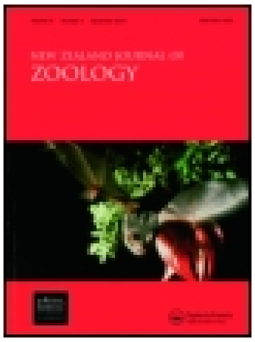

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RESEARCH ARTICLE

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Recommendations for non-lethal monitoring of tree wētā (*Hemideina* spp.) using artificial galleries

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ABSTRACT
Wildlife sanctuaries in Aotearoa/New Zealand involve community groups that often prefer using non-lethal monitoring methods for invertebrates. We examined one method for monitoring tree wētā with the aim of improving monitoring design. Pest management at our study site did not vary for 10 years before our study and remained unchanged between sampling, so we assumed that abundance of tree wētā would not vary significantly over the four years of the study. We recorded occupancy and marked every tree wētā (*Hemideina* spp.) using the same set of 38 artificial tree-hole refuges (galleries) every 1–2 weeks. We tested the prediction that non-lethal monitoring of tree wētā is a suitable proxy for relative wētā abundance by comparing the number of tree wētā using the same galleries four years apart. As expected, no change in numbers of wētā was detected. However, the level of site/gallery fidelity, seasonal fluctuations and movement between artificial galleries suggest that monitoring design needs to incorporate the life history and behaviour of these insects. We recommend comparison of wētā occupancy be restricted to the same season, galleries be placed more than 50 m apart and checked only once or twice a year.

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Introduction

Documenting invertebrate abundance and diversity often requires killing large numbers of specimens so sampling can be replicated, and specimens stored, sorted, identified, and counted. However, increasingly, community groups prefer to use non-lethal tools for monitoring invertebrates before, during and after control of mammalian predators (Drinkwater et al. 2019). As large herbivores, potential seed dispersers and a food source for native birds, bats and reptiles, tree wētā are an important component of New Zealand forest-ecosystems (Griffin et al. 2011) that could offer a monitoring solution should standardised non-lethal methods be developed (Watts et al. 2017).

The use of tree wētā as indicator species for forest restoration programmes was first suggested 20 years ago (Trewick & Morgan-Richards 2000) and counts of the large and common tree wētā (any species of the genus *Hemideina*) provide potential for use

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as proxies of changes in invertebrate populations in response to predator control. It is likely that on their own, however, tree wētā will not be indicators of all aspects of changing forest ecosystems (Watts et al. 2020), but they have the advantage over other invertebrate species of using arboreal day-time refuge holes. Tree wētā readily use artificial tree-hole refuges (galleries) which are relatively simple to access to count the tree wētā within, contributing to their potential usefulness as a species to monitor as forest ecosystems respond to changing species composition.

New Zealand has four species of common forest tree wētā (*Hemideina* spp.) that share many life history traits: *H. crassidens* (Blanchard 1851), *H. femorata* (Hutton 1896), *H. thoracica* (White 1846), and *H. trewicki* (Morgan-Richards 1995). These species are all large bodied (4–6 g; 35–60 mm as adults), nocturnal orthoptera that use tree-hole galleries for refuge during the day. They are primarily herbivorous and have an arboreal lifestyle with marked sexual dimorphism (Gibbs 2001). Tree wētā adults will share large tree cavities with other adult individuals, often forming harems (Moller 1985; Field & Sandlant 2001; Wehi et al. 2013a). Most New Zealand forests have a single *Hemideina* species (Trewick & Morgan-Richards 1995) but all North Island forests and more than half of South Island forests are home to one or other of these four common tree wētā.

Tree wētā have been the subject of a handful of published monitoring projects (Kelly 2006; Bowie et al. 2014; Wehi et al. 2015). For example, non-lethal methods that involve counting tree wētā inside artificial refuge cavities have been used to monitor tree wētā response to rodent control operations (e.g. Ruscoe et al. 2013). Lethal pitfall trapping was implemented at Maungatautari Ecological Island where an increase in *Hemideina thoracica* individuals in traps was detected following mammal eradication (Watts et al. 2011, 2020). Some of these wētā studies, however, do not explicitly consider the life history and behaviour of these insects in their monitoring design.

