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ORIGINAL ARTICLE

Agroecological management of a soil-dwelling orthopteran pest in vineyards

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Abstract The efficacy of different combinations of undervine and inter-row treatments for managing a soil-dwelling orthopteran pest, weta (*Hemiandrus* sp.), in vineyards was investigated over 2 seasons. This insect damages vine buds, thus reducing subsequent grape yield. The undervine treatments comprised pea straw mulch, mussel shells, tick beans [*Vicia faba* Linn. var *minor* (Fab)], plastic sleeves on vine trunks (treated control) and control (no intervention), while inter-rows contained either the existing vegetation or tick beans. Treatments were arranged in a randomized complete block design with 10 replicates. Data were collected on weta densities, damage to beans and components of yield. The latter were numbers of bud laid down per vine, shoots per bud, clusters per shoot, grape bunches per vine, bunch weight and yield. The undervine treatments significantly affected all variables except the number of shoots per bud. In contrast, none of the variables was significantly affected by the inter-row treatments or their interaction with undervine treatments, apart from weta density. At the end of the experiment, weta density in the shell treatment was about 58% lower than in the control. As a result, there was about 39% significant yield increase in that treatment compared to the control. Although the undervine beans and sleeves treatments increased yield, there were no reductions in weta density. With undervine beans, the insect fed on the bean plants instead of vine buds. Thus, yield in that treatment was approximately 28% higher than in the control. These results demonstrate that simple agroecological management approaches can reduce above-ground damage by soil-dwelling insects.

Key words cover crops; grapevine yield; pest management; soil-dwelling insects; vineyards; yield loss

Introduction

Pests that spend the major part of their development living in the soil can be economically important in crop production (Klein, 1988; Brown & Gange, 1989; Blossey & Hunt-Joshi, 2003; Jackson & Klein, 2006). Their feeding activity can cause extensive damage to plants (Wood & Cowei, 1988; Blossey & Hunt-Joshi, 2003). For instance, larvae of the beetles *Melolontha* sp. Fabricius, 1775, *Holotrichaia* sp. Hope, 1837, *Leucopholis* sp. Dejean, 1833, *Oryctes* sp. Illiger, 1789, etc. are subterranean and feed on plant roots, while adults are polyphagous, feeding on leaves and sometimes, unripe fruits (Hill, 1983; Keller & Zimmermann, 2005; Jackson & Klein, 2006). Other taxa such as mole crickets (*Gryllotalpa* sp. Latreille, 1802), crickets (*Acheta* sp. Linnaeus, 1758, *Brachytrupes* sp. Serville, 1839) and larvae from some lepidopteran families (e.g., Hepialidae, Noctuidae,

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Pyralidae, Castiniidae) live in burrows in the soil, which they exit at night and damage plants by feeding on young shoots (Hill, 1983; Wylie & Martin, 2012).

The management of these pests is difficult because they are subterranean and their presence is not usually detected until the plants are damaged (Musick, 1985; Jackson, 1999). Many farmers, therefore, rely on prophylactic chemical use to prevent damage, but this can result in problems of pesticide residues in plants, outbreaks of secondary pests and insecticide resistance (Jackson *et al.*, 2000; Lacey & Shapiro-Ilan, 2008). Research aimed at developing alternative approaches for managing soil-dwelling insect pests has focused on the use of entomopathogenic microbes such as fungi [*Beauveria bassiana* (Balsamo) Vuillemin (1912), and *Metarhizium anisopliae* (Metchnikoff) Sorokin (1883)], nematodes (*Heterorhabditis* sp. Poinar, 1976, *Steinernema* sp.) and bacteria (*Bacillus* sp. Cohn, 1872, *Serratia* sp. Bizio, 1823) (Shah & Pell, 2003; Ansari *et al.*, 2008; Lacey & Shapiro-Ilan, 2008; Jackson & Jaronski, 2009; Pereault *et al.*, 2009). However, this strategy has some limitations, such as entomopathogenic and microbial products being unable to reach the target pest in the soil, as well as the failure of most applied microbes to survive in the soil environment (Jackson, 1999). Therefore, there is a need to explore other approaches for managing these pests.

In perennial crops (e.g., orchards and vineyards), mulch applied to understorey soil enhanced the abundance of generalist predators and other potential biocontrol agents and these were considered to reduce the population of subterranean stages of some insect pests (Robertson *et al.*, 1994; Mathews *et al.*, 2002; Brown & Tworkoski, 2004; Mathews *et al.*, 2004; Addison *et al.*, 2013; Campos-Herrera *et al.*, 2015). Also, weed management strategies such as sowing centipedegrass [*Eremochloa ophiuroides* (Munro)] in the understoreys of peach orchards proved effective for controlling the soil-dwelling stages of *Conotrachelus nenuphar* (Herbst, 1797) (Coleoptera: Curculionidae), by serving as a physical barrier to emergence of its adults (Akotsen-Mensah *et al.*, 2012). Trap cropping has been used to effectively manage many insect pests including those living in the soil [e.g., *Agriotes* sp. Eschscholtz, 1829 (Coleoptera: Elateridae)] in perennial fruit crops (Bugg *et al.*, 1991; Bugg & Waddington, 1994; Liang & Haung, 1994; Landl & Glauninger, 2011). It involves planting a crop that is more attractive to the pest as either a food source or oviposition site than is the main crop (Shelton & Badenes-Perez, 2006; Zehnder *et al.*, 2007a). However, this strategy is knowledge-intensive and if the choice of trap plant is not carefully chosen, deploying it could increase the occurrence of other pests with or without reducing that of the target one (Bugg & Waddington, 1994; Shelton & Badenes-Perez, 2006).

