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RESEARCH

Identification of potential invertebrate bioindicators of restoration trajectory at a quarry site in Hunua, Auckland, New Zealand

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Abstract: In 2009, the New Zealand company Winstone Aggregates initiated a restoration planting scheme to mitigate the ecological damage caused by mining at the Hunua Quarry, near Papakura, New Zealand. By employing several collection methods (pitfall traps, artificial cover objects, litter samples, weta motels), and comparing invertebrates found in the restoration area with those found in adjacent areas of mature forest and unplanted grassland, this study aimed to identify invertebrates that could be used as bioindicators of restoration trajectory. Multivariate analyses (NMDS, ANOSIM) indicated that the composition of some invertebrate assemblages (e.g. beetles, mites, springtails) may be used to determine whether assemblages in the restoration areas had converged towards those in the mature forest. The survey also identified specific taxa (e.g. cave weta, spiders) that were more abundant in, or exclusive to, the mature forest, and identified other groups (e.g. exotic earthworms, slugs, snails) that typified the grassland invertebrates. Thus, in future invertebrate assessments, an abundance of the former taxa, and lack of the latter, would provide an indication of restoration 'success', and assist in monitoring the trajectory of the invertebrate community from that found in the exotic grassland towards an assemblage more typical of the native forest habitat of this region.

Keywords: bioindicators, ecological monitoring, invertebrate conservation, restoration success

Introduction

Numerous environmental regulations now dictate how mining and quarrying companies must mitigate environmental damage caused by their activities, and restoration of spent mining and quarrying sites constitutes a major element of present-day applied ecological activity (Prach & Tolvanen 2016). Mining site restoration is mandatory in Australia (Jansen 1997), and federal USA laws ensure that closed mine sites undergo terrain reestablishment, topsoil replacement and restoration planting (Advameg 2016). In New Zealand, land rehabilitation has been a mining permit requirement since the 1980s, and the Resource Management Act 1991 stipulates that environmental damage caused by mining needs to be 'mitigated, avoided or remedied' (RMA 1991; Nathan 2012).

Ecological restoration not only aims to enhance the aesthetic value of a degraded site, but also improve soil quality and stability, and produce permanent vegetation stands typical of neighbouring undisturbed land (Prach & Tolvanen 2016). More specifically, ecological restoration aspires to increase biodiversity, re-establish key components of flora and fauna and, in doing so, restore the structure and functioning of the lost ecosystem (Longcore 2003; Cooke & Suski 2008). Thus, to appropriately restore an area the entire ecosystem must be considered, and not only the floral components that can be reinstated by planting initiatives (Keesing & Wratten 1998).

Invertebrates are a vital, functional component of most ecosystems and can make major contributions to local and regional biodiversity. Accordingly, several invertebrate taxa are recommended for use as monitoring tools in the evaluation of post-mining restoration success including: Collembola, Acari (Greenslade & Majer 1993; Andres & Mateos 2006), Hemiptera (Orabi et al. 2010), Lumbricidae (Majer et al. 2007a; Boyer et al. 2016), Coleoptera (Parmenter & MacMahon 1987), Formicidae (Majer et al. 2007b) and Lepidoptera (Holl 1996). Although many studies focus on a single higher invertebrate taxon, often the patterns observed with one taxon do not reflect those seen in others when comparing restored and reference communities (Longcore 2003). Therefore, a 'multi-taxon' approach to invertebrate bioindicators, often associated with multiple sampling methods, is frequently advocated (e.g. McGeoch 1998; Majer et al. 2007a; Davis & Utrup 2010; Řehounková et al. 2016).

Winstone Aggregates, New Zealand's largest aggregates provider, supplies materials for concrete manufacture and major infrastructure developments (Winstone Aggregates 2018). In 1955 the company bought Hunua Quarry, located in the Hunua Ranges Regional Park (Titchall 2015). To comply with current

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New Zealand legislation, the company has proceeded with ecological restoration as a means of reconciling environmental damage caused by its mining activities. Native plant species are grown in an on-site nursery, from seeds sourced in the Hunua area, until large enough for planting out. At the time that this study was undertaken, over 140 000 plants had been planted with an aim of generating an area of new forest to replace that removed during quarrying (Winstone Aggregates 2018). This study has adopted a space-for-time substitution approach, using a variety of collecting methods, to compare the abundance and diversity of invertebrates in the replanted area with those found in neighbouring, undisturbed mature forest, which we consider an appropriate reference state for the forest ecosystems in this area (Pickett 1989; Walker et al. 2010). Unrestored grassland was also sampled to assess whether the replanting process had caused a shift in the invertebrate fauna away from the highly modified habitat which formed the basis of the restoration area 6 years earlier.

Before a multi-taxon bioindicator approach can be developed, it is important to identify which individual invertebrate species show clear, statistically significant responses, to habitat restoration. The primary aim of the study was to identify invertebrates demonstrating potential as bioindicators of successful restoration trajectory by applying the following criteria: (1) show statistically significant ($P < 0.05$) differences in abundance among the three habitat types; (2) show a positive or negative unidirectional shift in abundance from the unplanted grassland site to the mature forest via the restored area; and (3) be sufficiently abundant (at least 10 specimens recorded) to provide meaningful results.

Additionally, multivariate analyses were performed on the data for some species-rich groups (Coleoptera, Collembola, Acari) to confirm that differences in the faunas among the three habitats occurred, and ascertain whether this approach could identify convergence of restoration and reference habitats at the scale of whole invertebrate assemblages. Finally, as one of the frequent aims of restoration is to increase biodiversity of degraded land, we calculated numerous summary biodiversity indices to examine whether sensible and consistent patterns occurred across the restoration sequence for multiple taxa.

