Analysis on infestation and related ecology of chigger mites on large Chinese voles (*Eothenomys miletus*) in five provincial regions of Southwest China

Bei Li, Xian-Guo Guo, Tian-Guang Ren, Pei-Ying Peng, Wen-Yu Song, Yan Lv, Peng-Wu Yin, Zhe Liu, Xin-Hang Liu, Ti-Jun Qian

* Institute of Pathogens and Vectors, Yunnan Provincial Key Laboratory for Zoonosis Control and Prevention, Dali University, Dali, Yunnan, 671000, China
* Nursing College of Dali University, Dali, Yunnan, 671000, China
* Institute of Microbiology, Qujing Medical College, Qujing, Yunnan, 655011, China
* Beijing Health Vocational College, Beijing, 102402, China
* Central Hospital of Yingshou Economic and Technological Development Zone, Yingshou, Liaoning, 115007, China

**ARTICLE INFO**

Keywords: Acari, Chigger mite, Trombiculidae, Ectoparasite, Rodent, *Eothenomys miletus*

**ABSTRACT**

Based on a long-term field investigation in the five provincial regions of Southwest China between 2001 and 2019, the present paper studied the infestation and related ecology of chigger mites (chiggers) on the large Chinese vole (*Eothenomys miletus*), an endemic and dominant rodent species in the regions. A total of 52331 chiggers were collected from 2661 voles, and 52261 mites were identified as 185 species and 13 genera in the family Trombiculidae with very high species diversity. The identified 185 chigger species on *E. miletus* (a single rodent species) even exceeded those recorded in some countries. The overall infestation prevalence (*Pr* = 53.96%), mean abundance (*Ma* = 19.64) and mean intensity (*Mi* = 36.39) on *E. miletus* were much higher than those on some other rodent species in the same regions. Although the species composition showed a moderate similarity (*J* = 0.63) between male and female hosts (*E. miletus*), the infestation indices (*Pm* = 56.25%, *Ma* = 21.67) of chiggers on male hosts were higher than those on the females (*Pm* = 51.23%, *Ma* = 17.09) (*P* < 0.05). Two dominant chigger species, *Leptotrombidium scutellare* (*Cr* = 19.17%) and *L. sinicum* (*Cr* = 11.06%), showed an aggregated distribution pattern among different individuals of their host *E. miletus*, and a relatively high degree of positive association existed between the two dominant chigger species with *PCC* = 0.57, *DI* = 0.60 and *OI* = 0.62 ($X^2$ = 885.46, *P* < 0.001). *Leptotrombidium densipunctatum, Walchia koi, Heleniuma huai, L. scutellare* and *W. ewingi* showed a high degree of environmental adaptability to their environments with high niche breadths. The theoretical curve of the species abundance distribution of chigger community on *E. miletus* was successfully fitted with Preston’s lognormal distribution model. Based on the theoretical curve fitting, the expected total number of chigger species on *E. miletus* was roughly estimated to be 223 species, and 38 chigger species were probably missed in the sampling investigation.

**1. Introduction**

Chigger mites (trombiculid mites) are a large group of tiny arthropods and they are widely distributed in the world (Shatrov and Kudryashova 2006; Nielsen et al., 2021). It has been controversial about the taxonomic status of chigger mites. In some literature, all chigger mites have been placed in two families (Trombiculidae and Leuwenhoekiidae) under the order Trombidiiformes (Vercammen-Grandjean and Langston 1976; Nielsen et al., 2021). Of the complex life cycle of chigger mites, only the larval stage (often called “chiggers”) is the ectoparasite of other animals (the hosts), especially rodents and other small mammals (Li et al., 1997; Shatrov and Kudryashova 2006; Chaisiri et al., 2019). Chiggers are the exclusive vector of *Orientia tsutsugamushi*, the causative agent of scrub typhus (tsutsugamushi disease). Scrub typhus is an acute febrile zoonosis (zoonotic disease), which is...
prevalent in some parts of Asian (including China) and pacific regions with about one million new cases each year and more than one billion people at risk (Chakraborty and Sarma 2017). From 2006 to 2017, the annual incidence of scrub typhus increased more than 21 times in Southwest China (Xin et al., 2020). Besides transmitting O. tsutsugamushi, some chiggers are also suspected to be the potential vector of hantavirus, the pathogen of hemorrhagic fever with renal syndrome (HRFS) (Yu and Tesh 2014; Ding et al., 2021; Xiang et al., 2021). Accounting for 24.5% of China’s land area, Southwest China is a huge geographical territory covering five provincial regions, Yunnan, Sichuan, Guizhou, Chongqing and Tibet (Xizang Autonomous Region), and it is an important focus of scrub typhus and HFRS in China (Zhang et al., 2011a).