Overall, these strategies have mostly been effective against the soil-dwelling stages of coleopteran and lepidopteran insect pests but evidence for their efficacy on burrowing insects in the order Orthoptera is not conclusive. This work therefore studied the efficacy of 2 types of mulch [pea straw (*Pisum sativum* L.) and mussel shells (*Perna canaliculus* Gmelin, 1791)] and a cover crop [*Vicia faba* Linn. var. *minor* (Fab.)] for the management of a soil-dwelling orthopteran pest, weta [*Hemiandrus* sp. "promontorius" (Johns, 2001)], in vineyards. This insect damages vines (*Vitis vinifera* L.) by feeding on either the compound bud or the primary bud inside the compound bud at budburst (Joanne Brady Constellation Brands NZ pers. comm, 2014). The latter leads to low yield from clusters growing on shoots arising from the inferior secondary buds, or sometimes no yield or canes for the next season if the whole compound bud is destroyed (Creasy & Creasy, 2009; Joanne Brady Constellation Brands NZ pers. comm, 2014). Damage is currently managed by tying plastic sleeves around vine trunks. These are slippery and make it difficult for weta to access the tender growing buds on the canes. However, this management technique is labor intensive and costly and sleeves often need to be repaired/replaced, leading to further costs. The current work therefore, contributes information on the use of cultural strategies (e.g., mulch and cover crops) to mitigate damage by soil-dwelling orthopterans. It also suggests the type of mulch and vineyard location that will produce optimum control of such pests. This will help reduce pesticide use in vineyards.

Materials and methods

Study period and site

This study was conducted in the Awatere Valley, Marlborough, New Zealand in the 2014–2015 and 2015–2016 seasons. The vine cultivar studied was Sauvignon Blanc. The work took place at a different site in each season in vineyards belonging to Constellation Brands, New Zealand. The experiments were established in September and the grapes harvested in March in each season. These vineyards were subjected to conventional management practices, involving the use of pesticides for weeds, pests and diseases management. For insect pests, methoxyfenozide (with trade name Prodigy) was applied at flowering for caterpillars of the leafroller complex [*Epiphyas postvittana* (Walker, 1863), *Ctenopsuestis* spp.,