Methods

Study area

The Hunua Ranges (Papakura, South Auckland) are a series of sharp-slanted ranges (up to 688 m high) formed from blocks of uplifted greywacke. The Ranges consist of over 20 000 ha of native forest where tawa podocarp, kauri-hard beech and taraire forest are the dominant classes of vegetation. Broadleaf forest species include taraire (*Beilschmiedia tarairi*), puriri (*Vitex lucens*), pukatea (*Laurelia novae-zelandiae*), swamp maire (*Syzygium maire*) and kahikatea (*Dacrycarpus dacrydioides*), with areas of secondary forest dominated by mapou (*Myrsine australis*), kānuka (*Kunzea robusta*) and tree fern (*Cyathea* and *Dicksonia* spp.) (Lindsay et al. 2009). The area receives 1900–1950 mean annual sunshine hours, and the climate tends to be humid and mild with few extremes of weather, with 50% higher mean rainfall (1400–2000 mm annually) and 2–4°C lower mean annual temperature (at 12°C) than lower lying areas of Auckland (Chappell 2013).

The study area was adjacent to the operating quarry at Hunua (37° 5'14.32"S 175° 0'9.62"E) and consisted of three areas with different vegetation status: a mature forest, an ecological restoration replanting area, and an unplanted grassland (Fig. 1). The mature forest area (45 ha) consisted of primary or secondary growth forest containing the native tree species described above. The restored area (39 ha) was planted with 24 local eco-sourced tree, shrub and sedge species (see

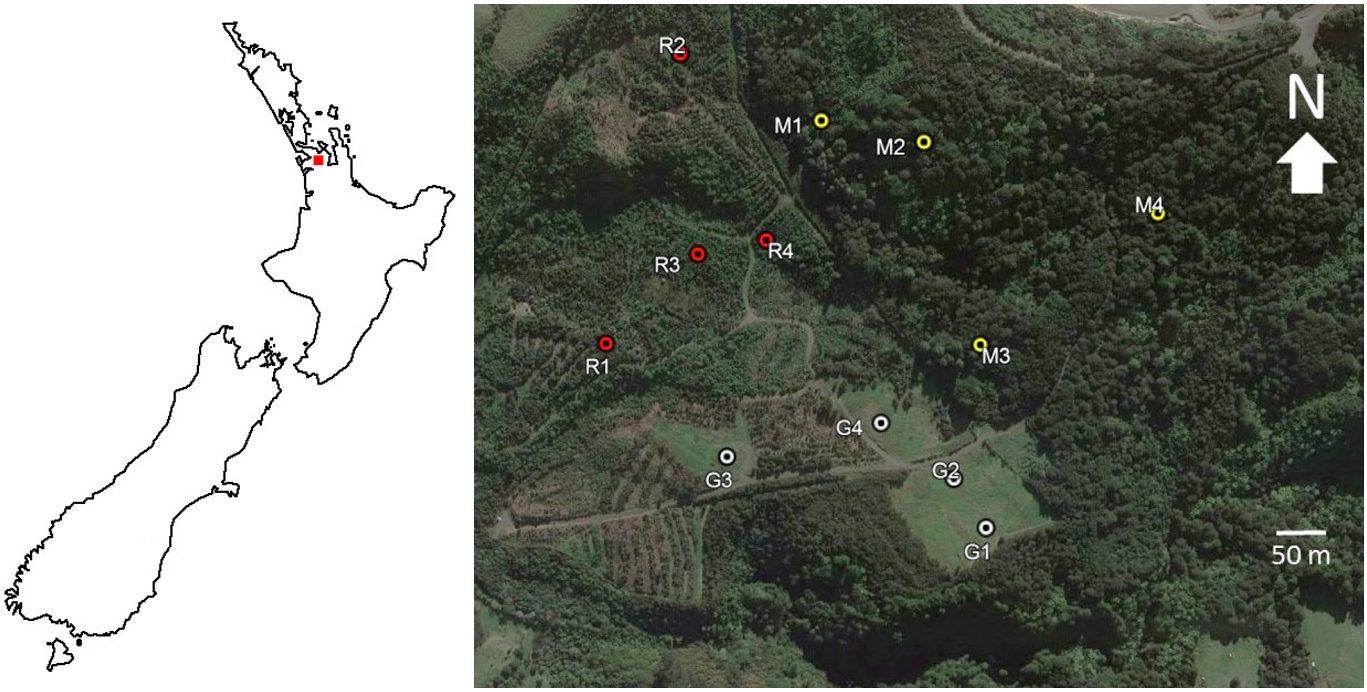

Figure 1. Map of New Zealand showing general location of Hunua, and aerial view of study site (from Google Earth) showing the location of the unplanted grassland site (G; white circles), restoration site (R; red circles) and mature site (M; yellow circles) at the Winstone Aggregates Hunua Quarry (37° 04′ 48″ S 174° 59′ 44″ E).

Table S1 in Supplementary Material): between 2009 and the end of 2014 over 140 000 specimens were planted in this area. By 2014, the trees were approximately 3 m in height and some canopy closure was evident. The unplanted grassland area (2 ha) consisted of a mixture of exotic grass species, dominated by cocksfoot (*Dactylis glomerata*), which is un-grazed although occasional control of gorse is undertaken.

Invertebrate collection

To sample invertebrates, four independent sampling stations, at least 50 m apart, were established in each of the three vegetation areas described above (Fig. 1). The whole study area was within an area of approximately 400 × 500 m, and the overall proximity of the sampling stations minimised the potential influence of environmental factors such as soil type, aspect, slope, rainfall and temperature on invertebrate abundance and activity. Similarly, the sampling stations were all positioned to face north to remove any effects of orientation and aspect on the invertebrates collected.

At each sampling station, invertebrates were recorded using four methods: weta motels (four motels per station); pitfall traps (four traps per station); artificial cover objects (four wooden discs per station); and leaf litter extraction (one sample per station). For the first three of these methods, the animals recorded in each of the four sub-samples were pooled to give a single value for each independent sampling station.

Weta motels are artificial timber refuges for weta (Orthoptera: Anostostomatidae & Rhaphidophoridae) and other invertebrates, and resemble a bird nest-box in their construction (Bowie et al. 2006, 2014; Hodge et al. 2007). Weta motels were attached either to stakes or trees depending on whether a suitable tree was available. The motels were placed out on 19 November 2014 and assessed for occupation on 18 December 2014 and 19 January 2015. Weta resident in the motels were identified *in situ* (by MB).