Belonging to the genus Eothenomys and the family Cricetidae in the order Rodentia, the large Chinese vole or Yunnan red-backed vole (Eothenomys miletus Thomas, 1914) is an endemic rodent species in China, and it is mainly distributed in Southwest China (Huang et al., 1995; Zhang 2011; Jiang et al., 2016; Wei et al., 2021). As a dominant rodent species in the distributed regions, E. miletus often destroys crops and plants as an important pest in agriculture and forestry. Besides, E. miletus is also an important infectious source and reservoir host of some zoonoses such as plague, endemic typhus (murine typhus), scrub typhus and HRFS, etc. (Zheng et al., 2007; Zhang et al., 2011b; Guo et al., 2013).

Based on field investigations in three provincial regions (Yunnan, Guizhou and Sichuan) of Southwest China during 2001 and 2013, a previous study in our research group once reported chigger mites on E. miletus in the investigated regions (Peng et al., 2016b). The field investigations in the previous study, however, did not cover all the five provincial regions of Southwest China because of financial limitation at the time (Li et al., 2021). To continue and deepen the previous study, field investigations between 2001 and 2019 in the present study covered all the five provincial regions of Southwest China and investigation sites increased from previous 39 sites to the present 91 sites. The present study is an attempt to illustrate the species composition and diversity, overall infestation and the related ecological issues of chiggers on E. miletus in the whole Southwest China, which will update the knowledge of chiggers on E. miletus and provide more detail and comprehensive information for the surveillance of chiggers and some other related studies in the region.

2. Materials and methods

2.1. Field investigation and collection of chigger mites

The field investigations were conducted in 91 investigation sites between 2001 and 2019, which covered all the five provincial regions of Southwest China, Yunnan, Sichuan, Guizhou, Chongqing and Tibet (Fig. 1, Appendix). The investigations in 39 of the total 91 sites had been made in three provincial regions of Southwest China (Yunnan, Guizhou and the South of Sichuan) between 2001 and 2013 in the previous studies (Peng et al., 2016b). The rest 52 sites were newly added in other two provincial regions, Chongqing and Tibet after 2013 (Fig. 1, Appendix). Of the total 91 sites, only three were in eastern Tibet, and no investigation was conducted in western Tibet, a vast plateau where E. miletus has not been recorded so far (Huang et al., 2008). In each investigation site, rodents (rats, mice and voles) and other small mammals (insectivores and tree shrews) were captured with mouse traps (18 × 12 × 9 cm, Guixi Mousetrap Apparatus Factory, Guixi, Jiangxi, China), which were randomly placed in different habitats (residential area, farmland, bush and woodland) in the evening and then checked the next morning (Peng et al., 2015, 2016b). Each trapped small mammal (animal host) was separately placed in a white cloth bag and then transported to the field laboratory where ectoparasitic chiggers were conventionally collected, and the collected chiggers were preserved in a vial containing 70% ethanol (Kennedy 1976; Li et al., 1997). After the collection of chiggers, each animal host was identified into species according to its appearance (body size, shape and hair color), body measurements (body weight, body length, tail length, ear height and hind foot length) and other morphological characteristics (Huang et al., 1995; Wilson et al., 2017). In the laboratory, the collected chiggers were mounted onto glass slides with Hoyer’s solution. After dehydration, drying and transparency, the mounted chigger specimens were identified into species under microscopes (Kennedy 1976; Li et al., 1997; Stekolnikov 2013). Based on the identification of animal hosts and chiggers, all the large Chinese voles (E. miletus), together with the

Fig. 1. Investigation sites (n = 91) in the five provincial regions of Southwest China between 2001 and 2019 (The sites marked “•” were newly increased sites after 2013 and those marked “▴” were the sites where large Chinese voles, E. miletus, were captured. The name abbreviations of the investigation sites were shown in “Appendix”).
chiggers on the body surface of the voles, were chosen as the target of the present study. The capture of animal hosts was officially permitted by the local authority of wildlife service. The use of animals for research was officially approved by Animals’ Ethics Committee of Dali University. Representative specimens of animal hosts and chiggers with clear and typical morphological characteristics were deposited in the specimen repository of Institute of Pathogens and Vectors, Dali University, Dali, Yunnan, China.