We observed marked tree wētā using 38 artificial refuge cavities (galleries) during 2016 and then again over three months in 2020. Our aim was to make recommendations about non-lethal monitoring of tree wētā populations in New Zealand forest restoration programmes based on improved knowledge of wētā behaviour. Using evidence of site/gallery fidelity, distance travelled, and time between first and last sighting, we make recommendations about how far apart wētā galleries should be placed and how often wētā occupancy of galleries should be recorded to detect changes in relative abundance.

Methods

Study species and site

Data collection was conducted at the Turitea water catchment reserve (175.661858°S, 40.428119°E) in the Manawatu-Whanganui region, New Zealand. Thirty-eight wooden artificial tree-cavity-boxes (wētā galleries) were fixed to tree trunks in 2014 in a regenerating forest fragment between the Turitea stream and the water treatment plant, on a slope of approximately 30° (Figure 1). All galleries were fixed to mahoe tree trunks (*Melicytus ramiflorus*), with one exception fixed to a ponga trunk (silver fern; *Alsophila dealbata*). Each gallery had a circular entrance hole (15 mm diameter) and a wooden panel that swivelled to reveal a cavity of approximately 25–40 mm wide by 80–130 mm long,

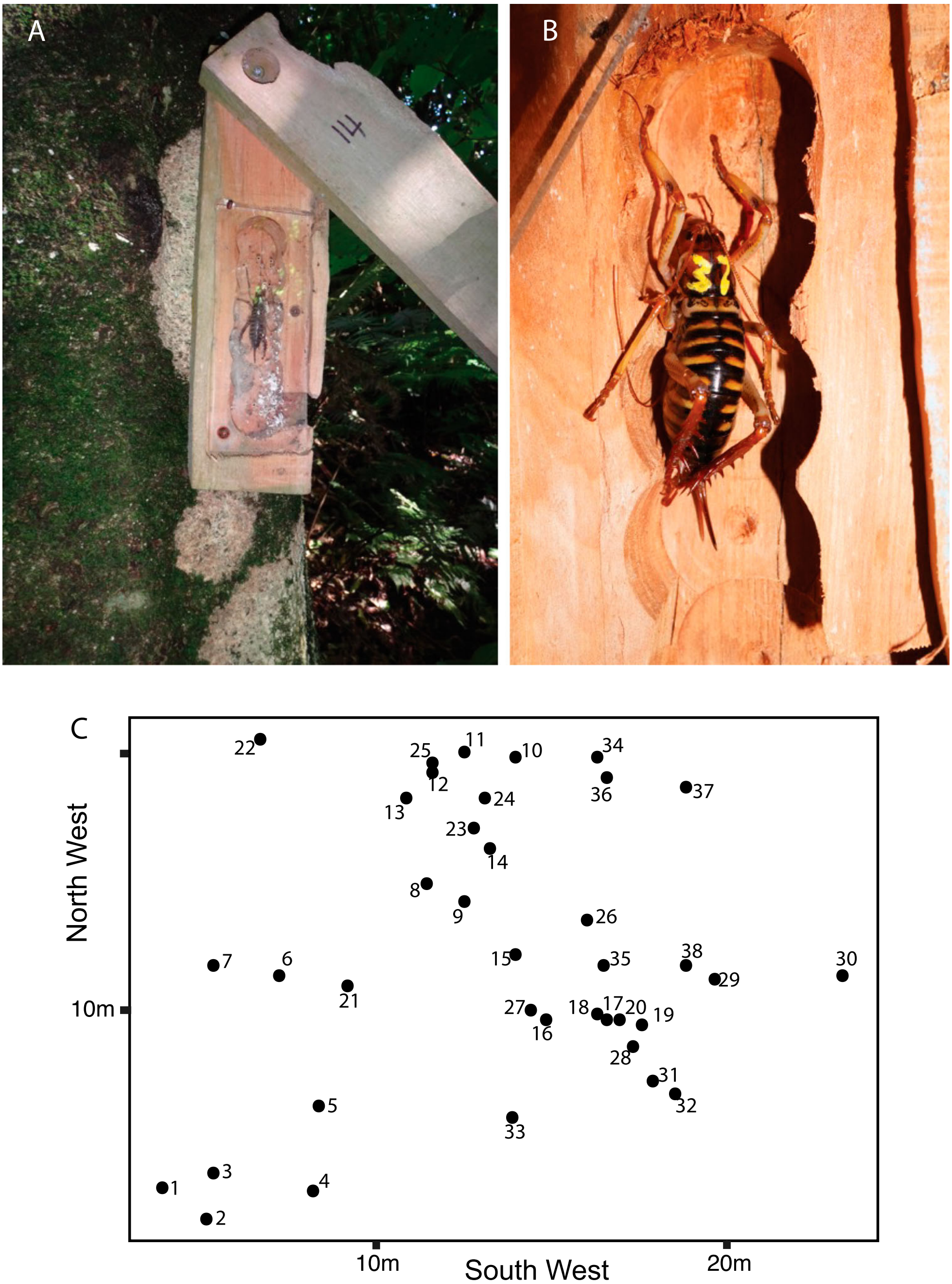

Figure 1. A, Artificial wētā gallery attached to tree trunk with tree wētā inside. **B,** Plastic cover of artificial wētā gallery removed to allow marking of adult female wētā (*Hemideina crassidens*) pronotum with nail polish. **C,** Spatial map of the locations of the 38 artificial wētā galleries attached to mahoe trees at the Turitea water catchment reserve, Manawatu, New Zealand. Spots represent approximate locations from manual compass and distance measurements.

covered by a transparent piece of plastic (Perspex®). Observations were made during the day with minimal disturbance to the occupants (Figure 1).

At our study site both *Hemideina crassidens* (Wellington tree wētā) and *Hemideina thoracica* (Auckland tree wētā) are present although at most locations in New Zealand a single *Hemideina* species occurs (Trewick & Morgan-Richards 1995; Morgan-Richards et al. 2017). The two species and putative F_1 hybrids were identified using their characteristic number of hind tibia spines and dorsal coloration (McKean et al. 2016). Adults were identified in this study by the shape and colour of ovipositor (females) and cerci being curved, harder and darkened (both sexes), while subadults lacked the darker colour and shape and juveniles were smaller in size.

To plot a spatial map of each wētā gallery we measured at least two distances between closely placed wētā galleries, as well as their approximate coordinates on a digital compass. Because angles and distances cannot be measured accurately in a forest, the X and Y coordinates were estimated by using multiple measurements from other galleries. An iterative estimation process was then used where each estimated location (X, Y coordinate) was based on the centroid of estimates of the locations which are themselves based on estimate locations. The result was a two-dimensional array which ignored changes in topology. We used this to calculate the minimum distance between artificial galleries in which the same individual wētā was observed, to provide evidence of wētā dispersal.