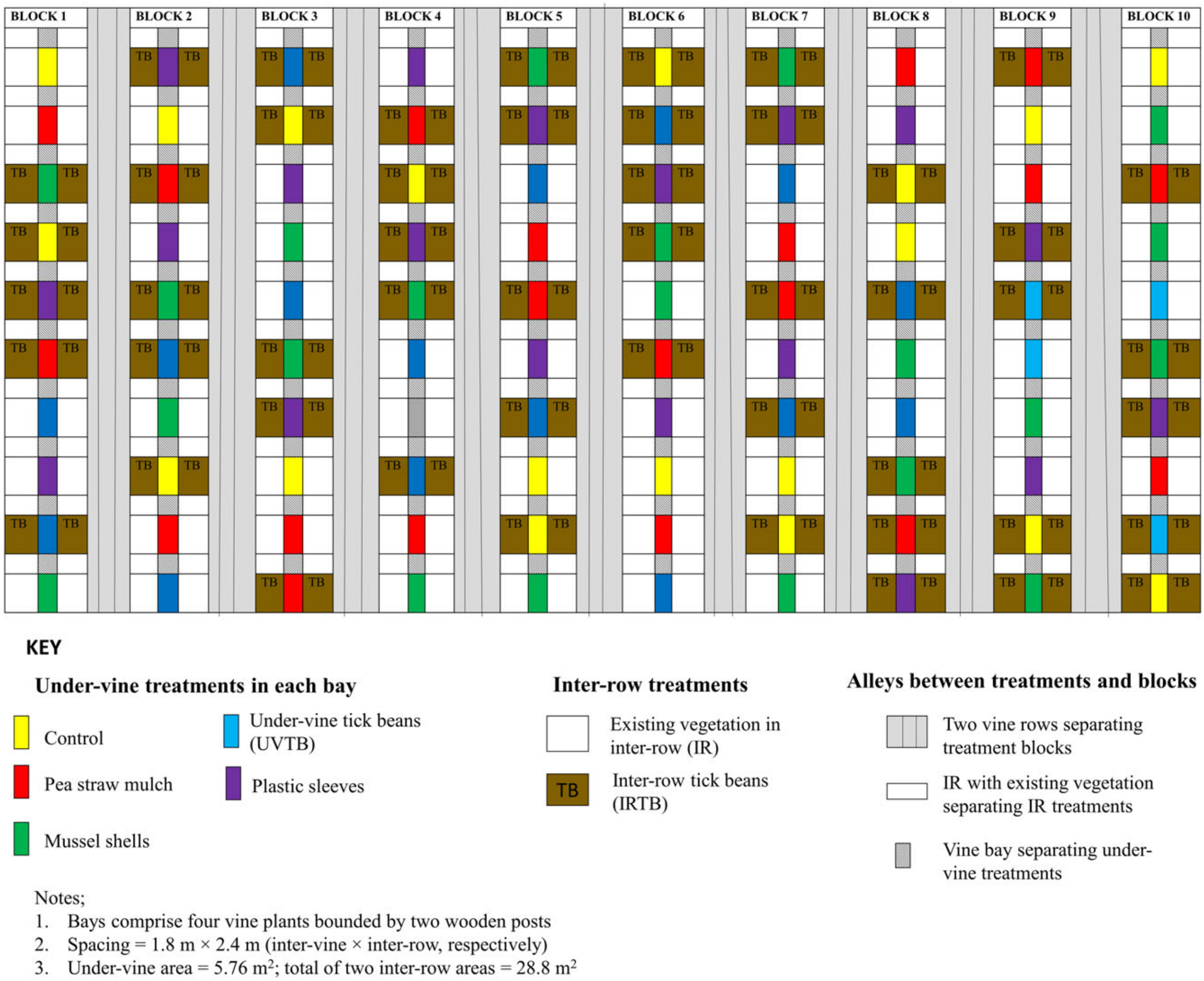

Fig. 1 Experimental layout in the vineyard in the 2014–2015 season, as 10 blocks of a 5 × 2 factorial. UVTB = undervine tick beans; IRTB = inter-row tick beans.

Planotortrix spp.]. This insecticide had no effect on weta and its application occurred outside the period weta cause damage in vineyards. Karate (lambda-cyhalothrin) is usually applied in the headlands of vineyards in response to the flight of grassgrubs [*Costelytra zealandica* (White, 1846)], but this was not sprayed in the vineyard blocks used for this experiment because of its potential effect on weta.

The climate in the Awatere Valley is more extreme than in other parts of the Marlborough region. It has mean daily minimum and maximum temperatures of 7.5 and 18.1 °C, respectively. This valley has an annual rainfall range of 557–1042 mm (http://www.wineresearch.org.nz/category/weather-data/awatere-valley-dashwood-weather-data/, accessed on 29 July, 2016).

Experimental layout

Treatments formed a 5 × 2 factorial structure, with 2 treatment factors, "undervine" and "inter-row" (see Fig. 1). The undervine treatment factor comprised 5 levels: control (no intervention), pea straw mulch, tick beans, mussel shells and plastic sleeves. The inter-row factor had 2 levels: the existing ryegrass (*Lolium perenne* L.)-dominant vegetation and tick beans. The 5 × 2 = 10 treatments were randomly allocated to 10 plots within each of 10 blocks, in a randomized complete block design (Table 1). "Plot" refers to an undervine area and the 2 inter-row areas on either side of it in a bay, while "block" consisted of all the plots in a vine row. A bay comprised 4 vine plants, which were bounded by 2 wooden posts.

Table 1 List of undervine and inter-row treatment pairs.

Undervine treatments	Inter-row treatments
Control (bare ground[†]/no intervention)	Existing ryegrass-dominant vegetation
Mussel shells	Existing ryegrass-dominant vegetation
Pea straw mulch	Existing ryegrass-dominant vegetation
Tick beans (UVTB)	Existing ryegrass-dominant vegetation
Plastic sleeves on stem	Existing ryegrass-dominant vegetation
Bare ground	Tick beans (IRTB)
Mussel shells	Tick beans (IRTB)
Pea straw mulch	Tick beans (IRTB)
Tick beans (UVTB)	Tick beans (IRTB)
Plastic sleeves on stem	Tick beans (IRTB)

[†]Bare ground means glyphosate was used to remove all the weeds.

IRTB = inter-row tick beans; UVTB = undervine tick beans.

Vines had a within-row spacing of 1.8 m and a between-row spacing of 2.4 m. The undervines and inter-rows in each bay occupied areas of 5.76 m^2 (=7.2 × 0.8) and 28.8 m^2 [=7.2 × (2 × 2.4 − 0.8)], respectively. The plots within the blocks were separated by a distance of 7.2 m (the length of a bay), while blocks were 4.8 m apart (2 buffer rows). In all, there was a total of 100 plots (i.e., 10 plots/block and 10 blocks). Figure 1 shows the experimental layout for the 2014–2015 season. The treatments were rerandomized in 2015–2016.

Tick beans were used as a cover crop because results from preliminary laboratory bioassays showed a high preference for this species by the weta (Smith, 2015). The seeds were sown at a rate of 135 kg/ha. Previous studies have shown that application of mulches in perennial crops increases the diversity of their associated arthropod assemblage to include pests' natural enemies, and that this could be exploited in pest management (Brown & Tworkoski, 2004; Mathews *et al.*, 2004; Addison *et al.*, 2013). This was the rationale for the inclusion of pea straw as a mulch treatment here. Mussel shells were included because of their potential as a physical barrier to weta exiting their burrows. The straw and shells were spread to completely cover the 5.76 m^2 undervine area in each replicate to a height of 0.10 m.

The inter-row treatment, existing ryegrass-dominant vegetation, paired with either bare ground or plastic sleeves served as untreated or treated controls, respectively.