2.2. Statistical analysis on infestation of E. miletus with chiggers

According to the conventional statistical methods, the constituent ratio (Cj) was used to calculate the proportion of each chigger species on E. miletus. The prevalence (Pw), mean abundance (MA) and mean intensity (MI) were used to analyze the infestation of E. miletus with chiggers. Jaccard’s similarity index (J) was used to compare the species similarity of chiggers between male and female hosts (Margolis et al., 1982; Liu et al., 2019; Xiang et al., 2021; Li et al., 2022).

2.3. Analysis on spatial distribution pattern and interspecific relationship of dominant chigger species

The patchiness index (m’/m), clump index (I) and Cassie index (Cj) were used to analyze the spatial distribution pattern of dominant chigger species on E. miletus (Lloyd 1967; Costa et al., 2010; Liu et al., 2019).

Based on a 2 × 2 contingency table (see Table 4 in “Results”), Chi-square test (χ²) was used to qualitatively determine the interspecific association between any two dominant chigger species (Xu et al., 2016), and then Pearson correlation coefficient (PCC), Dice coefficient (DI) and Ochiai coefficient (OI) were used to quantitatively measure the degree of the interspecific association (Yule 1912; Driver and Kroebber 1932; Xu et al., 2016).

\[ \chi^2 = \frac{(ad - bc)^2}{(a + b)(c + d)(a + c)(b + d)} \quad \text{PCC} \]

\[ DI = \frac{2a}{2a + b + c} \quad \text{OI} \]

\[ = \sqrt{a + b/\sqrt{a + c}} \]

In the above formulae, the specific meaning of a, b, c, d and n were shown in the annotation of Table 4 in “Results”. In the analysis of Chi-square test (χ²), a positive association is determined to exist between two chigger species when ad > bc, while a negative association between two chigger species when ad < bc. The value of PCC ranges from –1 to 1. The closer to 1 the PCC value is, the stronger the positive association would be. The closer to –1 the PCC value is, the stronger the negative association would be. When the values of DI and OI reach 0, the two chigger species would be considered to be mutually independent. The values of DI and OI range from 0 to 1. The closer to 1 the DI and OI values are, the stronger the positive association would be.

2.4. Analysis on niche breath and overlap of main chigger species

Based on the constituent ratios (Cj) of some main species of chiggers on E. miletus in different environment gradients or environment series (different altitudes, latitudes and habitats), Shannon-Wiener’s niche breadth (Bj) was used to measure the environmental niche breadth of a certain chigger species in a certain environment series (Colwell and Futuyma 1971; Peng et al., 2017). According to Bj calculation, the multidimensional niche breadth (Bj) based on the principal component analysis (PCA) was used to evaluate the comprehensive niche breadth of a certain chigger species in the multidimensional environment series, the combined environment series of altitudes, latitudes and habitats (Xu 1999; Shi et al., 2006). The cosine similarity (cosθj) was used to evaluate the environmental niche overlaps of different chigger species (species i and j) in the selection of different environment series, altitudes, latitudes and habitats (Guo 1999; Luo and Guo 2015). The above niche overlaps were expressed in the dendrogram of hierarchical clustering analysis which was done under SPSS 20 (Luo and Guo 2015).

\[ B_j = \log \frac{\sum N_i - \left(1/ \sum N_i \left( \sum N_i \log N_i \right)^2 \right)}{\log \left[ \sum B_i^2 \right]} \cdot \cos \theta_j \]

In the above formulae, Nj = the number of chigger species i on grade j of a certain environment series (altitudes, latitudes or habitat in the present paper), r = the number of grades in a certain environment series, n = the number of grades in the combined environment series, Pj = the constituent ratio of chigger species i on grade h of a certain environment series, and Pj = the constituent ratio of chigger species j on grade h of a certain environment series. The values of Bj and cosθj range from 0 to 1. When the values of Bj and cosθj close to 0, it means that there is nearly no distribution of the examined chigger species in a certain environment series. When the values of Bj and cosθj reach 1, it means that the examined chigger species is distributed in all the grades of a certain environment series.