Pest management in the Turitea water catchment reserve

Palmerston North City Council pest control within the Turitea water catchment reserve was maintained at the same level from 2006 until 2020 (Turitea Management Plan 2006, Palmerston North City Council). Four mammal species were the target of control activities within the reserve: bushtail possum (*Trichosurus vulpecula*), goat (*Capra hircus*), red deer (*Cervus elaphus*) and pig (*Sus domesticus*). Control methods consisted of ungulate-proof fences, trapping, poisoning (cyanide cholecalciferol, brodifacoum) and hunting. There was no direct control of mustelids (*Mustela* spp.), rodents (*Rattus* spp. and *Mus musculus*), hedgehogs (*Erinaceus europaeus*) or cats (*Felis catus*). Because control of browsing mammals was constant for 10 years before our study began and remained in place between 2016 and 2020 we did not attempt to measure tree wētā density but assumed that relative abundance did not change over the time scale of our study. Our assumption that the relative abundance of tree wētā was unchanging was not undermined by a similar ratio of the two *Hemideina* species observed in 2016 and 2020 (see results). The two tree wētā species generally competitively exclude one another, the outcome dependent on local climatic variables (Bulgarella et al. 2014) and therefore changes in the abundance of one (or both) species is likely to impact their ratio (McKean et al. 2016).

Wētā marking and resighting

All 38 numbered artificial wētā galleries were checked approximately every week or fortnight between 3 January and 31 December 2016. In total, galleries were checked a total of

27 times over the year. Galleries were checked again four years later when all wētā recorded in 2016 could be assumed to have died (Green 2005), and after pest management programmes had remained constant for 14 years (2006–2020). Observations were made nine times during spring/summer, each week from 4 October until 13 December 2020 (with two exceptions). Every time the galleries were checked we marked the tree wētā that were inside the galleries with a unique combination of coloured nail varnish on their pronotum (or we recorded their existing marking; Figure 1). We marked each tree wētā by removing the plastic cover and applying coloured varnish without disturbing the insect to reduce the likelihood that the individual would abandon its refuge (Figure 1B). For each wētā we recorded: sex, approximate age (adult, subadult, juvenile), species, gallery number and unique marking. Identification of age and sex of some individuals was difficult due to their small size or their position in a gallery with other wētā, these records have been removed from the data before analysis.

