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Infestation of *Glycaspis brimblecombei* (Hemiptera: Psyllidae) on three *Eucalyptus* species in selected ecological zones in Malawi

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Abstract

The study determined variations in incidence, severity and damage of *Glycaspis brimblecombei* among *Eucalyptus* species and ecological zones, and the interaction between *Eucalyptus* species and ecological zones. Additionally, the study determined variation in pest abundance between the upper, middle and lower parts of the tree crown. The study was conducted in six districts located in four ecological zones in Malawi. *Eucalyptus* stands established in 2014–2016 or coppices from trees cut in that period were sampled for *G. brimblecombei* infestation. A significant interaction was found between *Eucalyptus* species and ecological zones on *G. brimblecombei* infestation. Significant differences were observed between ecological zones in *G. brimblecombei* infestation with lowest incidence, severity and damage being found in the cooler ecological zone M. *Eucalyptus camaldulensis* and *Eucalyptus tereticornis* showed high susceptibility to *G. brimblecombei* compared to *Eucalyptus grandis*. There were no significant differences in abundance between the upper, middle and lower tree crown parts of each *Eucalyptus* species. Control efforts for this psyllid should focus on breeding and planting of resistant *Eucalyptus* varieties in specifically recommended sites. The uniform distribution of the pest on different tree crown parts implies that use of contact insecticides on a large scale would be tedious and expensive.

Résumé

L'étude a permis de déterminer les variations d'incidence, de gravité et les dommages causés par Glycaspis brimblecombei parmi les espèces d'*Eucalyptus* et les zones écologiques, ainsi que l'interaction entre les espèces d'*Eucalyptus* et les zones écologiques. En outre, l'étude a déterminé la variation de l'abondance des organismes nuisibles entre les parties supérieures, moyennes et inférieures de la cime de cette arbre. L'étude a été menée dans six quartiers situés dans quatre zones écologiques de Malawi. La population d'*Eucalyptus* a été établie en 2014-2016 dont taillis d'arbres coupés au cours de cette période ont été échantillonnés pour l'infestation par *G. brimblecombei*. Une interaction significative a été observée entre les espèces d'*Eucalyptus* et les zones écologiques lors de l'infestation de *G. brimblecombei*. Des différences significatives ont été observées entre les zones écologiques d'infestation par *G. brimblecombei*, l'incidence et la gravité et les dommages les plus faibles ayant été constatés dans la zone écologique plus froide, M. *Eucalyptus* camaldulensis et *Eucalyptus* tereticornis présentaient une sensibilité élevée à *G. brimblecombei* par rapport à *Eucalyptus* grandis. Il n'y avait pas de différences d'abondance significatives entre les cimes supérieure, moyenne et inférieure de chaque espèce d'*Eucalyptus*. Les efforts de lutte contre ce psylle doivent être axés sur la sélection et la plantation de variétés d'*Eucalyptus* résistantes dans des sites spécifiquement recommandés. La distribution uniforme de l'organisme nuisible sur différentes parties de la cime des arbres montre que l'utilisation d'insecticides de contact à grande échelle serait fastidieuse et chère.

KEYWORDS

forest entomology, insect pest, red gum lerp psyllid, Southern Africa

1 | INTRODUCTION

Glycaspis brimblecombei Moore (Hemiptera: Psyllidae), also known as red gum lerp psyllid, belongs to a genus of jumping plant lice called *Glycaspis* Taylor (Mannu et al., 2018; Tsagkarakis, Kalaitzaki, & Balotis, 2014; Wylie & Speight, 2012). It is native of Australia and feeds on different *Eucalyptus* species (Frasconi, Rossi, Antonelli, & Loni, 2013; Mannu et al., 2018). *Glycaspis brimblecombei* was detected outside Australia for the first time in 1998 in California, USA (Dhahri, Ben Jamaa, Garcia, Boavida, & Branco, 2014), and has since been introduced in several continents, including Central and South America, Europe and Africa (Frasconi et al., 2013). In Africa, it was reported in Mauritius in 2001 (Wylie & Speight, 2012), Madagascar in 2004 (Peris-Felipo, Mancusi, Turrisi, & Jiménez-Peydró, 2011), South Africa in 2012, Zambia in 2015 (Chungu et al., 2016), Tanzania in 2016 (Petro, Mpiri, & Mkude, 2017) and Zimbabwe (Ndlela, Manyangadze, Sachisuko, Lingen, & Makowe, 2018).

