromiko). Four kohuhu specimens showing elevated growth are located on the bench of eastern waste piles in Fig. 1

and are enriched in either pyrite-bearing quartz conglomerate (Fig. 4a), or coal debris (Fig. 6), mostly the latter. These areas, which occur irregularly across the mine site, are now surrounded by more fully vegetated areas (Fig. 6).

Coal-rich substrate typically has a low pH (down to 2.5), with the lowest pH in the central zones and progressively higher pH towards the margins (Fig. 6). The area of Fig. 6, and immediately north of it, has semi-continuous patches of coal-rich substrate with a pH below 4 (Fig. 7a), and the few surviving introduced plants are stunted and unhealthy, many with yellow leaves. In contrast, immediately adjacent substrate patches, while still coal-bearing, have pH > 4 (Fig. 7a). In addition, there is a strong contrast in boron contents of these substrates, with the low pH coal-rich material having greater B contents (up to 7 mg/kg) than the coal-bearing substrates (Fig. 7a). Despite these geochemical hindrances to introduced plant survival, natural colonization of both coal-rich and coal-bearing patches has been steadily occurring, principally by *L. scoparium* and *K. ericoides*, reaching between 50 and 90 % canopy cover in 10 years. These specimens contain significantly lower B content in their foliage (sampled and analysed by methods described by Craw et al. 2006) than plantings in the first year of introduction (Fig. 7b). On one coal-rich area, natural colonisation has been additionally hindered by ongoing impacts of wind exposure and surface erosion.

Plants introduced on pyrite-bearing quartz conglomerate on the acid slope in the centre of the mine site (Figs. 1a, 4a) have also repeatedly died, apart from a few surviving shrubs on fly ash- and limestone-amended parts of this slope. Hydroseed establishment was also unsuccessful, so the area has remained predominantly bare since rehabilitation began. Like the coal-rich patches, pH is lowest in the central zones and higher on the margins. Branches of manuka with seed capsules, collected from bush residuals, have produced successful seed germination to date, on the lower parts of the affected area. In 2013, these seedlings were up to 20 cm high, and have survived flushes of AMD during periods of heavy rainfall. The boron content in their foliage, 33 mg/kg, is similar to levels in natural manuka growing on non-acid quartz and the coal rich/coal bearing substrates elsewhere (Fig. 7b).

Ecosystem Development

On loess, the mass planting programme has successfully fast-tracked the development of the desired forest-type habitat. Regeneration of other indigenous species from the natural seed bank has enhanced the diversity of this new loess vegetation and diversity of invertebrates (Table 2). Young, second-generation seedlings produced by the plantings indicate the start of an understory developing for future vegetation across this part of the mine site. This native regeneration occurred despite abundant resprouting of gorse on the loess substrate, with some ongoing intervention with herbicides and physical clearance by site managers.

On waste rock, the revegetation success has been more variable. Currently, there are three main types of habitat; areas, dominated by: (a) successful plantings forming a young forest-type flora, similar to the loess above, (b) poor plantings forming a stunted and senescing shrubland, and