Data collection

The 2 middle vines in each bay were assessed for number of buds laid down per vine, number of shoots/bud, clusters/shoot, number of grape bunches/vine, bunch weight (g), and grape yield (expressed in tons/ha), while initial and final weta densities were measured in the area between those 2 vines. Weta feeding damage (%) was recorded on tick bean plants located in the undervine and inter-row areas between the same 2 mid-vines in each plot.

Initial weta density was estimated by sampling the undervine areas of bays in the rows immediately opposite (i.e., to the right) of the experimental plots. This was to avoid disturbing the weta in the latter. Earlier studies of this pest found its density undervines to be relatively spatially uniform (Nboyine *et al.*, 2016). Hence, the density in the sampled bays was assumed to be similar to that in the experimental plots. To estimate this insect's density, the top 5 mm of soil between the 2 mid-vines in each sampled bay was scraped off to expose all burrows in that area. The burrows were counted, after which 3 of them were randomly selected and excavated with a shovel to a depth of 300 mm. The soil was spread on the ground and carefully searched to count the insects. Data were expressed as the number of weta-occupied burrows in an area of 1 m^2. Weta density at the end of the experiment was estimated for all treatments and replicates as above. The shells, mulch, and beans between the 2 middle vines were carefully removed before scraping off the top soil as above for the final density estimates.

The number of buds on the canes of each vine were counted before budburst, while the number of shoots and clusters (inflorescences) were counted after budburst. The data collected were then used to compute the ratios of numbers of shoots per bud and clusters per shoot.

Tick bean damage was estimated for undervine and inter-row areas by counting the number of bean plants with weta feeding damage in a 1.44 m^2 (= 1.8 m × 0.8 m) area. This was expressed as a percentage of the total number of plants within the area.

Data analysis

The data from each season were subjected to an analysis of variance (ANOVA) for a 5 (undervine) × 2 (inter-row) factorial laid out in 10 randomized blocks. Means were separated using their least significant difference (LSD) at a 5% probability level. For data on weta density, the effect of the treatments was determined by computing the logarithmic ratio of final to initial density before performing an ANOVA on it. This ratio measures the change in density due to the treatment effects.

To combine the results over the 2 trials (seasons), a randomized complete block ANOVA was performed, using the 10 treatment means for each variable measured in each trial, as a 5 (undervine) × 2 (inter-row) factorial with 2 blocks (= trials). Treatment means were again separated using their LSDs.

Results

In general, for all variables measured, the main effect of inter-row and the undervine × inter-row interaction were not statistically significant, with 2 exceptions, which are described later. Therefore, the results reported here focus on the main effect of the undervine treatments.

Number of buds laid down and effects of undervine management on components of yield

The mean numbers of buds laid down/vine at the start of the trial were 31.8 (± 1.32 SE) and 38.2 (± 1.48 SE) for the 2014–2015 and 2015–2016 seasons, respectively. There were no significant differences between treatments for the numbers of buds laid down in each season or for the results of their combined analysis.

Similarly, the number of shoots/bud was not significantly affected by the undervine treatments in either seasons ($P = 0.345$ and 0.406 for 2014–2015 and 2015–2016, respectively) or in the combined analysis results ($P = 0.512$). However, the overall mean number of shoots/bud in 2014–2015 (0.77) was significantly lower than in 2015–2016 (0.98) ($P < 0.001$).

There was, however, a significant main effect of undervine treatments on the number of clusters/shoot in 2014–2015 ($P < 0.001$) and 2015–2016 ($P < 0.001$). Combining the means of the two seasons also showed a significant undervine treatment effect ($P < 0.001$). The number of clusters/shoot in the shell treatment was approximately 1.3 times higher than that in the control (Fig. 2A). There were no significant differences between the number of clusters/shoot in shell, sleeves or undervine tick bean (UVTB) treatments. The control and straw mulch treatments were not significantly different from each other in terms of the number of clusters/shoot. The overall mean of this variable in 2015–2016 (1.60) was not significantly different from that in 2014–2015 (1.70) ($P = 0.083$).

The mean bunch weight was significantly affected by the undervine treatments in 2014–2015 ($P = 0.006$). In contrast, there was no significant undervine treatment effect for this variable in 2015–2016 ($P = 0.290$). The combined analysis showed a significant main effect of undervine treatments ($P = 0.017$). The mean bunch weights in UVTB, sleeves and shell treatments were about 8%–16% higher than in the control ($P = 0.017$) (Fig. 2B). The overall mean bunch weight in 2015–2016 (105.00 g) was significantly higher than in 2014–2015 (80.20 g) ($P < 0.001$).

There was a significant undervine treatment effect for the number of bunches/vine and total grape yield in both seasons, and in the combined results. Yield was approximately 28%, 30%, and 39% higher in UVTB, sleeves, and shell treatments, respectively, compared to the control (Fig. 2D). The number of bunches per vine also increased significantly by 22%–37% in those treatments compared with the control (Figs. 2C and D). The overall mean grape yield and number of bunches/vine were significantly higher in 2015–2016 than in 2014–2015 ($P < 0.001$).