Glycaspis brimblecombei nymphs and adults cause damage by sucking plant phloem sap through their straw-like mouthparts (de Queiroz, Melissa, Camargo, Dedecek, & Oliveira, 2016; Tuller et al., 2017; Wylie & Speight, 2012). It feeds on both young and mature leaves (de Queiroz et al., 2016; Tuller et al., 2017) and can thus infest trees of any age (de Queiroz et al., 2016). Severe infestation results in defoliation, shoot and branch dieback and, in extreme cases, death of some highly susceptible species (Huerta, Faúndez, & Araya, 2010; Pogetto, Wilcken, Gimenes, De Souza Christovam, & Prado, 2011; Wylie & Speight, 2012). The honeydew which is secreted by the nymphs causes development of black fungi (sooty mould), which reduces leaf photosynthesis (Huerta et al., 2010; Wylie & Speight, 2012). Although red gum lerp psyllid attacks a wide range of *Eucalyptus* species, it prefers members of the red gum species group: *Eucalyptus camaldulensis* and *Eucalyptus tereticornis* (Huerta et al., 2010; Mannu et al., 2018; Wylie & Speight, 2012). In southern California, red gum lerp psyllid infestation resulted in the death of thousands of mature *E. camaldulensis* trees and the removal costs of the dead trees were estimated at millions of dollars (Wylie & Speight, 2012).

In 2008, approximately 11.5% (2.2 million hectares) of the total *Eucalyptus* plantation area in the world occurred in Africa (Rejmánek & Richardson, 2011). *Eucalyptus* is the most widely planted genus in Africa, covering 22.4% of the total African plantations (Chamshama & Nwonwu, 2004). The government of Malawi through its department of forestry manages over 90,000 hectares of forest plantations, of which 26,640 hectares comprise *Eucalyptus* species (Government of Malawi, 2001). Private plantations cover 275,000 hectares (Government of Malawi, 2001) with *Eucalyptus* being the dominant species. *Eucalyptus* species dominate private plantations, especially those established in tobacco and tea estates. *Eucalyptus* species, mainly *Eucalyptus grandis*, *E. camaldulensis* and *E. tereticornis*, are the main hardwood species being planted, and they are planted for different purposes, including fuelwood, poles and timber (Government of Malawi, 2001; Kafakoma & Mataya, 2009; Mauambeta, Chitedze, Mumba, & Gama, 2010). Forest plantations play an important role in reducing pressure on indigenous forests (Petro, 2015).

Despite most *Eucalyptus* planting programmes being relatively free of pests, such problems have gradually increased with time (Hurley et al., 2016; Hurley, Slippers, Sathyapala, & Wingfield, 2017; Paine, Steinbauer, & Lawson, 2011) and they threaten the growth and productivity of *Eucalyptus* plantations worldwide (Paine et al., 2011). Modelling of the global distribution of red gum lerp psyllid by de Queiroz et al. (2013) indicates that southern Africa, which includes Malawi, falls in the region (between latitudes 20° and 40°) with highest probability of *G. brimblecombei* occurrence. In 2015, the Forestry Research Institute of Malawi (FRIM) observed *G. brimblecombei* infesting *Eucalyptus* trees across the country (Meke, Moyo, Jenya, & Nthenda, 2015). Therefore, the introduction of this pest in the country represents a potential danger to the country's plantation forestry. Since it was detected in 2015, no specific information necessary for the development of sustainable control measures of this pest in the country has been documented. Therefore, the objective of this study was to determine extent of *G. brimblecombei* infestation on *E. camaldulensis*, *E. tereticornis* and *E. grandis* in different ecological zones in Malawi. Specifically, the study determined the following: (a) variations in the incidence, severity and damage of *G. brimblecombei* among *Eucalyptus* species and ecological zones, and the interaction between *Eucalyptus* species and ecological zones, and (b) variation in the abundance of *G. brimblecombei* between the upper, middle and lower parts of the tree crown. Such information is a prerequisite for the development of sustainable and effective pest management strategies (Petro et al., 2017; Zheng et al., 2014).

TABLE 1 Characteristics of the sites where *Glycaspis brimblecombei* was sampled

Zone[a]	Districts sampled	Mean annual temperature (°C)[b]	Mean annual rainfall (mm)[b]	No. of stands sampled	Altitude (m) range of stands sampled
D	Mchinji	21.9	951.2	6	1,055–1,180
	Lilongwe	20.9	805.4	5	1,055–1,180
E	Ntchisi	21.5	855.9	8	970–1,315
M	Mzimba (Viphya)	19.9	949.0	10	1,680–1,730
L	Nkhata Bay	24.0	1,637.7	2	510–650
	Karonga	24.8	871.5	6	510–650

[a]Classification according to Hardcastle (1978).
[b]The World Bank Group Climate Change Knowledge Portal (2018).