Site/gallery fidelity resulted in many individuals being recorded in the same artificial gallery on subsequent visits. Tree wētā do not feed every night (Wehi et al. 2013b) but as the minimum time between observations was seven days, we assume that individual wētā had left and returned to the gallery at least once between resightings (Wehi et al. 2020). Because moulting results in loss of unique markings, our estimates of site/gallery fidelity are minimum values. However, rate of moulting is not expected to differ between sexes (Minards et al. 2014).

Data analysis

We compared the sex ratio and age structure of tree wētā resighted in 2016 with all marked wētā in 2016 to determine whether site fidelity was higher for one sex or age. We used the ratio of males and females in each age class (adult, subadult, juvenile) from the full data for 2016 to calculate expected values if resightings were random and used a chi-squared test to compare with observed resightings. Because we recorded movement between galleries for only 36 individuals, we have not performed statistical tests on these data, but summarise distance moved by sex.

Occupancy rate of artificial galleries by *Hemideina* species is expected to vary due to local density and seasonal changes in behaviour (Trewick & Morgan-Richards 2000; Wehi et al. 2013a). We looked for evidence of seasonal variation in wētā occupancy rates in our data (summer December–February; autumn March–May; winter June–August; spring September–November). To compare sexes and seasons, we used a generalised linear model with the response variable being number of tree wētā seen inside the galleries during each visit. The Poisson family generalised linear model was used with the default log link function. If overdispersion issues were detected, a quasiPoisson family was used in preference. If occupancy rate of artificial galleries was a useful proxy for abundance of tree wētā we predicted that we would not detect a change in numbers of wētā observed between October–December of 2016 and October–December of 2020. Here we are assuming no change in abundance of tree wētā between 2016 and 2020. All analyses were performed using R version 4.0.2 (R Core Team 2020).

Results

Capture and resightings

At any time during 2016 an average of 24.7 wētā were seen sheltering inside the 38 artificial galleries. Over the year we made a total of 689 observations of tree wētā (including resightings) involving 311 uniquely marked wētā. The total number of wētā observed in the galleries was highest in March (late summer/autumn) when many galleries contained more than one adult (Figure 2). Site fidelity resulted in 45.7% of the 2016 wētā ($n = 142$) being resighted at least once. During the winter fewer unmarked wētā were recorded each visit than in late summer/autumn (Figure 2). The age and sex of 41 wētā were not