Effects of undervine management on weta density

In both seasons, initial weta densities were not significantly different between the treatments (Table 2). The density at the start of the experiment was approximately 1.10 and 1.60 weta/m^2 for the 2014–2015 and 2015–2016 seasons, respectively. The final density was, however, affected by the inter-row treatments, but in 2014–2015 ($P = 0.016$) only. The density was higher when the inter-rows were sown with beans than when the existing vegetation was maintained.

There was also a significant main effect of undervine treatments for final weta density in both seasons and in the results of the combined analysis. Among the undervine treatments, final density was significantly lower in the shell treatment than in the control, straw mulch, UVTB and sleeves treatments (Table 2). However, there were no significant differences between the control and straw mulch, UVTB and sleeves treatments.

The change in weta density (i.e., $\log_{10}$ final/initial weta density) in each season and their combined results showed a significant undervine treatments effect. This change was significantly higher in the shell treatment than in the others. There were no significant differences among the control, straw mulch, UVTB and sleeve treatments for their change in density. In 2015–2016, there was a significant interaction effect for change in weta density ($P = 0.043$). In that season, there was a significant 73% reduction in weta density when shells were used undervines and beans were sown in the inter rows. In contrast, weta density decreased by only 20% when shells were used undervines and the existing vegetation was maintained (Table 2).

The initial and final weta densities were significantly lower in 2014–2015 than in 2015–2016. However, the

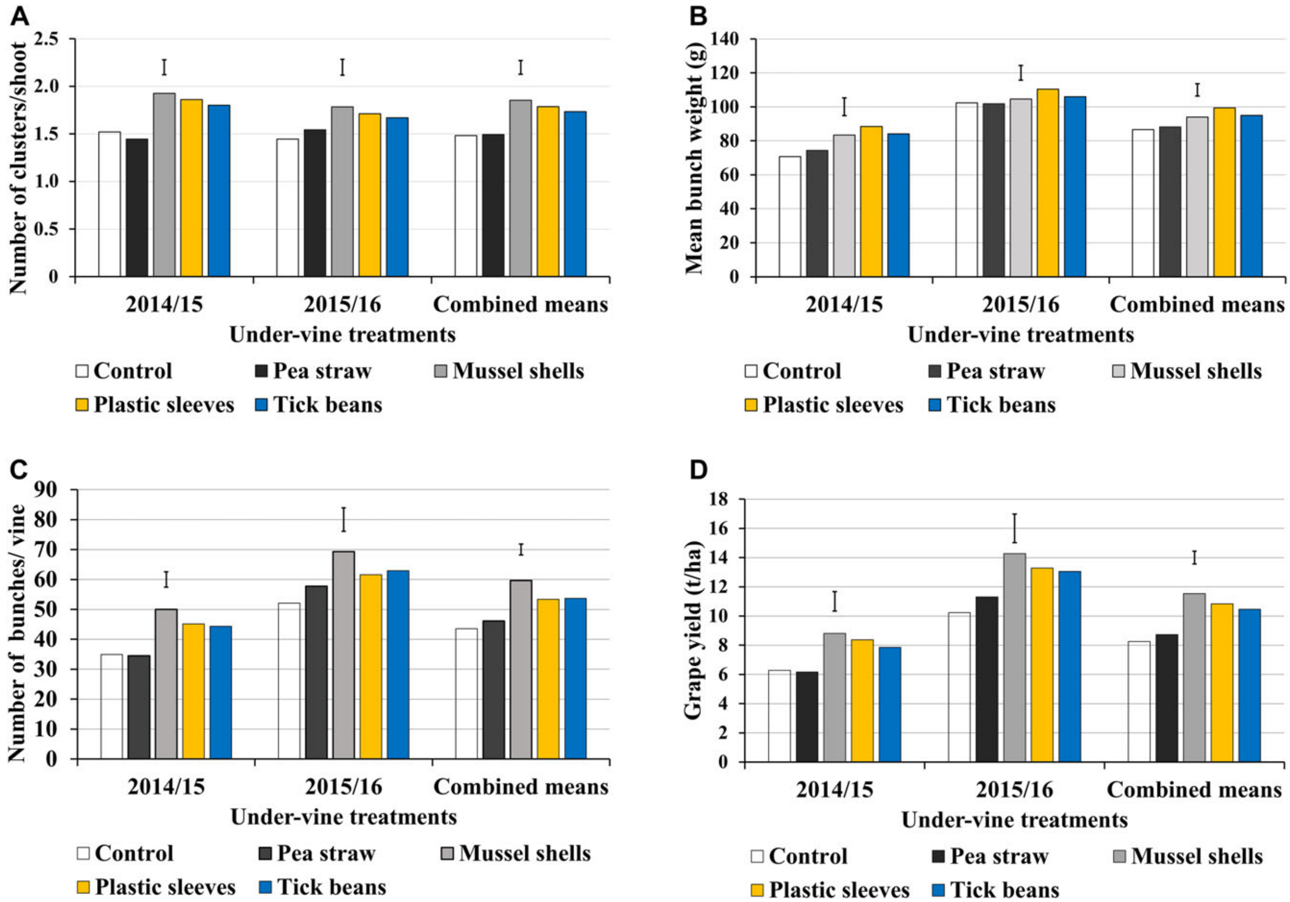

Fig. 2 Main effect of undervine weta management strategies on components of yield in 2014–2015 and 2015–2016 seasons and their combined means. Bars represent LSD at 5% level of probability. (A) Number of clusters per shoot; (B) mean bunch weight (g); (C) number of bunches/vine; and (D) grape yield (tons/ha).

extent of density changes was not significantly different between the seasons ($P = 0.992$; Table 2).