2 | MATERIALS AND METHODS

2.1 | Study sites

Six districts, Mchinji, Lilongwe, Ntchisi, Mzimba, Nkhata Bay and Karonga, located in four ecological zones of Malawi were selected for the study (Table 1). These districts were selected based on the presence of stands of the three commonly grown *Eucalyptus* species in Malawi, *E. camaldulensis*, *E. tereticornis* and *E. grandis* (Meke et al., 2015). The selected districts were located in the central and northern regions of Malawi (Figure 1).

2.2 | Sampling and data collection

Field assessments were done from August to October 2017. *Eucalyptus* stands established in 2014–2016 or coppices from trees cut in that period were selected for ease of examining the whole crown foliage and collecting terminal shoots. Information on the

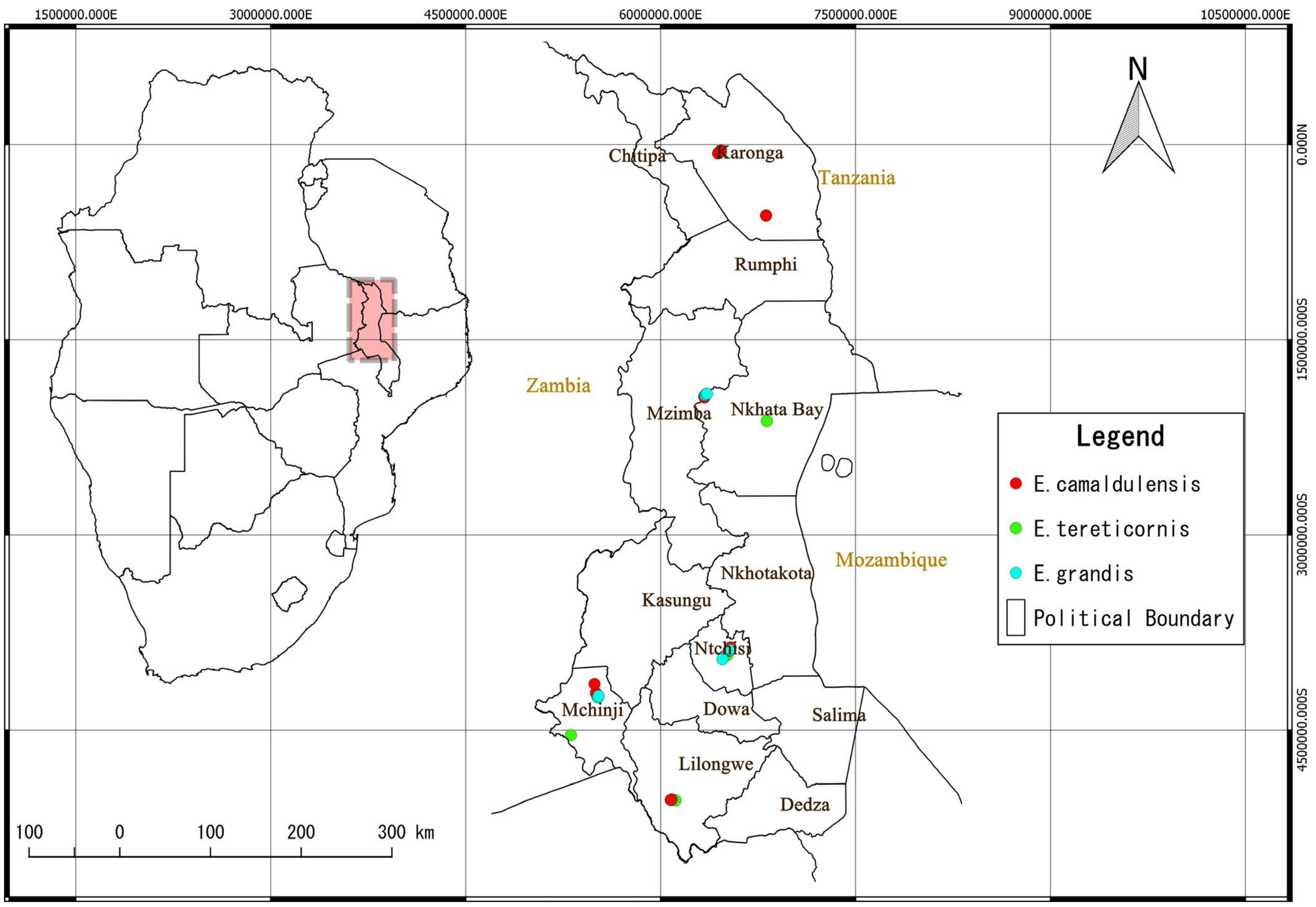

FIGURE 1 Map showing locations where *Glycaspis brimblecombei* infestation was sampled in Malawi

