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; Major et al. 2007a; Davis & Utrup 2010; Rehounková 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
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 taraire), puriri (Vitex lucens), pukatea (Laurelia novae-zelandiae), swamp maire (Syzygium maire) and kahikatea (Dacrycarpus dacydioides), 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 sheltering under them on 18 December 2014 and 19 January 2015. Weta resident in the motels and the animals observed under the motels were assessed for occupation on 18 December 2014.

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*'), Simpson's diversity index (SDI), Simpson's evenness index (SEI), and species dominance. The indices were calculated as:

\[
H' = -\sum_i p_i \ln(p_i)
\]

(1)

\[
J' = H'/\ln(S)
\]

(2)

\[
SDI = 1 - \sum_i p_i^2
\]

(3)

\[
SEI = SDI / \left[1 - (1/S)\right]
\]

(4)

where *p* was the proportion of individuals consisting of the *i*th 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, PRIMER 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 (Neonatus 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.

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        | 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        | 2014     | 0 ± 0               | 0 ± 0       | 0.25 ± 0.25| 0.368   |
|                  | 2015     | 0 ± 0               | 0 ± 0       | 0.25 ± 0.25| 0.368   |

Wet motels

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
Cohlopora succincta), 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 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   |
|                   | Scarabacidae        | 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   |
| Platyzhimethes    | 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 gracilis*) 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*, *Laomamarino*, *Phirignathus sp.*, *Alloiscus dimorphus* and *Cavella 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 Ceryloniidae (*Hypodactella* 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 Staphyllinidae was highly abundant in the unplanted grassland (153 specimens) but was not found in the mature forest. Similarly, the carabid *Rhysiturnus 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, F2,9 = 3.01, P = 0.166), only those species represented by four or more specimens (R = 0.80; homogeneity of dispersion, F2,9 = 1.85, P = 0.337), and when family level designations were used (R = 0.65; homogeneity of dispersion, F2,9 = 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       | 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     | 3.00 ± 0.58         | 21.25 ± 4.61| 21.25 ± 1.71| 0.023 |
| Pseudoscorpions| 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    | Pinosoma sp.                   | -                    | 1        | 1      | 0.577   |
| Coccinellidae   | Coccinellidae indet.           | -                    | -        | 2      | 0.368   |
| Corylophidae    | Corylophidae indet.            | -                    | 2        | -      | 0.111   |
| Curculionidae   | Mandalotus miricollis          | -                    | 1        | -      | 0.368   |
|                 | Phrynixes sp.                  | -                    | 3        | 6      | 0.092   |
|                 | Scelodolichus sp.              | 2                    | -        | -      | 0.111   |
| Elateridae      | Argyrynus variabilis           | 18                   | 2        | -      | 0.059   |
| Hydrophilidae   | Hydrophilidae indet.           | 12                   | 1        | 19     | 0.262   |
| Leiodidae       | Aridius costatus               | -                    | 5        | 5      | 0.089   |
|                 | Leiodius 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   |
| Mycetopogidae   | Mycetopogidae indet.           | -                    | -        | 10     | 0.028   |
| Ntittulidae     | Epurea sp.                     | -                    | 54       | -      | 0.005   |
| Scarabaeidae    | Heteronychus arator            | 20                   | -        | -      | 0.005   |
|                 | Saproxytes 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    |
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 (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 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.
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      |        |
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 replanting continues,
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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