Weta feeding damage to tick beans

The extent of damage to tick beans was significantly different between the treatments in each season (Table 3). However, the combined analysis of the 2 seasons' means of weta damage to beans showed a significant treatment effect only at the 10% probability threshold ($P = 0.055$). The "UVTB only" treatment was the most damaged while the "inter-row tick beans (IRTB) only" and "Pea straw + IRTB" treatments were the least affected. The extent of feeding damage among IRTB, UVTB + IRTB, shells + IRTB, mulch + IRTB, and sleeves + IRTB treatments was not significantly different. The damage to beans in 2014–2015 was significantly lower than that in 2015–2016 ($P = 0.008$; Table 3).

Discussion

Effect of weta damage on the yield of grapevines

The yield of grapevines has a number of different components. These are buds per vine, shoots per bud, clusters per shoot, berries per cluster and the weight of individual berries (Dry, 2000; Keller, 2010). Weta damage to buds at budburst affected each of these yield components, except the number of shoots/bud. This was unaffected because secondary shoots arose and replaced the primary ones after weta had damaged most of the primary buds in the control and straw mulch treatments. However, these secondary shoots were relatively less productive than the primary ones, and their clusters, bunch number and bunch weights were smaller (Dry, 2000; Creasy & Creasy, 2009). In contrast, the efficacy of undervine beans, sleeves and shell treatments at reducing damage to primary buds resulted in higher numbers of

Table 2 Effect of management on density of weta in vineyards.

Undervine treatments	Inter-row treatments	Mean weta density in 2014–2015			Mean weta density in 2015–2016			Combined mean of weta density		
		Initial	Final	Log_{10}† (final/initial)	Initial	Final	Log_{10}† (final/initial)	Initial	Final	Log_{10}† (final/initial)
Control	Existing vegetation	0.98	0.99	0.041 (1.10)	1.67	1.35	−0.042 (0.91)	1.32	1.25	−0.001 (1.00)
Pea straw	Existing vegetation	1.07	0.90	−0.071 (0.85)	1.72	1.06	−0.296 (0.51)	1.39	0.97	−0.160 (0.69)
Mussel shells	Existing vegetation	0.97	0.32	−0.535 (0.29)	1.49	0.96	−0.096 (0.80)	1.23	0.71	−0.316 (0.48)
Tick beans	Existing vegetation	1.29	1.13	−0.017 (0.96)	1.82	1.32	0.056 (1.14)	1.56	1.34	0.019 (1.04)
Plastic sleeves	Existing vegetation	1.10	0.92	−0.089 (0.81)	1.70	1.72	0.055 (1.14)	1.34	1.39	−0.017 (0.96)
Control	Tick beans	1.15	1.13	−0.046 (0.90)	1.46	1.65	0.012 (1.03)	1.31	1.43	−0.017 (0.96)
Pea straw	Tick beans	1.06	1.17	0.116 (1.31)	1.63	1.40	−0.069 (0.85)	1.35	1.22	0.024 (1.06)
Mussel shells	Tick beans	0.92	0.49	−0.292 (0.51)	1.49	0.50	−0.576 (0.27)	1.21	0.47	−0.434 (0.37)
Tick beans	Tick beans	1.27	1.28	0.041 (1.10)	1.48	1.47	−0.014 (0.97)	1.37	1.36	0.024 (1.06)
Plastic sleeves	Tick beans	1.17	1.08	−0.014 (0.97)	1.77	1.60	0.063 (1.16)	1.47	1.39	0.013 (1.03)
Mean		1.10	0.94	−0.087	1.62	1.30	−0.091	1.36	1.15	−0.090 (0.87)
LSD (5%)‡		0.42	0.32	0.25	0.78	0.59	0.28	0.24	0.51	0.33
LSE (5%)§		0.30	0.23	0.18	0.55	0.42	0.80	0.17	0.36	0.23
P values										
Main effects										
Undervine (UV)		0.246	<0.001	<0.001	0.913	<0.001	<0.001	0.060	0.004	0.020
Inter-row (IR)		0.703	0.016	0.098	0.513	0.740	0.403	0.440	0.677	0.804
Interaction effect										
UV × IR		0.944	0.984	0.407	0.946	0.287	0.043	0.590	0.609	0.695
Significance of mean weta density in 2014–2015 versus 2015–2016 season								<0.001	0.002	0.992

Note: Figures in brackets are back transformed means.

†Log_{10} (final/initial) = change in weta density.

‡LSD (5%) = Least significant difference at 5% probability level.

§LSE (5%) = Least significant effect at 5% probability level—if a $\log_{10}$ ratio of final to initial density is greater in magnitude than the LSE (5%), then the change in density is significantly different to zero.

Table 3 Weta feeding damage (%) on tick beans in 2014–2015 and 2015–2016 seasons.