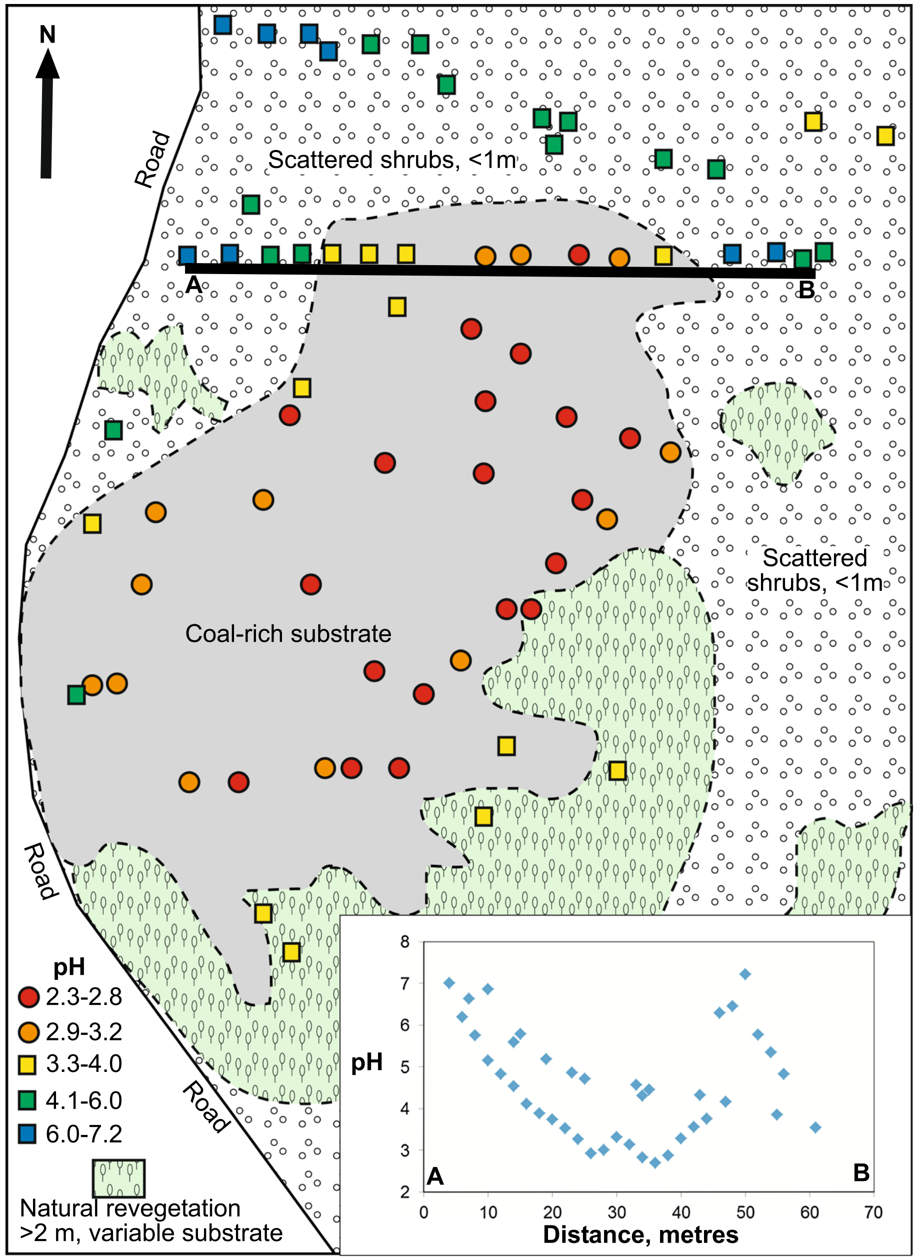

Fig. 6 Map of substrate pH and vegetation around a poorly vegetated patch of coal-rich waste rock (see Fig. 1b). The pH variations along a more detailed transect across part of the coal-rich patch (*line A–B*) are shown in the *inset*

(c) natural colonisation of an expanding seral shrubland. For the first habitat type, second-generation seedlings produced from planted individuals are common on substrate with a low grass cover (Fig. 4b). For the second habitat type, a slow deterioration of plantings over time, combined with only rare second-generation seedlings, indicates that the planted species will be displaced from future vegetation development. Progressively, the habitat is changing towards a naturally-colonised manuka, kanuka, and adventive species shrubland. The third habitat type has undergone the same revegetation transition from planted to naturally-colonised species as the second type, but over a shorter time period, within the first three years of planting. Natural colonisation by mainly manuka and kanuka now form an expanding vegetation cover on around 30 % of waste rock. Manuka and kanuka stem density is greater than in areas with plantings, up to 4/m^2, and there have been multiple cohorts of seedling establishment since rehabilitation began. Young seedlings of mature forest canopy species (e.g. kamahi) are beginning to establish among the manuka and kanuka, indicating a sustainable pathway of future habitat development (Table 2).