Pitfall traps consisting of plastic cups (69 mm diameter, depth 94 mm) were sunk into the ground using a soil corer (which minimised ground disturbance) and 100 ml monopropylene glycol placed in each trap as a preservative. Square plastic roofs were put over the cups and held down by wire, leaving a gap of 15 mm to prevent entry of rain and debris but allowing invertebrates to enter the trap. The pitfall traps were placed out on 19 November 2014 and retrieved 30 days later on 18 December 2014.

Near each set of weta motels and pitfall traps an area was cleared to reveal bare soil. Wooden discs (400–600 mm diameter) were placed in these spaces to act as artificial cover objects or 'cryptozoa boards', a system previously used to survey invertebrates in disused quarries, ecological reserves and restoration plantings (Bowie & Frampton 2004; Hodge & Standen 2006; Hahner & Bowie 2013). The discs were placed out on 19 November 2014 and were assessed for invertebrates sheltering under them on 18 December 2014 and 19 January 2015. The records from the two dates were pooled. A single leaf litter sample (300 × 210 mm) was collected from each sampling station on 19 November 2014. These litter samples were placed into a Berlese extractor for one week, using 40 Watt bulbs as a light/heat source, and specimens collected into sample vials containing 70% ethanol.

Specimen identification

Weta in the weta motels and the animals observed under the wooden discs were identified *in situ* where possible. All of the specimens collected from the leaf litter samples and the pitfall traps were preserved in 70% ethanol and returned to Lincoln University, New Zealand, for processing. In order to measure invertebrate diversity, specimens found in the leaf litter samples were initially separated into recognisable taxonomic units (RTU), with digital photos used as a reference guide to distinguish different RTUs. Insects from the pitfall traps were separated into major taxonomic divisions, and the Coleoptera subsequently identified to species (or RTUs).

Statistical analysis

To identify any statistically significant differences in abundance of individual taxa among the three vegetation classes we used non-parametric Kruskal-Wallis tests (due to the prevalence of zeroes in the final data sets), and then inferred differences between pairs of treatments by visual inspection of mean values. The large number of taxa involved in the survey meant that a high number of tests were performed, increasing the chance of Type I statistical errors. However, as these significance tests were used as a screening process to identify potential bioindicator taxa, we wished to avoid non-detection of potentially useful results (Type II statistical errors). Therefore, we did not correct for multiple testing and retained the use of $P < 0.05$ level as an indication of statistically significant differences.

For the beetles obtained in the pitfall traps, a number of summary indices describing ecological diversity were calculated based on the whole catch obtained in each vegetation class. These were: number of families, number of species (S), the Shannon-Weiner Index (H'), evenness (J'), Simpson's diversity index (SDI), Simpson's evenness index (SEI), and species dominance. The indices were calculated as:

$$H' = -\Sigma p_i \times \ln(p_i) \quad (1)$$

$$J' = H' / \ln(S) \quad (2)$$

$$SDI = 1 - \Sigma p_i^2 \quad (3)$$

$$SEI = SDI / [1 - (1/S)] \quad (4)$$

where p_i was the proportion of individuals consisting of the ith species and S was species richness. Dominance was calculated as p_{max}, where p_{max} was the proportion of individuals represented by the most abundant species in the collection. To compare diversity (H' and SDI) between each pair of habitat types, a permutation test was used, where the data from two samples were pooled and then randomly assigned to two groups (Species Diversity and Richness Package v4, Pisces Conservation Ltd, UK; 2007). The proportion of random permutations (1000) that resulted in a difference in diversity as great as or greater than that found between the original samples was then used to provide a probability that the two samples had equal diversity.

The species-sample matrices obtained for the pitfall-collected beetles and litter-collected mites and springtails were extremely sparse, with the majority of cells equal to zero. To avoid samples appearing similar due to a prevalence of shared absences (see Legendre & Gallagher 2001), we compared the compositions of the faunas among the three vegetation types using non-metric multidimensional scaling (NMDS) and analysis of similarity (ANOSIM) using square-root transformed data (Community Analysis Package v4, Pisces Conservation Ltd, UK; Henderson & Seaby 2008). As ANOSIM can confound differences among groups with

differences in scatter within groups, a multivariate homogeneity of dispersion test (PERMDISP) was performed on each data set (PRIMER v7 + PERMANOVA software, PRIME e, Albany, NZ; Warton et al. 2012). For the NMDS, a Bray-Curtis similarity measure was employed and principal components analysis used to give initial positions of the samples. For the beetles, these multivariate procedures were performed three times, on matrices including: abundance of all species, only species with total abundance ≥4 across measured sites, and abundance of families.

Results

Weta motels

Thirty Auckland tree weta (*Hemideina thoracica*) were observed in the motels over the two observation dates, 27 (90%) of which were recorded at the restored site (Table 1). One cave weta (*Neonetus* sp.) was observed on each assessment date at the mature forest. With this collection method, neither of these species met all our required criteria to be considered a potential bioindicator of restoration trajectory.

Wooden discs

A variety of invertebrate taxa was found under the wooden discs, although few taxa were found in high numbers or with any consistency in each vegetation category (Table 2). Harvestmen (Opiliones), exotic earthworms (Lumbricidae) and the exotic tiger slug (*Limax maximus*) were either exclusively, or predominantly, found in the restoration area, and thus did not represent viable bioindicators of restoration trajectory.

However, the other exotic slugs (*Arion* spp. and *Deroceras* spp.) and snails (*Helix aspersa*, *Oxychilus alliarius* and *Cohlopoca buccinella*), did show potential as bioindicators, as more than 10 specimens of each group were recorded, they were significantly different in abundance among sites, and they showed a unidirectional shift from relatively high abundance in the unplanted grassland, to zero occurrence in the mature forest areas (Table 2).