Undervine treatments	Inter-row treatments	Mean weta feeding damage (%) on tick beans in different seasons		Combined mean feeding damage (%)
		2014–2015	2015–2016	
Tick beans only	Existing vegetation	79.6	85.0	82.3
Control	Tick beans	50.9	73.7	62.3
Tick beans	Tick beans	66.9	74.3	70.6
Mussel shells	Tick beans	61.3	71.5	66.4
Pea straw	Tick beans	51.4	70.6	61.0
Plastic sleeves	Tick beans	63.5	72.3	67.9
Means		62.3	74.6	68.42
LSD ($P = 5\%$)		16. 5	7.5	12.8
P value		0.014	0.004	0.055
Significance of mean feeding damage in 2014 versus 2015 season				
P value				0.008

primary shoots. Consequently, the yield in the latter treatments was higher than that in the control and straw mulch treatments.

The yield of Sauvignon Blanc increases linearly with the number of clusters per vine up to the point where the availability of assimilates becomes limiting (Naor *et al.*, 2002). In this study, the number of clusters per vine in undervine beans, sleeves, and shell treatment probably exceeded this threshold. Hence, the lack of differences between the yields of vines in those treatments.

The differences between yield in the two seasons were partly due to weather patterns (Khanduja & Balasubrahmanyam, 1972; Keller, 2010). The weather in a particular year determines the number of bunches per bud, or fruitfulness, in the following season (Dry, 2000; Vasconcelos *et al.*, 2009). In contrast, bunch size (i.e., berry numbers and weight) is determined by the weather in the current season (Khanduja & Balasubrahmanyam, 1972; Sommer *et al.*, 2000; Sánchez & Dokoozlian, 2005; Vasconcelos *et al.*, 2009). Both 2014–2015 and 2015–2016 had good weather in their preceding season. However, temperature and light intensity during spring and flowering, when bunch size is determined, were relatively higher for the 2015–2016 than in 2014–2015 (http://www.wineresearch.org.nz/category/weather-data/awatere-valley, accessed on 29 July, 2016). Thus, the relatively good weather at budburst and flowering in 2015–2016 enhanced the yield in that season. Also, the number of buds laid down in 2015–2016 was higher than in 2014–2015. During the latter season, there was a regionwide outbreak of powdery mildew [*Erysiphe necator* Schwein. (1834)], which further negatively affected yields. All of these factors contributed to the significant yield differences between the two seasons.

Efficacy of weta management strategies

In the absence of appropriate management strategies, yield loss due to *H.* sp. "promontorius", averaged over the 2 seasons, was approximately 30.5%. The phenological stage (between budburst and the 2-leaf stage) at which this insect damage vines is the same as that of the rust mite, *Calepitrimerus vitis* (Nalepa). However, the highest loss due to the latter in vineyards is estimated at 23.7% (Walton *et al.*, 2007). Other economically important vineyard pests such as leafrollers (Lepidoptera: Tortricidae) and mealybugs (*Planococcus* Migula 1894 spp.) (Hemiptera: Pseudococcidae) are reported to directly and/or indirectly cause up to 12% and 50% yield losses, respectively (Lo & Murrell, 2000; Walton & Pringle, 2004; Atallah *et al.*, 2011). However, the latter pests can be managed with pesticides and/or biological control agents. These methods do not easily work with weta and other similar orthopteran pests because of their nocturnal and subterranean behavior (Musick, 1985).

To reduce this yield loss, the current work tested the effects of ground cover manipulation on this insect and its damage to vines. This strategy is often used for pest management in perennial crops (Zehnder *et al.*, 2007b; Fiedler *et al.*, 2008). Depending on the species of plant sown, it works by either serving as a trap plant for insect pests or providing resources (shelter, nectar, alternative food, and pollen; SNAP) that increases the "fitness" of natural enemies of pests. However, the latter does not always lead to suppression of target pest species population (Landis *et al.*, 2000; Berndt *et al.*, 2002; Rea *et al.*, 2002; English-Loeb *et al.*, 2003; Cook *et al.*, 2006; Midega *et al.*, 2008; Simpson *et al.*, 2011; Paredes *et al.*, 2015; Villa *et al.*, 2016). Here, tick beans sown undervines served as alternative food for weta, thus reducing their damage to vine buds at budburst. This strategy was effective because there were higher densities of this insect in the undervine areas where the beans were sown (Nboyine *et al.*, 2016).

In contrast, beans sown in the inter-rows were ineffective at preventing damage. This was probably due to low weta density in those areas (Nboyine *et al.*, 2016). Since weta densities are higher undervines than in the inter-rows, the insects had more frequent contacts with vines than bean plants in the IRTB treatment. This resulted in the vine buds sustaining significant damage in spite of the availability of alternative food in the inter-rows. However, feeding on beans in IRTB treatment increased slightly when access to the vines by weta was denied by either tying the vine trunks with sleeves or spreading shells undervines.