The evolving ecosystems of the three main waste rock habitat types, and on the loess substrate, are characterised by distinctly different invertebrate assemblages. Due to the longer establishment of historic vegetation, loess had a

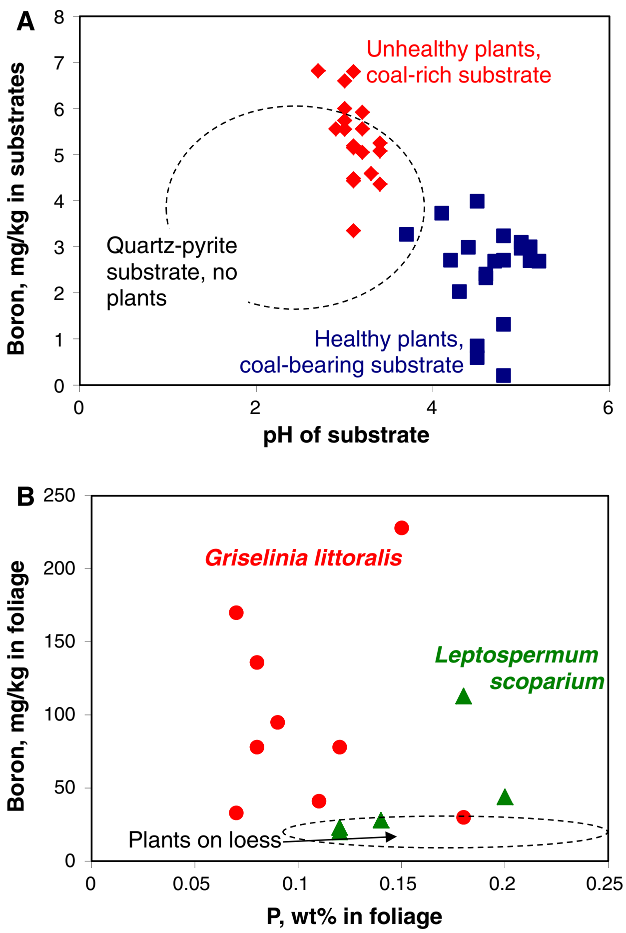

Fig. 7 Chemical comparisons of substrates and plants on coal-rich and adjacent coal-bearing substrates on waste rock in the area of, and to the north of, Fig. 5. **a** Substrate pH and boron contents. **b** Phosphorus and boron contents of foliage in two shrub species on the two substrates in 2004. Values for plants surviving in 2013 are shown in *black*. Typical compositions of plants on loess are shown for comparison (*dashed ellipse*)

higher baseline diversity of invertebrates than the waste rock. Eighteen months after planting, there was no significant differences between the general structure of surface-dwelling invertebrate assemblages on the loess compared to a nearby mature forest, based on ordinal abundance (Rufaut et al. 2010). However, the most abundant group sampled, Collembola, was significantly higher on planted loess than in the mature forest (Rufaut et al. 2010). Recent taxonomic work shows that there appear to be more adventive species of Collembola in the loess habitat than in the mature forest, which contains at least one family that is dependent on intact native vegetation (Table 2).

On waste rock, the baseline condition of unvegetated surfaces with minimal historic plant cover was virtually devoid of surface-dwelling invertebrates (Rufaut et al. 2006). After the introduction of a hydroseed ground cover, Collembola numbers increased to densities up to 200 individuals/soil core (1.1/cm^2) within 6 months but the relative abundance of other taxa remained low (Rufaut et al. 2006). The proportion of Collembola fell as other taxonomic groups (re)colonised and increased in abundance following population establishment and recruitment (Fig. 8). This process occurred more rapidly in the waste rock habitats containing healthy plants with good growth rates and regeneration. Actual numbers of invertebrates were consistently significantly lower in the naturally colonised areas than in planted vegetation (Rufaut et al. 2010). The best-established naturally-colonised habitat (c, above) also contains a distinctly different type of Collembola (springtails) species assemblage from the planted areas that are dominated by adventive species, shared with loess (Table 3). A second group for which species determinations were made, Coleoptera, shared few species between loess and waste rock (Table 3). Rove beetles (Staphylinidae) were particularly common on waste rock, where they formed different assemblages at each sampling location (Table 3).