Pitfall traps

The pitfall traps captured a wide variety of invertebrate taxa typical of grassland and forest habitats and a number of potential indicators were identified (Tables 3 & 4). Cave weta were over eight times more abundant in the mature forest than in

Table 1. Weta observed in weta motels at the unplanted grassland, restored and mature forest sites in the Hunua Quarry restoration area on two assessment dates (17/12/14 and 19/1/15). Value given is the mean number (± SEM) of weta found in four sampling stations (each consisting of four motels). Each P value was obtained from a Kruskal-Wallis test with 2 degrees of freedom and n = 4. Statistically significant results (P < 0.05) are shown in bold.

Species	Date	Unplanted grassland	Restored	Mature	P
Tree weta *Hemideina thoracica*	2014	0 ± 0	2.75 ± 0.95	0 ± 0	**0.027**
	2015	0 ± 0	4.00 ± 0.91	0.75 ± 0.25	**0.008**
Cave weta *Neonatus* sp.	2014	0 ± 0	0 ± 0	0.25 ± 0.25	0.368
	2015	0 ± 0	0 ± 0	0.25 ± 0.25	0.368

Table 2. Invertebrates observed under wooden discs placed out at the unplanted grassland, restored and mature forest sites in the Hunua Quarry restoration area. Each value given is the mean number of animals found in four sampling stations (each consisting of four wooden discs). Each P value was obtained from a Kruskal-Wallis test with 2 degrees of freedom and n = 4. Statistically significant results (P < 0.05) are shown in bold.

Taxa		Unplanted grassland	Restored	Mature	P
Coleoptera	Carabidae	2.75 ± 0.75	3.00 ± 1.78	2.00 ± 1.68	0.750
	Curculionidae	0.75 ± 0.75	0 ± 0	0 ± 0	0.368
	Elateridae	0 ± 0	0.25 ± 0.25	0 ± 0	0.368
	Scarabaeidae	0 ± 0	0.25 ± 0.25	0 ± 0	0.368
	Staphylinidae	0.25 ± 0.25	0.50 ± 0.29	0 ± 0	0.295
Blattodea	Blattidae	1.0 ± 0.707	0.5 ± 0.5	0 ± 0	0.303
Orthoptera	Gryllidae	0.25 ± 0.25	0 ± 0	0 ± 0	0.368
Arachnida	Araneae	0.75 ± 0.75	1.25 ± 0.63	1.0 ± 0.58	0.701
	Opiliones	0 ± 0	1.5 ± 0.87	0 ± 0	**0.027**
Myriapoda	Diplopoda	0.25 ± 0.25	4.00 ± 1.22	5.50 ± 2.60	0.064
	Chilopoda	0 ± 0	0.25 ± 0.25	0 ± 0	0.368
Annelida	Earthworms	9.50 ± 4.37	15.8 ± 4.61	1.00 ± 0.71	**0.048**
Platyhelminthes	Flatworms	0.5 ± 0.29	1.0 ± 0.71	0 ± 0	0.256
Mollusca	Exotic snails	13.0 ± 5.11	5.25 ± 0.75	0 ± 0	**0.008**
	Tiger slugs	0 ± 0	6.00 ± 3.67	0 ± 0	**0.028**
	Exotic slugs	5.50 ± 1.50	0.75 ± 0.75	0 ± 0	**0.014**

the restored and unplanted areas, and similarly the numbers of spiders (Araneae) were considerably higher in the restored and mature forest than in the unplanted grassland (Table 3). Conversely, three ant species (Formicidae: *Amblyopone australis*, *Pachycondyla castanea* and *Tetramorium grassii*) were found which, collectively, were more abundant in the unplanted grassland than the restored and mature forest (Table 3).

As with the wooden discs, exotic slugs were most abundant in the unplanted grasslands and least abundant in the mature forest. This pattern was also seen with exotic earthworms (Lumbricidae) and the common garden snail (*Helix aspersa*). Additionally, one or two specimens of each of five native snail species were collected only in the mature forest: *Thalassohelix ziczag*, *Laoma marino*, *Phrixgnathus* sp., *Allodiscus dimorphus* and *Cavellia buccinella*.

In total, 887 beetles, belonging to 40 species in 18 families, were collected in the pitfall traps. Almost half (19) of the 40 species were represented by five or more individuals and only six species were recorded as singletons (Table 4). Overall, more individual beetles were collected in the unplanted grassland than the restored area and mature forest. However, the various diversity indices based on the overall catches did not give a clear separation of the three vegetation classes. The Shannon-Weiner Index (*H'*) value was significantly lower in the unplanted grassland than both the restoration (permutation test, P = 0.009) and mature forest areas (P = 0.031), but there was no difference between the mature forest and restoration area (P = 0.417) (Table 4). The beetle diversity in the unplanted grassland as measured by Simpson's Diversity Index (SDI) was not different to that found in the restored area (P = 0.357) and mature forest (P = 0.204), but was different between the restored area and mature forest (P = 0.030). The mature forest also had the lowest diversity scores in terms of evenness (*J* and SEI) and dominance (Table 4). If more simplistic measures of diversity were considered, the unplanted grassland had approximately half the number of beetle families and species than found in the restored and mature forest areas (Table 4).

Seven of the 40 beetle species were found to differ significantly (P < 0.05) in abundance among the three vegetation types, six of which met all three criteria to be considered valid bioindicators (Table 4). The carabid *Holcaspis mucronata* was most abundant in the mature forest compared with the unplanted grassland and restored areas. It was found at all four of the mature forest sampling stations but was not recorded at all in the unplanted grassland. Also, a species of Cerylonidae (*Hypodacnella* sp.) and an undetermined species of Mycetophagidae were collected in three of the four samples from the mature forest but none from the grassland and restored areas (Table 4). Conversely, an undetermined species of Staphylinidae was highly abundant in the unplanted grassland (153 specimens) but was not found in the mature forest. Similarly, the carabid *Rhytisturnus miser* was 16 times more abundant in the unplanted grassland than in the mature forest.