2.5. Description of species abundance distribution

In the present study, all the chigger species on E. miletus were considered a community unit. The species abundance distribution of the chigger community was depicted in a semi-logarithmic coordinate system, in which the X-axis representing chigger individuals was labeled with log intervals based on log(N) and the Y-axis standing for chigger species was labeled with arithmetic scales. The following lognormal distribution model based on Preston’s method was used to fit the theoretical curve of the species abundance distribution, and the determination coefficient (R²) was used to evaluate the fitting goodness of the theoretical curve (Preston 1948; Peng et al., 2017; Liu et al., 2019; Ding et al., 2021).

\[ \hat{S}(R) = S_0 e^{-[\alpha(R - R_0)]^2} \] (The lognormal distribution model)

\[ R^2 = 1 - \frac{\sum_{k=0}^{m} \left[ S(R) - \hat{S}(R) \right]^2 \hat{S}(R)}{\sum_{k=0}^{m} S(R)^2 \hat{S}(R)} \]

In the above formulae, \( \hat{S}(R) \) is the theoretical number of chigger species in the R-th log interval, \( R_0 \) is the corresponding log interval at the highest point of the actual curve of species abundance, \( S_0 \) is the number of chigger species at \( R_0 \) log interval, \( e = 2.7182 \ldots \) (the base number of natural logarithm), \( \alpha = \) the spread constant which is determined according to the highest determination coefficient (R²) in the fitting process of the theoretical curve, \( S(R) = \) the actual number of chigger species in R-th log interval, \( m = \) the number of log intervals and \( \hat{S}(R) = \) the average number of chigger species at each log interval.

2.6. Estimation of expected total species

According to the fitting result of the theoretical curve of species abundance, the expected total number of chigger species on E. miletus (S), together with the number of probably missed chigger species in the sampling investigation (\( S_0 \)), were roughly estimated with the following formulae (Ding et al., 2021; Chen et al., 2022).

\[ S_T = \left( S_0 \sqrt{\bar{x}} \right) / \alpha; S_M = S_T - S_0 \]
### Table 1

Identified chigger mites (chiggers) from large Chinese voles (*E. milletus*) in the five provincial regions of Southwest China (2001-2019).