Eucalyptus species and age of stand was obtained from records if available or from custodians of the trees. A total of 37 *Eucalyptus* stands and 1,426 trees were sampled for incidence, severity and abundance of *G. brimblecombei*. The stands consisted of three *Eucalyptus* species, *E. camaldulensis*, *E. tereticornis* and *E. grandis*.

2.3 | Sampling technique

Stratified random sampling was employed in each *Eucalyptus* stand as suggested by van Laar and Akça (2007). Each *Eucalyptus* stand was divided into two or three blocks of about equal size depending on size (Nyeko, Mutitu, Otieno, Ngae, & Day, 2010; Petro, Madoffe, & Iddi, 2014). Within each block, plots of 10 × 10 tree lines (2 m × 2 m espacement) were randomly established from which 20 trees were randomly sampled (Nyeko et al., 2010) for incidence and severity of *G. brimblecombei* infestation. From the 20 trees, another sample of six trees was randomly selected for the assessment of *G. brimblecombei* abundance. When mixed *Eucalyptus* species occurred within a stand, at least 30 trees of the target species were sampled. For the purposes of sampling, all coppices from one stump were treated as a single tree.

2.4 | Field assessment of *G. brimblecombei*

Assessment of *G. brimblecombei* incidence (proportion of infested trees) was done on all 20 trees randomly selected in every plot. Incidence of red gum lerp psyllid infestation on a tree was based on the absence or presence of a lerp (waxy cover) produced by this pest on a tree (Petro et al., 2017). The severity of *G. brimblecombei* infestation was assessed visually on the whole crown foliage of each selected tree. Visual assessment was done in each cardinal direction, using severity scales adapted from Petro et al. (2017) as indicated below:

1. None (trees with no visible lerp)
2. Minor (trees with lerps on 1%–25% of total shoots)
3. Moderate (trees with lerps on >25%–50% of total shoots)
4. Severe (trees with lerps on >50%–75% of total shoots)
5. Very severe (trees with lerps on >75%–100% of total shoots).

Abundance of red gum lerp psyllid was assessed on a sub-sample of six trees within each plot. From each tree, a 30-cm terminal shoot was randomly collected (Dahlsten et al., 2003) from the lower, middle and upper crown branches in each cardinal direction, north, south, west and east (Kabashima, Paine, Daane, & Dreistadt, 2014; Leather, 2008). Categorisation of the tree crown into three levels was done visually by considering the crown as having three equal vertical sections, while cardinal directions were identified using a global positioning system (GPS). The number of lerps on each 30-cm terminal shoot was counted and recorded on a data sheet. In this study, abundance of *G. brimblecombei* thus referred to the density or number of lerps per 30-cm terminal shoot.

For every *Eucalyptus* stand, altitude and location coordinates were collected using a GPS. This was done within the stand if the canopy was open or on the edge of the stand in case of a closed canopy.

2.5 | Data analysis

For each plot, descriptive statistics were used to determine incidence (proportion of infested trees) and number of trees in each severity category. Incidence (proportion of trees infested) of *G. brimblecombei* per plot was calculated by dividing the number of infested trees by number of sampled trees as suggested by Petro et al. (2017). Average severity per plot was calculated using the formula adapted from Petro et al. (2017):

$$\text{Average servity} = \frac{(1\times a) + (2\times b) + (3\times c) + (4\times d) + (5\times e)}{N\,(\text{Total number of trees assessed per plot})} \qquad (1)$$

where 1, 2, 3, 4 and 5 are severity categories, and *a*, *b*, *c*, *d* and *e* are the numbers of trees examined in each severity category within the plot. For each plot, damage index was worked out by multiplying mean incidence and average severity (Petro et al., 2017).