Although there appeared to be only a few beetle species exhibiting clear preferences for one habitat above the others, the NMDS analysis clearly grouped the samples from each habitat, especially the four samples taken from the unplanted grassland (Fig. 2). The ANOSIM procedures indicated that significant differences in sample composition (P < 0.001) occurred among the three groups when including all the beetle species (R = 0.79; homogeneity of dispersion, $F_{2,9}$ = 3.01, P = 0.166), only those species represented by four or more specimens (R = 0.80; homogeneity of dispersion, $F_{2,9}$ = 1.85, P = 0.337), and when family level designations were used (R = 0.65; homogeneity of dispersion, $F_{2,9}$ = 2.64, P = 0.195). Also, when the groups of samples were compared in a pairwise fashion, all three groups of samples were found to be significantly different in composition from each other (P < 0.05).

Even when using the relatively coarse taxonomic level of family, the beetle samples from the three different vegetation areas formed obvious clusters, with the exception of one sample from the mature forest, the M1 sample, which was also distinct in the other two NMDS analyses (Fig. 2). From the raw data, it is not easy to see why this sample was so different

Table 3. Invertebrates (excluding Coleoptera) collected in pitfall traps placed in the unplanted grassland, restored and mature forest sites in the Hunua Quarry restoration area. Each value given is the mean number of animals found in four sampling stations (each consisting of four pitfall traps). Each P value was obtained from a Kruskal-Wallis test with 2 degrees of freedom and n = 4. Statistically significant results (P < 0.05) are shown in bold.

Taxa		Unplanted grassland	Restored	Mature	P
Insecta	Cave Weta	0.25 ± 0.25	0.50 ± 0.50	4.00 ± 0.82	**0.018**
	Ground Weta	0 ± 0	0.25 ± 0.25	0.75 ± 0.75	0.573
	Dermaptera	0 ± 0	1.75 ± 1.44	0 ± 0	0.113
	Diptera	67.0 ± 17.4	48.5 ± 13.3	31.5 ± 12.4	0.333
	Formicidae	176.7 ± 44.9	71.5 ± 36.0	22.0 ± 11.6	**0.039**
	Apocrita (wasps)	4.00 ± 0.58	16.0 ± 13.7	3.50 ± 0.29	0.867
	Lepidoptera	0.25 ± 0.25	1.25 ± 0.75	0.75 ± 0.48	0.537
Arachnida	Araneae	3.00 ± 0.58	21.25 ± 4.61	21.25 ± 1.71	**0.023**
	Pseudoscorpiones	0 ± 0	0.75 ± 0.48	1.00 ± 0.58	0.256
Myriapoda	Chilopoda	0.75 ± 0.48	0.75 ± 0.25	5.75 ± 2.17	0.244
	Diplopoda	7.75 ± 3.42	5.00 ± 0.71	7.50 ± 1.26	0.523
Mollusca	Garden Snails	28.0 ± 13.1	1.25 ± 0.48	0.75 ± 0.48	**0.020**
	Other Snails	45.0 ± 24.4	3.50 ± 2.60	1.50 ± 0.29	0.167
	Exotic slugs	21.8 ± 3.64	16.5 ± 6.91	1.00 ± 1.00	**0.031**
Annelida	Lumbricidae	10.0 ± 3.76	8.50 ± 1.32	0.50 ± 0.29	**0.036**

Table 4. Coleoptera collected in pitfall traps placed in the unplanted grassland, restored and mature forest sites in the Hunua Quarry restoration area. Each value given is the total number of animals found in four sampling stations (each consisting of four pitfall traps). Each P value was obtained from a Kruskal-Wallis test with 2 degrees of freedom and n = 4. Statistically significant results ($P < 0.05$) are shown in bold. Diversity indices were calculated using the whole collection from each site.

Family	Species	Unplanted grassland	Restored	Mature	P
Anthicidae	*Sapintus aucklandensis*	-	2	3	0.256
	Sapintus pellucidipes	-	-	3	0.368
Carabidae	*Clivina vagans*	9	1	-	0.241
	Ctenognathus bidens	72	110	163	0.777
	Ctenognathus cardiophorus	2	-	2	0.577
	Ctenognathus lucifugus	1	1	-	0.577
	Holcaspis mucronata	-	3	17	**0.019**
	Lecanomerus atriceps	-	1	1	0.577
	Mecodema crenicolle	-	5	6	0.142
	Rhytisternus miser	49	22	3	**0.020**
Cerylonidae	*Hypodacnella* sp.	-	-	13	**0.028**
Cerambycidae	*Ptinosoma* sp.	-	1	1	0.577
Coccinellidae	Coccinellidae indet.	-	-	2	0.368
Corylophidae	Corylophidae indet.	-	2	-	0.111
Curculionidae	*Mandalotus miricollis*	-	1	-	0.368
	Phrynixus sp.	-	3	6	0.092
	Scelodolichus sp.	2	-	-	0.111
Elateridae	*Argrypnus variabilus*	18	2	-	0.059
Hydrophilidae	Hydrophilidae indet.	12	1	19	0.262
Lathridiidae	*Aridius costatus*	-	5	5	0.089
Leiodidae	*Zeadolopus* sp.	-	-	2	0.111
	Leiodidae indet. 1	-	3	1	0.573
	Leiodidae indet. 2	-	-	1	0.368
Lucanidae	*Mitophyllus parrinus*	1	-	-	0.368
Melandryidae	*Hylobia* sp.1	-	3	-	0.113
	Hylobia sp.3	-	1	2	0.573
	Hylobia sp.2	-	1	-	0.368
Mycetophagidae	Mycetophagidae indet.	-	-	10	**0.028**
Nitidulidae	*Epurea* sp.	-	54	-	**0.005**
Scarabaeidae	*Heteronychus arator*	20	-	-	**0.005**
	Saprosites sp.	-	1	-	0.368
	Saphobius sp. 1	-	-	2	0.111
	Saphobius sp. 2	-	-	5	0.368
Staphylinidae	*Silphotelus* sp.	-	-	2	0.368
	Staphylinidae indet. 1	-	12	11	0.151
	Staphylinidae indet. 2	-	1	-	0.368
	Staphylinidae indet. 3	-	3	-	0.113
	Staphylinidae indet. 4	153	3	-	**0.010**
Zopheridae	*Pristoderus bakewelli*	3	15	1	0.174
	Syncalis sp.	-	-	7	0.368
Individuals		342	257	288	
Families		8	14	14	
Species		12	26	25	
Dominance (%)		44.7	42.6	56.6	
Shannon-Weiner *H'*		1.636	2.009	1.890	
Evenness *J*		0.659	0.617	0.587	
Simpson's diversity index (SDI)		0.729	0.762	0.667	
Simpson's evenness index (SEI)		0.793	0.790	0.692	