| Names of chigger mites (chiggers) | Individuals | Names of chigger mites | Individuals |
|-----------------------------------|-------------|------------------------|-------------|
| Leptorhyncha simulacria (Nagayo et al., 1921) | 1000 | T. hambusoides Wang et Yu, 1965 | 489 |
| L. sinicum Yu et al., 1981 | 5778 | T. qingye Wen et al., 1984 | 32 |
| L. eothemomydis Yu et Yang, 1986 | 3929 | T. chiliti Wen et Xiang, 1984 | 27 |
| L. demespunctatum Yu et al., 1982 | 3336 | T. xiuwu Wen et Xiang, 1984 | 17 |
| L. huminilo Yu et al., 1982 | 3578 | T. qinping Yu et Yang, 1979 | 3 |
| L. rusticum Yu et al., 1986 | 1804 | T. Quanyi Wen et Xiang, 1984 | 2 |
| L. amphicola Wen et Xiang, 1984 | 966 | T. Juayei Wen et al., 1984 | 2 |
| L. jinnal Wen et Xiang, 1984 | 698 | Neotrombicula microti (Ewing, 1928) | 194 |
| L. wangii Yu et al., 1986 | 634 | N. microtomi Wen et al., 1984 | 72 |
| L. gongsanense Yu et al., 1981 | 555 | N. despina Yu et Wang, 1981 | 27 |
| L. chingshanense Yu et al., 1982 | 446 | N. arretes Hu et Yang, 1985 | 8 |
| L. yui (Chen et Hsu, 1955) | 389 | N. marmotar Wen et al., 1984 | 6 |
| L. bishanense Yu et al., 1986 | 379 | N. japonica (Tanaka et al., 1930) | 5 |
| L. benshui Wen et Xiang, 1984 | 265 | N. longinensis Yang et al., 1995 | 4 |
| L. delinense (Walch, 1922) | 228 | N. sinica (Wang, 1964) | 3 |
| L. bilii Wen and Xiang, 1984 | 223 | N. longinensis Wen et Xiang, 1984 | 2 |
| L. yangshengense Yu et Yang, 1986 | 187 | N. gamaensis Yang, 1985 | 1 |
| L. dianchi Wen et Xiang, 1984 | 128 | Helenium sinae (Hu et Chen, 1957) | 4398 |
| L. yunlingense Yu et Zhang, 1981 | 119 | H. lalai Zhao, 1990 | 746 |
| L. laojunshanense Yu et al., 1986 | 116 | H. yunnanensis Wen et Xiang, 1984 | 38 |
| L. robustiseta Yu et al., 1983 | 105 | H. miyogawara (Sasa kunoda et Miura, 1951) | 24 |
| L. caudatum Wen et al., 1984 | 105 | H. abarmornt Wang et al., 1984 | 23 |
| L. rupestris Traub et Nadchatran, 1967 | 104 | H. globularis (Walch, 1927) | 14 |
| L. shuqai Wen et Xiang, 1984 | 70 | H. kohni (Philip et Woodward, 1964) | 13 |
| L. longshanense Yu et al., 1981 | 67 | H. salubris Han et Chen, 1964 | 10 |
| L. hui Yu et al., 1986 | 57 | H. edibakeri Nadchatran et Traub, 1971 | 7 |
| L. sunweie Wen, 1984 | 57 | H. olaejejii (Schulger, 1955) | 4 |
| L. alpinum Yu et Yang, 1986 | 54 | H. rathikoung (Hu et Chen, 1957) | 1 |
| L. dilhumei Traub et Nadchatran, 1967 | 53 | H. asiochacta Sun et al., 1986 | 1 |
| L. akkarusch Barumpit, 1910 | 53 | Herpetacarus hastacruva Yu et al., 1979 | 3160 |
| L. allowittam Wang et al., 1981 | 50 | Herpetacarus tenebraculatus Yu et al., 1979 | 205 |
| L. yunnanensis Yu et al., 1980 | 50 | Herpetacarus tenuigradiensis Yu et al., 1980 | 7 |
| L. xiaowei Wen et Xiang, 1984 | 48 | Herpetacarus limon (Wen et Xiang, 1984) | 5 |
| L. sexesetum Yu et Hu, 1981 | 47 | Herpetacarus hisuetus Yu et Duan, 1980 | 3 |
| L. muntiaci Wen et Xiang, 1984 | 47 | W. micropelta (Traub et Evans, 1957) | 52 |
| L. impalaac Vermamens-Grandjean et Langston, 1975 | 46 | W. xihaiensis Zhao et al., 1986 | 38 |
| L. ryocanum Wang et Liu, 1989 | 46 | W. chinensis (Chen et Hsu, 1955) | 19 |
| L. xjaoyuanense Yu et al., 1981 | 42 | W. paraparcifera (Chen et al., 1955) | 35 |
| L. kitasatoi (Fukuzuki et Obata, 1956) | 35 | W. tormalis (Gater, 1932) | 17 |
| L. draftingnense Wang et al., 1981 | 32 | W. acuta (Chen, 1980) | 13 |
| L. spicinsetum Yu et al., 1986 | 26 | W. kritiochacta (Traub et Evans, 1957) | 8 |
| L. bayanense Yang, 1994 | 25 | W. shui Wen et Solar, 1984 | 4 |
| L. kuohuense Yang et al., 1959 | 22 | W. sawehuacina (Teng, 1963) | 3 |
| L. xianghense Yu et al., 1983 | 20 | W. nanfangi Wen et Xiang, 1984 | 1 |
| L. longiseta Wen et Xiang, 1984 | 20 | W. cordipelta Wen et Xiang, 1984 | 1 |
| L. apodemori Wen et Xiang, 1984 | 16 | W. rustic (Gater, 1932) | 1 |
| L. sheshui Wen et Xiang, 1984 | 14 | W. musulicum (Chen et Hsu, 1957) | 47 |
| L. qinggense Yu et al., 1981 | 13 | L. binghi Wen et Xiang, 1984 | 3 |
| L. apodemori Wen et Sun, 1984 | 13 | L. gaoyangensis Zhou et et Wen, 1984 | 1 |
| L. jiujingense Liao et Wang, 1983 | 13 | L. sidu Wen et Xiang, 1984 | 1 |
| L. cingliangense Yu et al., 1981 | 12 | Gaetacarlia longipalpis Yu et Yang, 1986 | 1182 |
| L. qixi Yu et et al., 1986 | 11 | G. lingupelta Jeu et al., 1983 | 938 |
| L. zhongshanense Yu et Yang, 1981 | 11 | G. yunnanensis Hu et al., 1965 | 496 |
| L. plurivexillare Yu et al., 1982 | 11 | G. radiopunctata Hsu et al., 1965 | 327 |
| L. parapatula (Womersley, 1952) | 10 | G. silvatica Yu et Yang, 1982 | 286 |
| L. trapezoidum Wang et al., 1981 | 9 | G. deqinensis Yu et Yang, 1982 | 286 |
| L. linhuaikongense (Chen et Hsu, 1957) | 9 | G. orientalis Wen et Xiang, 1984 | 102 |
| L. rubellum Wang et Liao, 1984 | 7 | G. chekiangensis Chiu, 1964 | 89 |
| L. flavimunatum Wang et Song, 1982 | 7 | G. latiscutata Chen et Fan, 1981 | 75 |
| L. inui Wen et Sun, 1984 | 7 | G. miyi Wen et Song, 1984 | 53 |
| L. cuoae Wang et al., 1996 | 6 | G. xiaowei Wen et Xiang, 1984 | 17 |
| L. bawangense Zhao, 1982 | 6 | G. jiameli Chen et al., 1980 | 17 |
| L. rectanguliscutum (Hu et Chen, 1964) | 6 | G. eury punctata Jeu et al., 1983 | 15 |
| L. salshoum Yu et al., 1982 | 5 | G. xiaowei Chen et al., 1980 | 17 |
| L. shuiyu Wen et al., 1984 | 5 | G. xiaowei Chen et al., 1980 | 17 |
| L. deplaniscutum Yu et Zl, 1981 | 4 | G. eury punctata Jeu et al., 1983 | 15 |
| L. itshashenese Wen et Song, 1991 | 4 | G. xiaowei Chen et al., 1980 | 17 |
Table 1 (continued)