Analysis of variance (ANOVA) in MINITAB 17 was used to determine variations in pest infestation (incidence, severity and damage) among *Eucalyptus* species and ecological zones, and interaction between these two main factors. Variation in the abundance of *G. brimblecombei* lerps between the lower, middle and upper crown parts of each *Eucalyptus* species was determined using ANOVA. Means were separated using Tukey's HSD, and 5% probability level was used to determine significance of variations. Prior to analysis, incidence data were square-root (largest possible value + 1–old variable)-transformed, severity and abundance data were $\log_{10}$ (old variable + 1)-transformed, and damage index data were square-root (old variable + 1)-transformed after testing for normality using the Shapiro–Wilk test. Means were separated using Tukey's HSD test, and 5% probability level was used to determine significance.

3 | RESULTS

3.1 | Infestation of *G. brimblecombei* on three *Eucalyptus* species in different ecological zones

The study examined 1,426 trees, the majority (43.5%) were *E. camaldulensis* followed by *E. tereticornis* (34.4%) and *E. grandis* (22.1%). Results of a two-way ANOVA showed a significant interaction between effects of *Eucalyptus* species and ecological zones on incidence, $F_{4,44} = 12.82$, $p < 0.01$; severity, $F_{4,44} = 15.40$, $p < 0.01$; and damage, $F_{4,44} = 16.00$, $p < 0.01$. Ecological zone L was not included in the two-way ANOVA due to insufficient number of species sampled.

One-way ANOVA to compare *Eucalyptus* species revealed that *G. brimblecombei* damage in zone E was significantly higher on *E. camaldulensis* (3.44) than on the other two species, *E. tereticornis* (1.05) and *E. grandis* (0.29), $F_{2,9} = 33.36$, $p < 0.01$ (Table 2). In zone M, damage was significantly higher on *E. camaldulensis* (2.04) and

TABLE 2 Incidence, severity and damage of *Glycaspis brimblecombei* infestation between *Eucalyptus* species in different ecological zones

Eucalyptus species and ecological zones	Total sample (no. of trees)	Incidence (%)	Average severity	Damage index	Severity class (% of total sample)				
					1	2	3	4	5
Zone D									
E. camaldulensis	260	69.2[a]	1.6[a]	1.1[a]	50.0	42.31	6.9	0.8	0.0
E. tereticornis	150	49.2[a]	1.4[a]	0.7[a]	65.3	21.33	6.0	4.7	2.7
E. grandis	80	89.5[a]	2.2[a]	1.9[a]	20.0	48.75	26.3	2.5	2.5
$F_{2,21}$-value		2.25	2.56	2.44					
p-value		0.13	0.10	0.11					
Zone E									
E. camaldulensis	110	100.0[a]	3.4[a]	3.4[a]	0.9	16.4	28.2	40.0	14.6
E. tereticornis	80	72.8[b]	1.6[b]	1.1[b]	56.3	32.5	5.0	6.3	0.0
E. grandis	90	25.0[b]	1.1[b]	0.3[b]	86.7	12.2	1.1	0.0	0.0
$F_{2,9}$-value		13.98	38.21	33.36					
p-value		< 0.01	< 0.01	< 0.01					
Zone M									
E. camaldulensis	110	95.3[a]	2.2[a]	2.0[a]	15.5	61.8	13.6	9.1	0.0
E. tereticornis	131	97.2[a]	2.2[a]	2.1[a]	13.7	55.7	26.7	3.1	0.8
E. grandis	145	3.3[b]	1.1[b]	0.0[b]	97.9	2.1	0.0	0.0	0.0
$F_{2,14}$-value		161.98	61.49	180.08					
p-value		< 0.01	< 0.01	< 0.01					

Note: For each incidence, average severity and damage index values followed by different superscript letters within a column are significantly different at 5% probability level. Zone L not included due to insufficient number of species sampled.

E. tereticornis (2.11) than on *E. grandis* (0.04), $F_{2,9} = 180.08$, $p < 0.01$ (Table 2). One-way ANOVA to compare zones showed that on *E. camaldulensis*, damage was significantly higher in zone E (3.44) compared to zone D (1.07), $F_{3,24} = 10.47$, $p < 0.01$, while on *E. grandis*, damage was significantly higher in zone D (1.92) compared to zones E (0.29) and *M* (0.04), $F_{2,11} = 98.16$, $p < 0.01$ (Table 3).

3.2 | Variation in the abundance of *G. brimblecombei* between different tree crown parts

ANOVA showed no significant differences in the abundance of *G. brimblecombei* between the three tree crown parts of each *Eucalyptus* species, $p < 0.05$ (Table 4).