Discussion

Effects of Low pH and Boron on Revegetation

Most or all of the planted native species had high mortality or failed to thrive on substrates with low pH (<4) and/or high boron. In contrast to the planted specimens, naturally-colonizing manuka and kanuka appear little affected by B concentrations in the substrate or the acidity. Artificially raising the pH of planting plots with high B, such as with fly-ash or limestone, appears to increase plant survival and height growth, suggesting that pH is the principal underlying limiting factor for revegetation of the mine site waste piles (Borden and Black 2005). Evidence gathered in the early stages of this rehabilitation programme suggested that B toxicity was negligible (Craw et al. 2006). At this more advanced stage, there are now many plants in the waste rock piles that have poor growth and limited shoot development that could be attributed to B toxicity. However, it is not yet possible to separate this effect from general nutrient deficiency in these quartz-rich substrates. Available P and N typically decline at pH < 6 and metal solubility increases with pH < 5 so that both plant toxicity and nutrient deficiency can potentially be inhibiting ill-adapted plant growth at the mine site. Hence, while pH appears to be the dominant limiting factor for vegetation establishment, we cannot discount other factors such as nutrient availability and boron toxicity.

Water turnover time in Main lake is $\approx$2 years (Begbie et al. 2007). Consequently, the water runoff quality effects of various engineering activities, such as weed removal, site re-profiling, and lime addition, have long since passed through the drainage system. We attribute the general pH rise in Main lake (Fig. 2b) to the on-going revegetation and

Table 2 Comparison of diversity of biological colonisation of variably revegetated waste rock and well-revegetated loess substrate ten years after rehabilitation began

	Waste rock with plantings	Waste rock with natural vegetation	Loess
Nematoda (flatworms)	Common	Common	Common
Collembola (springtails)	Abundant	Abundant	Abundant
Coleoptera (beetles/weevils)	Common	Common	Common
Hemiptera (plant bugs)	Common	Rare	Rare
Heteroptera (true bugs)	Rare	Rare	Common
Hymenoptera (wasps/ants)	Rare	Common	Rare
Annelida (worms)	Rare	Rare	Rare
Chilopoda (centipedes)	Rare	Rare	Rare
Diplopoda (millipedes)	Rare	Rare	Common
Amphipoda (landhoppers)	Common	Common	Common
Isopods (woodlice)	Rare	Rare	Common
Aranneae (spiders)	Common	Common	Common
Acari (mites)	Abundant	Abundant	Abundant
Opiliones (harvestman)	Rare	Common	Rare
Moss	Rare	Common	Rare
Lichen	Rare	Common	Rare
Grass[a]	Common	Rare	Common
Seral forest woody species	Rare	Abundant	Common
Mature forest woody species	Rare	Common	Abundant

[a] Rank pasture grass and hydroseed

associated ecosystem development. We suggest that the new vegetation covered much of the near-surface pyrite, limited acidic surface runoff, and facilitated water retention in the substrates, which in turn hindered pyrite oxidation (Begbie et al. 2007). Importantly, the new vegetation was accompanied by development of a functioning ecosystem that appears to be self-sustaining.

Natural Colonisation by *L. scoparium* and *K. ericoides*

Natural colonisation by manuka and kanuka is primarily controlled by seed dispersal opportunities, principally islands of intact, early-established vegetation. Our observations suggest that if manuka and kanuka seed can disperse into an area, they will successfully colonise, regardless of the chemical conditions in the substrate. Establishment begins in troughs of moisture and fine material accumulation caused by surface erosion of waste stacks, which is similar to observations by other authors (e.g. Frouz et al. 2011; Topp et al. 2001). It then proceeds to expand from these locations as the manuka and kanuka shrubs modify their environment by changing pH, moisture content, and nutrients levels (Rufaut et al. 2006). The effect of depressions and elevations of surfaces are usually pronounced in the early and intermediate stages of succession, such as are described here, and disappear once the waste rock is covered with vegetation and a humus layer develops (Frouz et al. 2008). Manuka and kanuka leaves and stems are tough and form a litter layer that is likely to break down at a slower rate than other species (Harris et al. 2004), hence delaying the formation of biological soil.