| Names of chigger mites (individuals) | Inhabitats | Prevalence |
|-------------------------------------|------------|------------|
| L. jianshanense Yu et al., 1982     | 2          | 17.2%      |
| L. Luoji Wen et Sun, 1984           | 2          | 17.2%      |
| L. shanghaiense and Lu, 1984        | 2          | 17.2%      |
| L. heinei Wen, 1984                 | 2          | 17.2%      |
| L. siculum Wen et al., 1984         | 2          | 17.2%      |
| L. chuanzi Wen et al., 1984         | 1          | 17.1%      |
| L. mudsinnian Yu et al., 1981       | 1          | 17.1%      |
| L. sinotapain Wen et Xiang, 1984    | 1          | 17.1%      |
| L. kawamura (Fukuzumi et Obata, 1953) | 1        | 17.1%      |
| L. bupecum Ma et Hsu, 1965          | 1          | 17.1%      |
| L. ixihani Wen et Xiang, 1984       | 1          | 17.1%      |
| L. gathangense Wang et al., 1985    | 1          | 17.1%      |
| L. taihanicum Meng et al., 1983     | 1          | 17.1%      |
| L. neotobract Xiang et Wen, 1986    | 1          | 17.1%      |
| L. postfidiatum Wang et al., 1983   | 1          | 17.1%      |
| L. sinotapain Wen et Xiang, 1984    | 1          | 17.1%      |
| L. xiaoxictum Teng, 1981            | 1          | 17.1%      |
| L. myotis (Ewing, 1929)             | 1          | 17.1%      |

In the above formulae, \( S_A \) = the number of actually collected chigger species, \( r = 3.1415 \ldots \) (the circumferential rate), and \( S_0 \) and \( a \) are the same as before.

3. Results

3.1. Infestation of E. miletus with chiggers

A total of 2661 large Chinese voles (E. miletus) were captured in 32 of 91 sampled sites (Fig. 1, Appendix), and 52331 chiggers were collected from E. miletus. And 52261 of 52331 collected chiggers were identified as 185 species and 13 genera in the family Trombiculidae (Table 1). The remaining 70 chiggers were unidentified because of the absence of key characters (broken body), key characters not clear due to debris, or suspected new species. The unidentified 70 chiggers were not included in the statistical calculation of the present study. The overall prevalence (\( P_0 \), mean abundance (MA) and mean intensity (MI) of E. miletus (host) with chiggers were 53.96%, 19.64 chiggers/per host and 36.39 chiggers/per host respectively. The prevalence and mean abundance of chiggers on male hosts (\( P_m = 56.25\% \), MA = 21.67) were higher than those on female hosts (\( P_m = 51.23\% \), MA = 17.09) (P < 0.05). The mean intensity of chiggers on male hosts (MI = 38.52) was also higher than that on female hosts (MI = 33.37), but without statistical significance (P > 0.05) (Table 2). The species similarity of chiggers was moderately similar between different sexes of the hosts, E. miletus (J = 0.63).