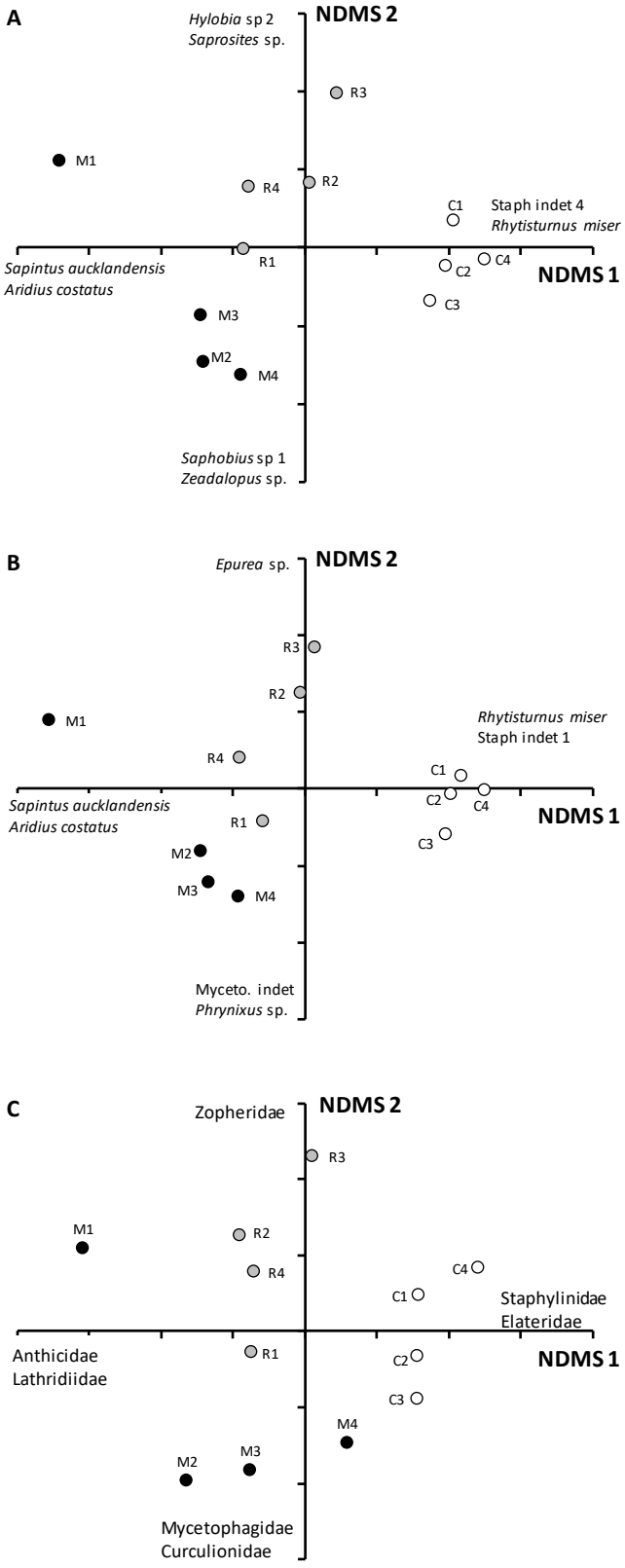

Figure 2. Scatter plots of NDMS Axis 2 versus NDMS Axis 1 scores of twelve pitfall samples of beetles collected from unplanted grassland (G: white), restored (R: grey) and mature forests (M: black) at Hunua Quarry. NDMS was performed on square root transformed count data for (A) all species (stress = 0.084), (B) species represented by ≥4 individuals (stress = 0.069) and (C) abundance of each family (stress = 0.111) in each sample.

from the other mature forest samples, although it contained no *Phrynixus* sp. and no Mycetophagidae, which were present in all of the other mature forest samples. Spatially, the M1 sample was close to the restored area, especially samples R2 and R4 (Fig. 1), and so might have been influenced by its proximity to the forest edge. However, sample M3 was also close to the forest edge, near to the unplanted grassland, and the beetles collected in this sample were similar to those collected deeper into the forest area (M2 and M4).

Leaf litter samples

A total of 66 mite RTUs and 17 springtail RTUs were collected from the leaf litter samples (Tables S2, S3). However, only one mite RTU (M32) and no springtail RTUs met all three of our criteria to be considered bioindicators.

For both taxa there were no statistically significant differences across the three sites in terms of numbers of individuals and species richness (Table 5). However, even though there was little separation of the three vegetation areas based on numerical summaries, the NMDS analyses suggested a separation of the mite and springtail collections assemblages in the unplanted grassland from those obtained in the mature forest (Fig. 3). The ANOSIM procedure on the mite data ($R = 0.52$; $P < 0.001$; homogeneity of dispersion, $F_{2,9} = 3.35$, $P = 0.198$) separated all three groups of samples from each other when compared in a pairwise fashion ($P < 0.05$; Fig. 3A). For the springtails, the ANOSIM procedure ($R = 0.46$; $P < 0.001$; homogeneity of dispersion, $F_{2,9} = 0.46$, $P = 0.782$) indicated that the collections in the mature forest and restored area were not significantly different ($P = 0.071$), whereas both the mature forest ($P = 0.014$) and restored site ($P = 0.043$) were separated from the grassland samples by the ANOSIM procedure (Fig. 3B).