Seed from local ecotypes has been the key to successful natural colonization; there was poor survival of imported nursery transplants of manuka. A similar effect was also observed by Baasch et al. (2012), who found local native grassland species performed better than cultivars on lignite-mined surfaces. Furthermore, highly successful natural colonisation by manuka and kanuka has played a role in the extensive mortality of plantings on waste rock. Plantings introduced near bush remnants have been locally outcompeted by the rapid growth of dispersed seed into cleared ground. Manuka and kanuka require high light levels for early seedling establishment so the land preparation, ground cover clearance, and pine tree removal apparently suited their physiology. The expansion of these species across the waste stacks is an effective example of inadvertent *directed succession* in rehabilitation practice, where early seral species respond positively to active environmental disturbance (Bradshaw 2000). Adaptations to local conditions of the mine site, via a long history of natural environmental perturbance, has ensured the colonization success of manuka and kanuka in this catastrophically disturbed anthropogenic setting. Copious amounts of small, light seed are irregularly released soon after flowering, and seedling density is greatest on the edge of already established patches (Esler and Astridge 1974). In settings where these species thrive, addition of introduced plantings was of little or no advantage for establishment of ground cover at this site.

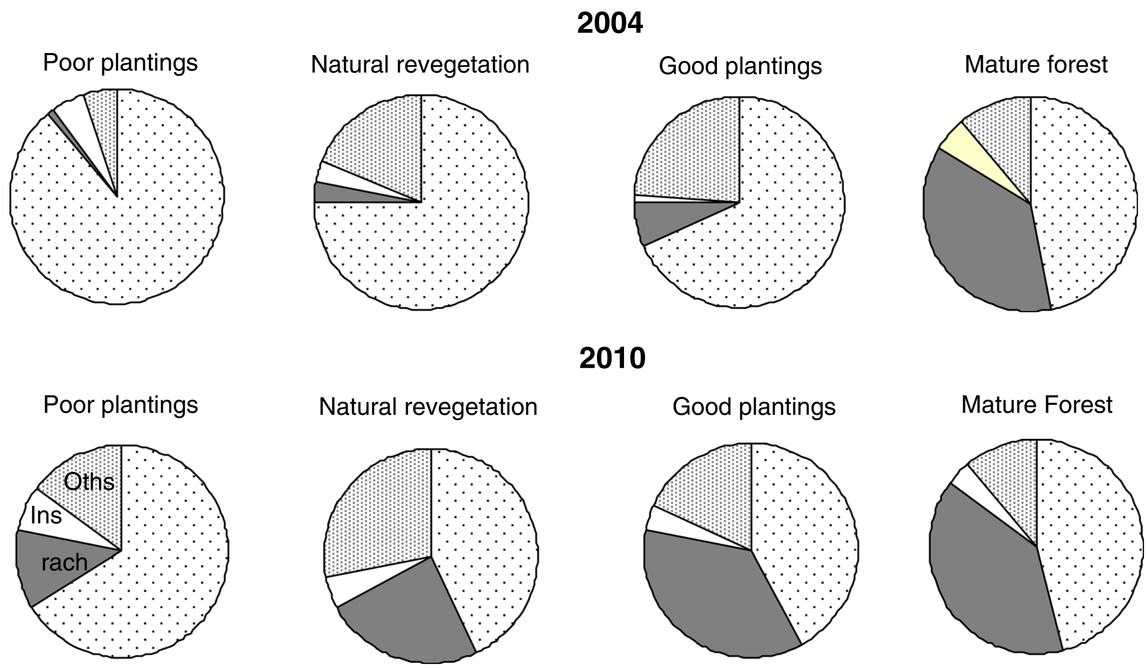

Fig. 8 Invertebrate assemblage development from baseline values in 2004 to 2010, on variably revegetated waste rock. Mature indigenous forest included as a potential benchmark for assemblage structure. Pie groups are proportion of total count: Ins = Insects; Arach = Arachnids; Oths = all other taxon