4 | DISCUSSION

4.1 | Infestation of *G. brimblecombei* on three *Eucalyptus* species in different ecological zones

Knowledge of the variation in infestation of *G. brimblecombei* on different *Eucalyptus* species in different sites is essential to effectively control this pest in the country. Results from this study indicate that *G. brimblecombei* has spread widely as it was observed in all ecological zones and on all *Eucalyptus* species studied. This implies that the pest is capable of surviving under a wide range of climatic conditions in Malawi. The study confirms predictions by de Queiroz et al. (2013) that Malawi falls within the region with the highest potential distribution of *G. brimblecombei*. The significant interaction effect of *Eucalyptus* species and ecological zones on *G. brimblecombei* incidence, severity and damage suggests that infestation of this pest on *Eucalyptus* trees is influenced by both the genetic makeup of the host and environmental factors.

Nyeko et al. (2010) indicated that differences in infestation on the same species in different sites may be attributed to differences in climatic variables, provenances, soil factors, silvicultural practices and crop type (coppice against first crop). Depending on the interaction of various environmental factors, an environment may be favourable or unfavourable to an insect (Ndlela et al., 2018). In the current study, lowest incidence (3.33%), severity (1.06) and damage (0.04) were observed on *E. grandis* in ecological zone M. Ecological zone M had the lowest mean annual temperature (19.86°C) among the three ecological zones. Cuello, López, Andorno, Hernández, and Botto (2017) correlated low temperatures with low *G. brimblecombei* infestation in a field experiment in Argentina. While comparing resistance of 21 *Eucalyptus* species to *G. brimblecombei* in northern California, Brennan, Hrusa, Weinbaum, and Levison (2001) noticed high infestation in warmer areas than cooler areas. Temperature affects the rate of growth, development, survival and range of an insect (Ndlela et al., 2018; Nyeko, Mutitu, & Day, 2009). Most insects are poikilothermic; that is, their body temperature changes with temperature change in their immediate environment (Gullan & Cranston, 2010), although not analysed in the current study. An

TABLE 3 Incidence, severity and damage of *Glycaspis brimblecombei* between different ecological zones on three *Eucalyptus* species

Eucalyptus species and ecological zones	Total sample (no. of trees)	Incidence (%)	Average severity	Damage index	Severity class (% of total sample) 1	2	3	4	5
E. camaldulensis									
Zone D	260	69.2^{b}	1.6^{b}	1.1^{b}	50.0	42.3	6.9	0.8	0.0
Zone E	110	100.0^{a}	3.4^{a}	3.4^{a}	0.9	16.4	28.2	40.0	14.6
Zone M	110	95.3^{ab}	2.2^{b}	2.0^{ab}	15.5	61.8	13.6	9.1	0.0
Zone L	140	76.9^{ab}	2.1^{b}	1.6^{b}	36.4	28.6	15.7	11.4	7.9
$F_{3,24}$-value		5.68	13.90	10.47					
p-value		< 0.01	< 0.01	< 0.01					
E. tereticornis									
Zone D	150	49.2^{b}	1.4^{a}	0.7^{a}	65.3	21.3	6.0	4.7	2.8
Zone E	80	72.8^{ab}	1.6^{a}	1.1^{a}	56.3	32.5	5.0	6.3	0.0
Zone M	131	97.2^{a}	2.2^{a}	2.1^{a}	13.7	55.7	26.7	3.1	0.8
Zone L	130	58.1^{ab}	1.5^{a}	0.9^{a}	72.3	13.1	5.4	5.4	3.9
$F_{3,18}$-value		3.88	1.91	2.63					
p-value		0.03	0.16	0.08					
E. grandis									
Zone D	80	89.5^{a}	2.2^{a}	1.9^{a}	20.0	48.8	26.3	2.5	2.5
Zone E	90	25.0^{b}	1.1^{b}	0.3^{b}	86.7	12.2	1.1	0.0	0.0
Zone M	145	3.3^{b}	1.1^{b}	0.0^{b}	97.9	2.1	0.0	0.0	0.0
$F_{2,11}$-value		59.62	67.58	98.16					
p-value		< 0.01	< 0.01	< 0.01					

Note: For each incidence, average severity and damage index values followed by different superscript letters within a column are significantly different at 5% probability level.

increase in temperature within the optimal range will speed up the metabolism of an insect and consequently increase its rate of development (Gullan & Cranston, 2010) and thus insect population (Mendel, Protasov, Fisher, & Salle, 2004).