Discussion

The main aim of this study was, by applying predetermined criteria, to identify potential indicator taxa that could prove useful in future monitoring events at both this site and other restoration sites. The information collected allows us to propose a number of taxa that could be used to help map the invertebrate assemblage trajectory at the restored site from that of the exotic grassland and towards that occurring at the mature forest (Table 6). For example, the unplanted grassland site had high numbers of exotic snails, slugs and earthworms, whereas the mature forest had more spiders, cave weta, and the beetles *Holcaspis mucronata* and *Hypodacnella* sp. (Table 6). In future, if the restoration process is successful, it would be expected that the restored site would show a decrease in those taxa associated with unplanted grassland and an increase in those taxa associated with the mature forest.

Carabid ground beetles have a long history of being used as bioindicators and as monitoring tools to gauge environmental impact (Kotze et al. 2009; Eyre et al. 2016). Previous New Zealand studies of habitat restoration also suggested that carabids have potential as indicators of restoration success (Reay & Norton 1999; Bowie et al. 2012). Additionally, as the taxonomy of New Zealand ground beetles is well treated in the literature, carabids represent a sensible and familiar group of insects for use in future monitoring events. Spiders were most abundant in the pitfall traps set out in the restored and mature forest and, therefore, as a group indicated some divergence in the overall invertebrate assemblage from that

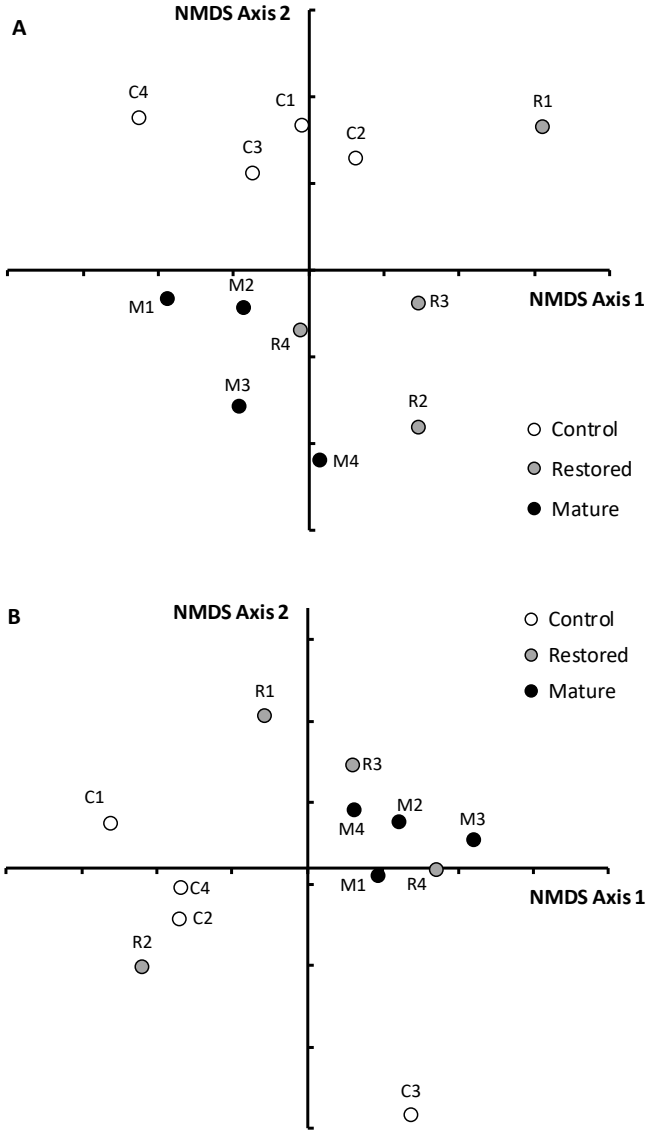

Figure 3. Scatter plots of NDMS Axis 2 versus NDMS Axis 1 scores of twelve leaf litter samples of (A) mites (stress = 0.098) and (B) springtails (stress = 0.123) collected in unplanted grassland (G: white), restored (R: grey) and mature forests (M: black) at Hunua Quarry. NDMS was performed on square root transformed count data.

found in grassland habitat. Unfortunately, in this study we did not identify the spiders to species level due to time constraints. There is an opportunity in future work to identify spider species associated with one habitat type or another.

Although not obvious candidates as bioindicators based on the data we collected and criteria we set, some invertebrate groups may still prove useful due to their rarity or endemic status. For example, the endemic snails *Laoma maria*, *Allodiscus dimorphus*, *Thalassohelix ziczag*, *Allodiscus dimorphus* and *Cavellia buccinella* were only found in the mature forest at Hunua. Due to their high conservation status, the future occurrence of these species in the recently planted areas would be meaningful indicators of restoration success. Similarly, dung beetles are often considered excellent bioindicators, due to their sensitivity to habitat perturbations and ease of identification (Nichols et al. 2008; Bicknell et al. 2014). Three species of dung beetle were present in our collections, two *Saphobius* species in the mature forest and a *Saprosites* species at the restoration site, and these species might also be considered valuable indicators in future monitoring studies of this site.

Invertebrate communities in early restoration sites often differ from those found in the reference ecosystem they are trying to attain, or may not respond in a predictable way to the species or the diversity of plants used in a replanting scheme (Longcore 2003; Davis & Utrup 2010). The replanted areas in this study were all less than 6 years old at the time of the invertebrate sampling, and often much longer time periods are required before restoration aims are met (Orabi et al. 2010). The NMDS and ANOSIM procedures indicated that the collections of diverse taxa, such as beetles, mites and springtails, all exhibited significant differences in faunal composition between the unplanted grassland habitat acting as a temporal control, and those occurring in the mature forest, which represents the target habitat. This separation forms a basis for the use of a whole-assemblage approach to examining restoration trajectory. Over time, if restoration is successful, ordination analysis should indicate that the invertebrates from the restoration area have separated from those of the unplanted grassland, but are statistically indistinct from those of the mature forest. Future work at this site is required to ascertain whether the compositions of the restoration and mature forest invertebrate assemblages have increased in their similarity or have fully converged.