Tick beans can be host to a range of arthropod herbivores at different growth stages. Some of the key insect pests at the vegetative stage include aphids [*Aphis fabae* Scopoli (Europe), *A. cracivora* Koch (Africa, America, and Australia), *Acrythosiphon pisum* Harris (worldwide)], thrips [*Thrips* spp. (worldwide)], budworms [*Helicoverpa armigera* (Hübner) (Australia, Eurasia, Africa)], whitefly [*Bemisia tabaci* (Genn.) (Africa)], grasshoppers [*Chortophaga australion* Rehn & Hebard, *Microcentrum rhombifolium* (Saussure) (America)], etc. (Nuessly *et al.*, 2004; Stoddard *et al.*, 2010). However, apart from the grasshoppers, the other pests are not potential grape pests. Their threat can be minimized by removing the bean plants from vineyards after budburst; later vine growth stages are not damaged by weta. Besides pests, tick bean is also host to as many as 27 natural enemies of insect pests in the absence of insecticide applications (Nuessly *et al.*, 2004). Some of these (especially the generalist predators) could contribute towards controlling the population of important vine pests such as leafroller complex, mites, etc.

Mulching the understoreys of vineyards or growing some plant species there can be an effective strategy for weed control, moisture retention and insect pest and disease reduction (Jacometti *et al.*, 2007a,b; Thomson & Hoffmann, 2007; Steinmaus *et al.*, 2008; Guerra & Steenwerth, 2012). In this work, mussel shell mulch halved the density of weta. The shells appeared to be a physical barrier to weta exiting their burrows at night. This is the first study of the effect of shell mulch on a soil burrowing orthopteran insect. However, Crawford (2007) reported a similar decrease in the abundance of earthworms in vineyards mulched with mussel shells. The worms were thought to abandon areas with the shells because of the reduction in availability of organic matter on the soil surface and/or their inability to occasionally reach the soil surface due to the shells. Here, this reduction in weta density resulted in an about 39% increase in grape yield compared to the control. In contrast to the present work, previous studies with mussel shells and other reflective mulches did not associate them with increased yield (Crawford, 2007; Creasy *et al.*, 2007; Sandler *et al.*, 2009).

The straw mulch did not reduce weta density and damage to vine buds. Mulch materials of plant origin can increase the assemblage of arthropod predators and microbial biocontrol agents, which in turn can reduce the numbers of insect pests (Thomson & Hoffmann, 2007; Addison *et al.*, 2013). This did not occur probably because there is no known arthropod predator for this insect. A similar study by Gill *et al.* (2011) also found that organic mulches had no effect on the abundance of orthopterans (Acrididae and Gryllidae) and that they were unaffected by the predator assemblage. Thus, damage by soil-dwelling orthopteran pests may not be effectively reduced with mulches of plant origin because there may be no relevant natural enemies of this group of insects or that the mulches do not serve as an effective barrier to the exit of these insects from the soil.

The 3 management approaches, undervine tick beans, shell mulch and sleeve treatments, reduced weta damage substantially and there were no significant differences between them in terms of vine yield components. The beans were less expensive (i.e., US\$ 0.88/kg and US\$ 73.33/ha for the entire undervine area only) and can easily be sown with planters modified for undervine seed sowing. In addition to increasing natural enemy assemblages that could potentially reduce the population of other vine pests, they improve soil nitrogen content and condition (Köpke & Nemecek, 2010). In contrast, mussel shells were freely available, but the cost of transporting them to vineyards was about US\$ 12.61/m^3 using smaller trucks. Accurate estimates of the transport cost of shells are difficult because it varies with distance between collection site and vineyard. However, this cost could be substantially reduced if they are transported in large trucks that can carry at least 10 tons of shells at a time. Shell mulches are applied once and they last for at least 5 years. Machines are also available for spreading the shells undervines. The sleeve treatment costs US\$ 300.00/ha, excluding the cost of repairing them annually. These sleeves have no additional beneficial role in vineyards apart from mitigating weta damage. Meanwhile, they litter vineyards when strong wind and/or grazing sheep remove them from vine trunks, thus polluting the environment. Hence, apart from the monetary cost, the labor needed to repair sleeves or replant beans annually, makes the use of shell advantageous even if initial cost is higher than any of the former. Furthermore, the negative consequences of plastics on the environment make bean treatment a better option because it provides other important ecosystem services, while mitigating weta damage.

The significant difference in mean weta density between the two seasons was mainly a site effect. Generally, the site used for the 2015–2016 trial had higher densities of this insect than that used for the 2014–2015 (Nboyine *et al.*, unpublished data). However, the efficacies of the management strategies tested were unaffected by these differences in density.

Conclusions

The use of pesticides to manage soil-dwelling insect pests is less effective than for other pest guilds and can result in outbreaks of secondary pests and leave residues in food. This work, therefore, shows how simple locally available and inexpensive materials can be deployed to reduce damage by this group of insect pests in perennials such as vines. Mussel shell mulch was the best strategy to reduce weta damage to vines. They appeared to be a good physical barrier to the insects exiting their burrow. Perhaps, other locally available dense materials, such as bark, could be used in perennial crops to reduce exit and/or emergence of soil-dwelling stages of arthropod pests at locations where mussel shells are unavailable or expensive. Tick beans sown undervines were also effective at reducing damage to vines by serving as alternative food to the insect. However, further studies to develop protocols on the number of vine rows that should be mulched with mussel shells or sown with undervine tick beans per hectare are needed.

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Disclosures

The authors declare that they have no conflict of interest.

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