The study revealed substantial differences in *G. brimblecombei* incidence, severity and damage between *Eucalyptus* species in each ecological zone (Tables 2 and 3). However, damage index is particularly important in describing infestation because it is a product of both incidence and severity. Considering the highest and lowest damage indices in each ecological zone, variation in infestation between *Eucalyptus* species was very high in zone M, 98.10%, followed by zone E, 91.57%, and zone D, 63.54%. According to several authors, *Eucalyptus species* showing a damage index (DI) = 0 are considered to be resistant, 0 < DI < 0.1 as tolerant, 0.1 ≤ DI < 0.5 as moderately susceptible and DI ≥ 0.5 as highly susceptible (Nyeko et al., 2010; Petro et al., 2017). Based on this classification, it means in ecological zone E, *E. camaldulensis* (DI = 3.44) and *E. tereticornis* (DI = 1.05) can be regarded as highly susceptible, while *E. grandis* (DI = 0.29) can be classified as moderately susceptible. In ecological zone M, *E. camaldulensis* (DI = 2.04) and *E. tereticornis* (DI = 2.11) can be classified as highly susceptible, while *E. grandis* (DI = 0.04) can be regarded as resistant. In ecological zone D, all three species, *E. camaldulensis* (with DI = 1.07), *E. tereticornis* (with DI = 0.70) and *E. grandis* (with DI = 1.92), can be considered as highly susceptible to *G. brimblecombei* infestation. These findings support the assertion that *Eucalyptus* species vary in their susceptibility to *G. brimblecombei* (Ndlela et al., 2018; Petro et al., 2017; Tuller et al., 2017). The results also support the view that members of the red gum family, *E. camaldulensis* and *E. tereticornis*, are highly susceptible to *G. brimblecombei* (Chungu et al., 2016; Cuello et al., 2017; Lucia, Naspi, Zerba, & Masuh, 2016; Petro et al., 2017; Tuller et al., 2017) and that *E. grandis* is resistant or moderately susceptible (Chungu et al., 2016; Lucia et al., 2016; Messoudi, Maatouf, & Rohi, 2017; Petro et al., 2017). The high damage index observed on *E. grandis* in zone D could

TABLE 4 Variation in the abundance *Glycaspis brimblecombei* lerps between tree crown parts

Crown part	*Eucalyptus* species *E. camaldulensis*	*E. tereticornis*	*E. grandis*
Lower	19.14^{a}	7.40^{a}	2.68^{a}
Middle	27.31^{a}	11.27^{a}	3.56^{a}
Upper	27.64^{a}	10.30^{a}	2.93^{a}
F-value	0.38	0.10	0.06
p-value	0.68	0.91	0.94

Note: Values followed by different superscript letters within a column are significantly different at 5% probability level.

be attributed to dispersal of psyllids from the highly infested nearby *E. camaldulensis* and *E. tereticornis* stands. Adult *G. brimblecombei* might migrate to nonhost *Eucalyptus* species growing in proximity with susceptible *Eucalyptus* species (Brennan et al., 2001; Cuello et al., 2017) as a survival mechanism when intraspecific competition increases or when host plant food becomes less suitable (Valente & Hodkinson, 2009). Although environmental factors also play a role, the variation in infestation is to a large extent genetically controlled (Nadel & Slippers, 2011). Findings from this study are important because they can be used to recommend which *Eucalyptus* species to plant in different *G. brimblecombei* infested areas. The results also suggest there is a potential for selective breeding of resistant genotypes, although further research is required to understand the mechanisms behind such resistance. Generally, this study indicates the possibility of controlling *G. brimblecombei* through planting of resistant or less susceptible *Eucalyptus* species as was also noted in other studies (Lawson, Griffiths, & Helen, 2013).

4.2 | Variation in the abundance of *G. brimblecombei* between different tree crown parts

There were no significant differences in the abundance of *G. brimblecombei* lerps between different tree crown parts of each *Eucalyptus* species. In Tanzania, Petro et al. (2014) also observed no significant differences in the abundance of *Leptocybe invasa* galls between different crown parts of *Eucalyptus* trees (1–6 years old). The lack of significant variation was attributed to the open crown structure of *Eucalyptus* trees (Petro et al., 2014). Similarly, Chilima and Leather (2001) found no significant differences between populations of *Pinus boerneri* (pine woolly aphid) on different levels of the crown (on outer shoot-end sections) of 5-year-old *Pinus kesiya* trees in Malawi and suggested it was due to an open-canopy structure. A study by Petro and Madoffe (2011) also found no evidence of preference of *P. boerneri* damage to any particular levels of the tree crown on *Pinus patula* and *Pinus elliotti* in Sao Hill Forest Plantation in Tanzania.