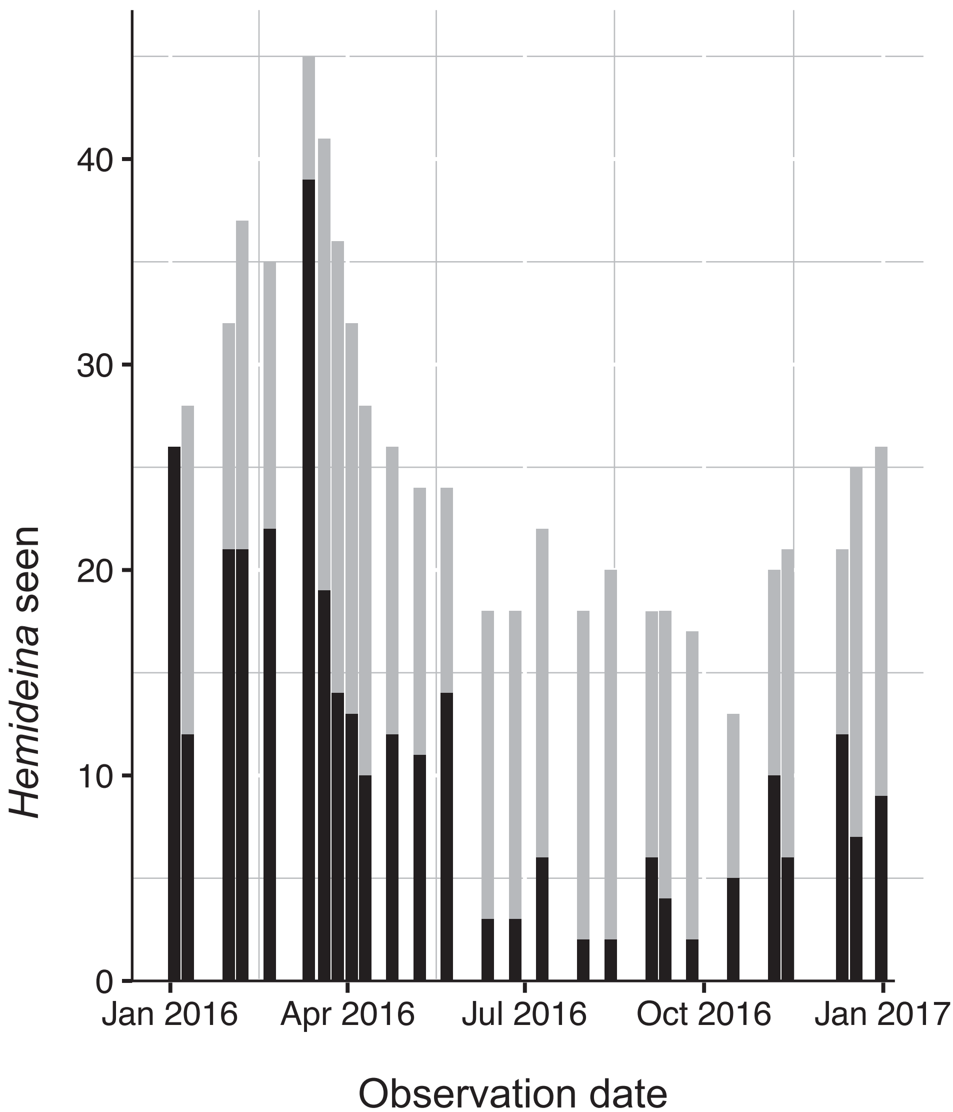

Figure 2. Number of tree wētā observed in 38 artificial galleries monitored over 12 months. Black bars = newly marked wētā, grey bars = resighted wētā.

recorded; for the remaining 270 wētā marked in 2016 the majority were *H. crassidens* ($n = 261$; 96.7%), seven were *H. thoracica* (2.6%) and two were putative hybrids (0.7%; see McKean et al. 2016). The tree wētā we resighted had the same sex ratio and age as the full sample (Figure 3; Chi-squared 3.399, d.f. = 5, $P = 0.6388$).

To examine seasonal variation in wētā abundance we fitted a generalised linear model assuming a Poisson family and associated log link (due to evidence of over dispersion). We detected seasonal variation in the total number of wētā using the galleries, with more new sightings in summer and autumn compared to winter and spring. In winter and spring, we saw fewer wētā in total, but the number of marked individuals returning to the same gallery (resightings) was stable (Table 1). From our model the predicted number of wētā using the 38 galleries at any time were: summer 28.75, autumn 32.0, winter 19.20, spring 17.83.

In 2020 we made 166 observations of wētā (including resightings) over three months (spring and early summer). A total of 74 individual wētā were found and uniquely marked. On average, 18 wētā were seen on each visit, with an average of 11.5 new wētā every subsequent occasion. The number of tree wētā observed in the galleries in 2020 falls within the range for our spring-summer data for 2016 (17.83–28.75).