Mites were the most diverse taxonomic group in our survey (66 RTUs) and have been suggested as being valuable

Table 5. Mites (Acari) and springtails (Collembola) obtained from leaf litter samples in the unplanted grassland, restored and mature forest sites in the Hunua Quarry restoration area. Abundance, species richness, and total species values given are: mean ± SEM. For total species the overall number of species recorded in each area is given. Invertebrates were collected from four sampling stations, with four litter samples taken at each station. Each P value was obtained from a Kruskal-Wallis test with 2 degrees of freedom and n = 4.

Taxa		Unplanted grassland	Restored	Mature	P
Mites	Abundance	74.5 ± 14.3	138.0 ± 67.3	108.5 ± 22.7	0.542
	Species richness	11.5 ± 1.3	14.8 ± 3.1	19.5 ± 3.3	0.131
	Total species	28	30	42	
Springtails	Abundance	29.0 ± 10.2	20.8 ± 11.0	55.8 ± 36.8	0.301
	Species richness	3.5 ± 0.5	4.75 ± 0.25	4.0 ± 1.1	0.319
	Total species	7	11	8	

Table 6. Invertebrate taxa showing associations with the two reference habitat types in the Hunua Quarry Restoration Project, New Zealand, and thus showing good potential as bioindicators of restoration trajectory.

	Unplanted grassland	Mature
Weta motels	-	-
Wooden discs	Exotic slugs	
	Exotic snails	
Pitfall traps	Exotic snails	Spiders
	Exotic slugs	Cave weta
	Exotic worms	
	Rhytisternus miser	*Holcaspis mucronata*
	Heteronychus arator	*Hypodacnella* sp.
	Staphylinidae indet. 4	Mycetophagidae sp.
Leaf litter	-	Mite RTU M32

bioindicators in mine restoration (Majer et al. 2007a). In similar restoration work at Punakaiki on the West Coast of New Zealand, and in conservation plantings on New Zealand dairy farms, mites have also been proposed as potential bioindicator taxa (Hahner & Bowie 2013; Smith et al. 2016; Curtis et al. 2017; Esperschuetz et al. 2018). In our study, although only one mite RTU met all our bioindicator criteria, we found clear differences among habitats, especially the grassland and mature forest, when using the whole mite assemblage. Although we concede that the complex taxonomy and difficulties with identification can make working with mites problematic, we feel the results provide additional evidence of the potential of soil/litter mites as bioindicators of habitat quality in New Zealand, and they warrant further investigation.

It is important to optimise sampling strategies for ecological monitoring, and results obtained by one method may differ from those obtained using another (Majer et al. 2007a). The different invertebrate sampling methods we employed allowed us to gauge the usefulness of each method and identify differences in how the perceived response of some taxa was modified by sampling method. For example, in the weta motels, few cave weta were present, and tree weta occurred mainly in the restoration site. However, the pitfall traps collected no tree weta, but captured many more cave weta in the mature forest compared with the other two habitats. In general, the pitfall samples provided a high diversity of taxa with sufficient numbers of specimens to make valid conclusions regarding their suitability as bioindicators. Thus, we advocate the use of pitfall sampling in future surveys of this site, and in other restoration schemes, as a primary means of invertebrate monitoring.

Previous studies into mine restoration have identified the requirement for high levels of wide ranging taxonomic skills in order to accurately identify invertebrates collected to the level of species. In this study we have compromised by using higher taxonomic levels (e.g. families or orders) for some groups or by adopting a morphospecies or RTU approach (Oliver & Beattie 1996; Longcore 2003). The use of coarse higher taxonomic groups is sometimes justified on the basis that the whole group is rare or endemic or typical of the habitat being recreated. On the other hand, the use of morphospecies or RTUs tends to be implemented more often where restoration success is gauged using species richness or ecological diversity indices. However, the diversity indices based on our beetle, mite and springtail collections did not unambiguously separate the three sampling areas. Although increasing species diversity is often considered a critical component of ecological restoration, the use of diversity measures as indicators of restoration success is not always straightforward as high species diversity can result from the presence of exotic or invasive invertebrates (Prach & Tolvanen 2016). Therefore, species diversity indices should be used in conjunction with other measures of ecological value of the species involved, such as their endemic status, rarity, and whether they are considered typical of the habitat being restored (Majer et al. 2007a; Gardner-Gee et al. 2015; Boyer et al. 2016; Řehounková et al. 2016).

Conclusion

This study represents an initial examination of the first stage of restoration replanting at the Hunua Quarry site. We accept that, currently, there is a lack of real replication in our study, as only one restoration project has been investigated, and only one example of each of the three vegetation types was surveyed for invertebrates. However, the study has provided an initial catalogue of the invertebrates occurring in this area of the Hunua Reserve, and identified significant differences in invertebrate diversity and abundance among the three habitats. A number of invertebrate taxa have been identified as potential indicators of restoration success, which might be used to focus future monitoring events, both at this site and at other mine or quarrying restoration projects. We are aware that in space-for-time studies there is some uncertainty regarding the use of undisturbed habitats as the terminal reference condition, as the restored areas do not share similar history regarding disturbance, soil amendments, stability, and so on (Pickett 1989). However, as the Hunua Quarry replantings continue, and the chronosequence of different aged restoration areas develop, future monitoring events can use the bioindicator taxa identified here to detect whether further divergence from baseline grassland habitat has occurred, and evaluate whether the restoration trajectory of the invertebrate community is moving towards that of the neighbouring mature forest.

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Supplementary Material

Additional supporting information may be found in the supplementary material file for this article:

Table S1. Species planted in restoration at Hunua Quarry.

Table S2. Total abundance and mean abundance per sample of mite RTUs in litter samples at the three forest sites at Hunua Quarry.

Table S3. Total abundance and mean abundance per sample of springtail RTUs in litter samples at the three forest sites at Hunua Quarry.

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