Crown structure affects the microenvironment (light, temperature, wind, humidity and other metabolic activities) within the canopy through its effect on the amount of solar radiation that reaches the different parts of the plant (Chilima & Leather, 2001; Petro & Madoffe, 2011). Differences in these microclimatic conditions have been shown to influence the distribution and performance of herbivorous insects on different tree parts (Chilima & Leather, 2001; Petro & Madoffe, 2011). Herbivorous insects have a preference for infesting those parts of the tree on which they can achieve the highest reproductive and developmental rates (Chilima & Leather, 2001). Leaves positioned in the microenvironment that receives highest solar radiation would have highest nitrogen content, which in turn affects the performance and population dynamics of insects (Chilima & Leather, 2001). An open crown structure receives light, moisture and wind in almost equal proportion (Chilima & Leather, 2001; Petro et al., 2014). This might explain the lack of significant variation in the number of lerps between the three crown parts (lower, middle and upper) from which sample terminal shoots were collected for this study. Following these findings, it is therefore suggested that when sampling for abundance of *G. brimblecombei* on young *Eucalyptus* trees, samples could be collected from terminal shoots in any direction at any convenient height on the crown. However, this finding also suggests that it could be difficult and expensive to use contact insecticides on a large scale, since it could mean spraying the whole crown. Therefore, efforts to control this pest might also be directed towards introduction and monitoring of the biological control agent, *Psyllaephagus bliteus* Riek (Hymenoptera: Encyrtidae), which has proven effective in other countries (see, e.g., Dahlsten et al., 2005; Huerta, Jaramillo, & Araya, 2011; Ndlela et al., 2018).

5 | CONCLUSION AND RECOMMENDATIONS

The study has shown that infestation of *G. brimblecombei* varies significantly among *Eucalyptus*. Among the three *Eucalyptus* species, *E. camaldulensis* and *E. tereticornis* showed high susceptibility to *G. brimblecombei* compared to *E. grandis*, and, as a result, may not be suitable for planting in ecological zones favourable to this pest. Significant differences in the infestation of this pest were also observed between ecological zones. Among the selected ecological zones, zone M showed the lowest *G. brimblecombei* infestation. Ecological zone M is a highland and experiences lowest mean annual temperature compared to the other zones. Thus, infestation of *G. brimblecombei* is affected by both genetic and environmental factors. The variation in *G. brimblecombei* infestation between *Eucalyptus* species presents an opportunity for selective breeding and planting of resistant or less susceptible varieties. Additionally, differences in infestation between ecological zones suggest future *Eucalyptus* planting programmes should also consider species site matching to avert threats posed by this pest.

No significant variations were found in the abundance of *G. brimblecombei* between different tree crown parts, implying that this psyllid has no preference for any particular part of the crown. Therefore, sampling of red gum lerp psyllid abundance on young *Eucalyptus* trees can be done on terminal shoots in any direction at any convenient height in the crown. However, lack of preference for any particular part of the crown suggests that it would be difficult and expensive to use contact insecticides on a large scale. This study was limited in that it provided single field visit findings on only three *Eucalyptus* species and a few selected ecological zones. Furthermore, the current study did not assess host reaction or pest behaviour to understand what mechanisms are responsible for host resistance to the pest. Therefore, there is a need for extensive and long-term ecological studies to further improve knowledge of *G. brimblecombei* infestation and facilitate its control in Malawi and other tropical countries. Based on this study, the following areas of research are recommended:

1. Seasonal variability of *G. brimblecombei* in the country to understand how the pest responds to climate changes.

2. A study on the mechanisms governing resistance of *Eucalyptus* species to *G. brimblecombei* and therefore be able to better predict susceptibility of new genotypes or current genotypes planted in new areas.
3. Introducing and monitoring the performance of the biological control agent, *Psyllaephagus bliteus* Riek (Hymenoptera: Encyrtidae), in highly infested areas.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest in any form regarding the publication of this article.

AUTHORS' CONTRIBUTIONS

The study was carried out in collaboration among all authors. Vitumbiko Jere, Jarret Mhango and Herbert Jenya designed the study. Vitumbiko Jere anchored the field study and gathered the data. Vitumbiko Jere and Jarret Mhango performed the statistical analysis. Vitumbiko Jere managed the literature search and produced the initial draft. Jarret Mhango, Dalo Njera and Herbert Jenya critically revised and made suggestions to the initial draft. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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