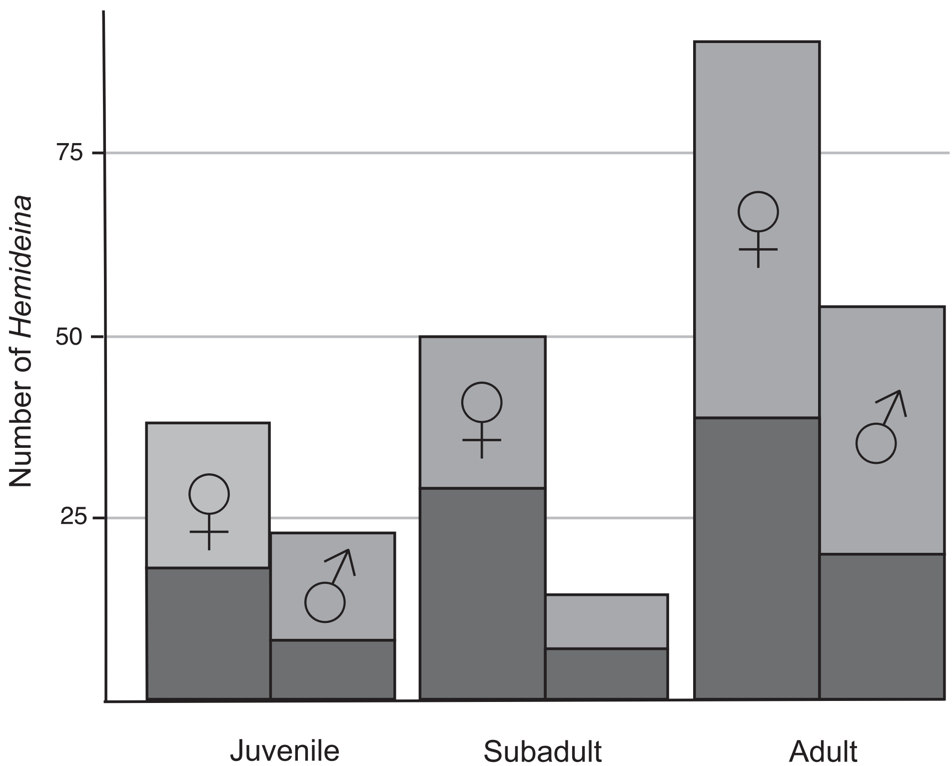

Figure 3. Total number of individual tree wētā observed and marked in 38 artificial galleries compared to the number of wētā that were resighted (seen more than once) over 12 months, 2016. Total wētā = pale bars, wētā resighted once or more = dark bars.

Table 1. The number of tree wētā (*Hemideina* spp.) seen inside the same artificial galleries at Turitea Reserve (Manawatu, New Zealand) was dependent on the season in which observations were made. Variation in the number of wētā observed was due to new arrivals (= first sightings) rather than seasonal changes in site/gallery fidelity. A generalised linear model assuming a quasiPoisson family and associated log link for wētā observations during 2016 revealed significantly fewer wētā were observed for the first time in winter and spring compared to summer and autumn.

	Estimate	Standard error	t value	Pr (>|t|)
(intercept)	2.5257	0.1531	16.502	<2e-16
Autumn	0.2151	0.2057	1.046	0.3012
Winter	0.2469	0.2296	1.075	0.2879
Spring	−0.0134	0.2347	−0.057	0.9546
First sighting	0.2624	0.2036	1.289	0.2040
Autumn: first sighting	−0.1998	0.2795	−0.715	0.4781
Winter: first sighting	−1.8718	0.4660	−4.017	0.0002
Spring: first sighting	−1.0699	0.3796	−2.818	0.0071

Movement and length of stay by individual wētā

Measures of site/gallery fidelity revealed that most individuals were observed just once. Of the 142 wētā that were resighted in 2016, 112 (78.9%) were resighted in the same gallery and 30 (21.1%) were seen after moving to a new gallery. Of the 30 wētā that moved to a different gallery, 23 were seen in two galleries and seven were resighted in three galleries. In 2020 six wētā were recorded in more than one gallery. Combining observations for 2016 and 2020, the average distance moved by females (8.2 m) was very similar to males (8.9 m), and adults were re-recorded about the same distance away as non-adults (9.6 m cf 4.8 m). The maximum distance we recorded an individual tree wētā moving was 34.55 m. We recorded some of the uniquely marked tree wētā using