Table 3 Comparison of some Collembola and Coleoptera species in 7 year waste rock and > 40 year loess habitats, 10 years after rehabilitation began

	Waste rock with plantings		Waste rock with natural vegetation	Loess
	Successful plantings	Poor planting success		
Collembola species				
Total	**2**	**3**	4 + **1**	**2**
Shared with other habitats	**2**	**1**	**1**	**2**
Coleoptera species				
Total	14 + **1**	2 + **1**	4	4
Shared with other habitats	2	0	2	1

Bold numbers correspond to adventive species

Adventive weeds have been unable to compete with manuka and kanuka, as the latter two species are apparently better adapted to the low nutrient status of the site. Elevated boron contents and low substrate pH also hinder adventive species invasions, to the advantage of manuka and kanuka colonisation. The most chemically extreme substrates at the mine site favour native species, and this is expected to persist throughout the trajectory of forest succession in the future. Our findings therefore do not agree with Prach and Hobbs (2008), who suggest that natural spontaneous succession decreases towards the stress end of the gradient when environmental conditions are extreme.

Development of Ecosystems

Initially, the primary source of waste rock heterogeneity was in the variation of original geological substrate and waste stack morphology related to erosional processes. Variability in the establishment of vegetation has provided a more recent source of habitat heterogeneity for colonizing invertebrates. Biological community succession is important in the ecological reconstruction of land abandoned after mining, where synchronisation of changes between substrate, vegetation, and substrate fauna typically exists (Frouz et al. 2008). Vegetation forms a cap over mineral soils but the underlying properties of the original substrate can still affect invertebrate recovery, especially for ground-dwelling taxa (Hendrychová et al. 2012). Substrate-invertebrate relationships are not yet quantified at Wangaloa but the extreme condition of substrate surfaces (above), where planted vegetation has failed, may be one reason for the observed lower invertebrate population density in natural manuka–kanuka colonisations. A contributing factor highlighted in other studies (e.g. Frouz et al. 2008; Tropek et al. 2010) is also the perseverance of bare ground around 'islands' of manuka–kanuka, which lowers the overall supply of resources to invertebrates, such as food and shelter, in a given area. However, the presence of bare ground can promote habitat specialist species and biodiversity at abandoned mine sites (Hendrychová et al. 2012; Tropek et al. 2012), whereas topsoil addition to abandoned mines promotes vegetation ruderalisation and invertebrate biodiversity reduction (Mudrák et al. 2010; Tropek et al. 2013). The species richness of the dominant group at Wangaloa, Collembola, agrees with the results from these studies.

Recently, there has been a shift of emphasis from diversity indices to life strategies of colonizing invertebrate species to better understand ecosystem recovery (Tropek et al. 2010). Sustainability of vegetation is a key factor in controlling mine water infiltration that leads to AMD, and this sustainability is largely determined by invertebrate detritivores, herbivores, and predators (Keesing and Wratten 1998). The trophic diversity of invertebrates at Wangaloa has developed considerably since the early days of rehabilitation in response to increasing species diversity. However, unresolved taxonomy and unfamiliarity with indigenous species' natural history limits quantification of trophic-level developments at the mine site. Our general observations in the field suggest that due to a greater relative increase in the proportion of non-Collembola taxa over time in natural manuka–kanuka colonization compared to planted vegetation, invertebrate diversity in a natural seral plant cover is recovering at a faster rate than in anthropogenic vegetation. This does not appear to have been observed before in other studies although it is well known that natural successions produce different invertebrate communities alongside technical reclamation (e.g. Hendrychová et al. 2012; Tropek et al. 2010). The accumulation of organic matter via plant litter seems to be a major factor structuring initial invertebrate recovery on mineral soils (Boyer et al. 2011; Frouz et al. 2008) but in the manuka–kanuka shrublands, moss and lichen form a greater component of ground cover than the small, tough leaves and stems from these two species. We interpret a more rapid invertebrate convergence on the mature forest benchmark to be a function of the dynamic nature of the seral vegetation, with higher structural heterogeneity than in the planted vegetation showing delayed regeneration and understory development. The underlying importance of habitat heterogeneity in supporting biodiversity development in post-mining landscapes is a common conclusion in other similar studies (e.g. Brändle et al. 2000; Frouz et al. 2008; Tropek et al. 2010).