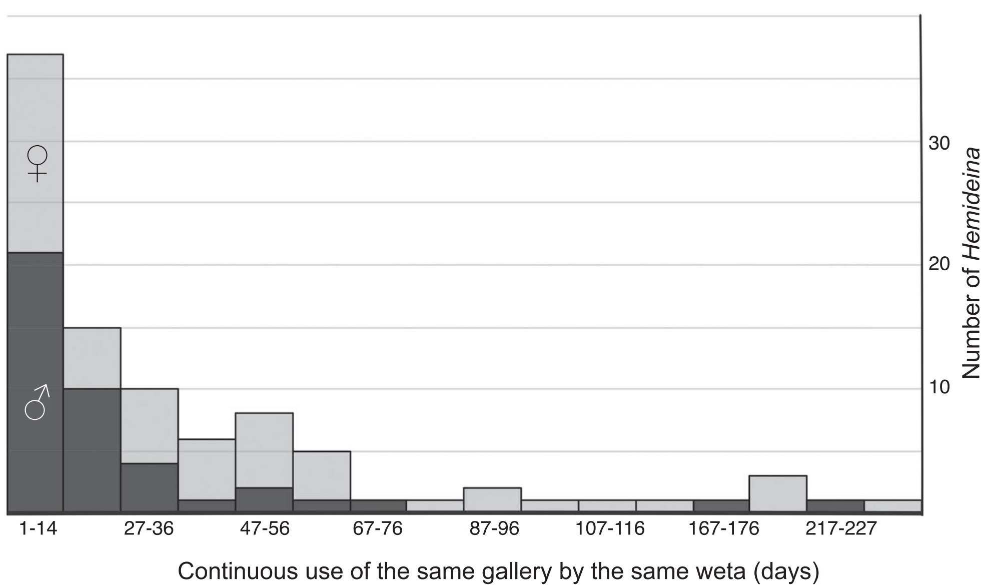

Figure 4. Insect site/gallery fidelity is illustrated with the length of time between first and last observations of resighted tree wētā using 38 artificial galleries in Turitea water catchment reserve in 2016 (interval widths vary by up to 4 days).

the same gallery for many weeks. We excluded all individuals observed a single time to illustrate the duration of occupancy of resighted wētā (Figure 4). Most of the individual wētā showing gallery fidelity of more than 80 days were female.

All artificial galleries were attached to tree trunks (and all were attached to mahoe, with one exception) but height from the ground varied. No correlation was found between gallery height and number of tree wētā observed in each gallery (Pearson's correlation coefficient; $r(36) = -0.24$, $p = 0.147$).

Discussion

To restore forest ecosystems, resources have been invested in reducing or removing invasive mammal species from numerous forest habitats around New Zealand. There are now over 80 wildlife sanctuaries around the country that each aim to involve community groups in the removal of pest species and restore local biodiversity (http://www.sanctuariesnz.org/). Assessing the success of these programmes requires monitoring of the species within the native ecosystems. Invertebrates are the most globally abundant and diverse animal group, and as herbivores, invertebrates convert plants (primary production) into food resources used by other animals (Prather et al. 2013). Forest invertebrates can also be important providers of ecosystem services such as decomposition and pollination (Noriega et al. 2018), thus monitoring and protection of invertebrates is an important part of forest restoration (Rohr et al. 2007; Prather et al. 2013). Although the abundance of insects has the potential to be used for assessing forest health and the successes of conservation efforts (Bowie et al. 2006; Majer et al. 2007), it was not our aim to provide evidence that tree wētā abundance is linked to healthy ecosystems, rather we aimed to take steps to improve monitoring tools with improved knowledge of tree wētā biology.

Many animal species return to the same refuge site and such site fidelity behaviour is likely to provide benefits to individuals for efficient location of a hiding place where they are safe from predators (Lewis 1995; Switzer 1997; Piper 2011). Although tree wētā are known to show site fidelity (gallery fidelity) few studies have documented how common it is. Almost half of all the tree wētā we recorded were observed more than once (46% in 2016). This level of gallery fidelity indicates that counting tree wētā using the same wētā galleries will not provide independent observations. Unexpectedly, age and sex did not influence rate of gallery fidelity. The rate of gallery fidelity was highest when temperatures were low and total number of wētā using the galleries was low. During winter and spring rate of moulting might be lower thus allowing records of the same non-adults as well as adults. With slower growth rate during the winter, wētā may have low requirement to move to larger refuge holes and individuals might also reduce their foraging activity when temperatures are low. However, the total number of wētā resighted each visit showed little seasonal variation, suggesting that rate of gallery fidelity is complex. Gallery fidelity by tree wētā throughout the year will prevent closely timed observations from being independent.

The number of wētā using our artificial galleries was higher in summer and autumn driven by observations of new individuals. The low occupancy might be the result of a change in the abundance of tree wētā if death rate is higher in spring and winter, but this was not supported by the gallery fidelity records. Alternatively, higher numbers might be the result of recruitment, but we were not observing nymphs newly hatched in our relatively large galleries at any time of year. Tree wētā are known to take about a year to mature and then can live a year as adults (Morgan-Richards 2000; Green 2005; Kelly 2006), but little synchrony with season has been recorded. In the summer and autumn sexual activity of adult *Hemideina* results in changes in their behaviour (Wehi et al. 2013a), suggesting that the seasonal change in numbers was likely to be a result of developmental and behavioural change.