Intact remnants of existing vegetation were discussed above as critical reservoirs for plant species colonization of adjacent waste rock. Proximity and connectivity of intact habitat to new vegetation also underlies the rate of ecosystem development by determining the rate of invertebrate recovery (Watts and Didham 2006). On waste rock devegetated for active rehabilitation, surviving invertebrates from an earlier succession may also be represented in the present day fauna (Rufaut et al. 2010). Naturally colonized manuka–kanuka on waste rock was located closer (typically < 50 m) to more remnants of a previous vegetation cover than sampled areas of planted vegetation, yet invertebrate numbers have been shown to be, on average, twice as high in the latter (Rufaut et al. 2010). Habitat isolation, therefore, does not appear to contribute to the documented variations in the rates of invertebrate assemblage development. The invertebrate assemblages on waste rock shared few Coleoptera species with the habitat remnants, despite the majority of species being forest generalists with dispersal ability. This suggests surrounding habitat types other than remnants are also contributing sources to the species pool of colonizing invertebrates and that habitat suitability is a major factor influencing establishment of invertebrate populations at the mine site.

Conclusions

Early attempts at establishment of vegetation cover at the closed Wangaloa coal mine were unsuccessful, and mine waters became acidified where they passed over or through pyrite-bearing waste rocks. This water–rock interaction also mobilised boron from coal fragments, resulting in elevated levels of dissolved B in the mine water. An intense programme of introduced plantings of a range of native species was intended to develop a more complete cover on the site, leading to long-term sustainable ecosystems that would inhibit water–rock interaction and therefore ameliorate the AMD. No soil had been stockpiled at the site during mining, so planting occurred directly into overburden material at the mine site, with minor topsoil use. This planting programme was partially successful, especially on loess-rich substrates, which have relatively high nutrient levels and higher pH than other available substrates on the site. Planting was less successful on quartz-rich and coal-rich substrates, especially those with low pH and elevated B contents. Nevertheless, the progressive establishment of the vegetation, effectively supplemented by natural colonisation over the past 12 years, has coincided with long-term raising of the pH of mine site discharge waters from $\approx$4.5 to $\approx$5.6. We attribute this long-term pH change to establishment of the vegetation, and this change appears to be sustainable without further intervention.

Natural colonisation by local shrub species, manuka and kanuka, has been extremely effective at providing the ecosystem services of ground cover and faunal development on substrates in which introduced plantings failed to thrive. These naturally colonising shrubs appear to provide both short-term (e.g. rapid ground cover) and long term (ecosystem stability and functioning) goals for rehabilitation at this site. Natural colonisation onto the waste stacks was facilitated by the presence of early-developed vegetation islands scattered over the mine site. These islands consist of local ecotypes of manuka and kanuka, which readily became established on bare ground, irrespective of the underlying chemistry. This natural colonisation was more effective than introduced plantings at providing a base for development of sustainable ecosystems.

Ongoing monitoring has highlighted potential interactions between plant performance and wider ecosystem development. Impaired growth and biomass production of planted primary vegetation in marginal substrates was associated with a delay in plant reproduction and invertebrate assemblage development. Natural vegetation colonisation compared to plantings (on virgin substrate) promoted more rapid ecosystem development via indigenous species and a faster return of functional attributes (regeneration, dispersal) than in the planted habitats. Planting has fast-tracked forest succession at moderately acidic sites but for the dominant invertebrate group, Collembola, more specialized species were contained from extreme natural successions by low pH and low nutrient status. Spontaneous succession is not popular as a process for achieving desirable land rehabilitation, yet our study supports other authors who have urged greater consideration of reserving land for natural processes. Better initial recognition of the natural potential could have streamlined active rehabilitation and enhanced mine water quality at the mine site.

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