Our second set of observations of the same galleries (in 2020) was beyond the possible life span of a tree wētā so were confident we were recording new individuals. We predicted that no change in the total number of wētā using the galleries would be detected four years after our 2016 observations because the management of four browsing mammal species within the reserve had been constant for 14 years and rodents (a known predator of tree wētā) were not controlled. When wētā numbers during the same months were compared 2020 with 2016 our expectations were met – suggesting that these direct counts were a suitable proxy for the relative abundance of *Hemideina* at this site.

We accept that a problem exists in fitting models to observations that are not independent of one another. The fitted values from generalised linear models are not affected, but if the standard errors used to justify significance of model coefficients are overstated, we will understate the significance of those predictors. We know from our observations that results from one gallery are not independent of the observations from neighbouring galleries because identifiable wētā have moved from one gallery to another. The proximity of the galleries has helped determine the range wētā have moved. If a future monitoring exercise is conducted to investigate wētā movement, we now know that detectors must be close enough for wētā movements to be detected. In contrast, if we want to monitor the number of wētā to evaluate ecosystem health, the results from galleries within dispersal range should be aggregated. This aggregation will then lead to spatially independent observations for analysis.

We must also consider the lack of temporal independence of observations. We observed that wētā have the potential to live long enough to be observed in multiple inspection times. If ecosystem monitoring is being undertaken, repeatedly observing a long-lived wētā is desirable. We again note that the fitted values from models are unbiased even if we do repeatedly observe some wētā; the wētā are after all actually observed. The needs of the real-world context trump the theoretical weaknesses of the approach. Modelling must either create observations with temporal independence by averaging over correlated observations or attempt to quantify the correlation to obtain more correct standard errors.

Models for spatial and temporal correlation do exist, such as generalised linear mixed models, but these models rely on having considerably greater amounts of data which may prove an expensive use of resources. For example, it would be better to have twice as many well-spaced artificial tree-hole refuges than to have to manage the intercorrelation among inconsistently and irregularly spaced ones. Similarly, having to manage multiple time points may not prove sufficiently useful in terms of the goal of forest ecosystem monitoring compared to the extra work in data collection and subsequent analysis.

Recommendations for non-lethal monitoring of tree wētā using artificial galleries

Location: Set up artificial refuge holes (wooden boxes) with small entrance holes (*c*. 15–20 mm diameter) and spacious cavity (e.g. 60×120 mm; Bleakley et al. 2006; or volume of 110 cm^3; Kelly 2006). Galleries can be mounted directly onto tree trunks at a height that allows easy visual inspection. We found no relationship between height from ground and use by tree wētā, but our range was very narrow (0.8–1.6 m from ground). Other studies suggest there may be density dependent effects (Rufaut & Gibbs 2003) and cave wētā (Rhaphidophoridae) may prefer galleries close to the ground (Bowie et al. 2006). The size of tree trunk and tree species is likely to influence wētā numbers (Wehi et al. 2015). If the goal is to compare before and after (time series) then these traits are of little importance as long as they do not change (i.e. gallery remains in the same location). However, if comparing among sites, then it is recommended that variability is reduced by using the same tree species of similar trunk dimensions. To maximise use by tree wētā select tree species they are known to eat (e.g. putaputaweta, mahoe, totara) and avoid sites with artificial lighting (Wehi et al. 2015).

Spacing and number: The furthest distance a wētā travelled in our study was 35 m. Plan studies around this distance. If you do not want to capture the same individuals, then the galleries would have to be placed further apart. Set up artificial refuge galleries 50–100 m apart from one another to reduce the chance of recording the same individual (Morgan-Richards et al. 2000). However, a cluster of closely spaced galleries can be used if comparing among years. We recommend using enough artificial refuge galleries to record at least 20 individuals. As occupancy rate will be site (and season) dependent, the number of galleries required must be estimated on prior knowledge. We recommend using 50 artificial refuge galleries unless other information is available.

Timing: Record the number of tree wētā using the galleries at the same time of year every year. If possible, record well before removal of mammalian predators and continue monitoring for at least five years. Given the seasonal change in their behaviour with harem formation, the number of wētā observed should always be compared for the same season. We recommend monitoring in the summer or autumn. Site fidelity rate is high so expect about half of the observations to be resightings if monitoring occurs more frequently than once a year.

Observations: Record species and sex of individuals. Our data suggest that female adult tree wētā may live longer than males.

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