3.2. Spatial distribution pattern and interspecific association of dominant chigger species on E. miletus

Leptotrombidium densipunctatum showed the highest niche breadths along different altitudes (\( B_1 = 0.66 \)), latitudes (\( B_2 = 0.69 \)), habitats (\( B_3 = 0.85 \)) and the combined environment series (multidimensional environment series, \( B_0 = 1.28 \) (Table 5). The niche breadths of Walchlia koi (\( B_0 = 0.95 \)), and Helenulca hsiu (\( B_0 = 0.94 \)), L. scutellare (\( B_0 = 0.87 \)) and W. ewingi (\( B_0 = 0.87 \)) were next to L. densipunctatum along the combined environment series (Table 5, Fig. 2). Based on the calculation of the cosines similarity, costh (Table 7), the hierarchical clustering analysis was used to illustrate the comprehensive niche overlaps of the 18 main chigger species along the combined environment series. The dendrogram of the hierarchical clustering analysis showed that the 18 main chigger species were classified into 4 overlapped groups when \( \lambda = 4 \) (Fig. 3). The first overlapped group included nine chigger species, namely L. sinicum, L. rusticum, L. gongshanense, L. scutellare, Herpetacarus hastoclavus, Trombiculindus yunnanus, L. jinmai, H. simena and L. eothemomys. There were three chigger species in the second overlapped group (H. hsiu, L. wangli and L. hiaiiel) and five chigger species in the third overlapped group (Gahrliepia linguipelta, W. ewingi, W. koi, L. densipunctatum and G. longipedalis). Leptotrombidium bambicola (only one chigger species), however, formed the fourth branch independently (Fig. 3).

3.4. Species abundance distribution of chigger community on E. miletus

The actual curve of species abundance distribution of chigger community on E. miletus was depicted in the semi-logarithmic coordinate system. As shown in Table 8 and Fig. 4, the theoretical curve of the species abundance distribution was successfully fitted with Preston’s lognormal distribution model with the theoretical equation of \( \bar{S}(R) = 34e^{-0.27R-2}\) (\( \alpha = 0.27, R^2 = 0.91 \)).

3.5. Expected total species of chiggers on E. miletus

Based on the theoretical curve fitting of species abundance distribution, the expected total number of chigger species on E. miletus in the five provincial regions of Southwest China was roughly estimated to be 223 species, and 38 chigger species were probably missed in the sampling investigation.

4. Discussions

4.1. Species composition and infestation of chiggers on E. miletus

The result of the present study showed that the identified 185 chigger species on E. miletus (a single rodent species) extremely exceeded all the
Niche breadths of 18 main chigger species on large Chinese voles (E. miletus) without the infestation of chigger species X and Y.

Table 2

| Sexes of the voles | Individuals of the voles | Overall infestations of chiggers on the voles hosts | Constituent ratios (C) and species richness (S) of chiggers |
|--------------------|--------------------------|--------------------------------------------------|---------------------------------------------------|
|                    | Examined | Infested | \(P_M\) (%) | MA | MI | Individuals | C (%) | S |
| Female             | 1183     | 606      | 51.23        | 17.09 | 33.77 | 20222 | 38.95 | 147 |
| Male               | 1463     | 823      | 56.25        | 21.67 | 38.32 | 31701 | 61.05 | 167 |
| Total              | 2646     | 1429     | 54.01        | 19.62 | 36.34 | 51923 | 100.00 | 185 |

Annotation: The animal hosts (E. miletus) without sex record were not included in the above table.

Table 3

Analysis on spatial distribution pattern of two dominant chigger species on E. miletus in the five provincial regions of Southwest China (2001–2019).

| Dominant chigger species | Patchiness index \((m^2/m)\) | Clump index \((f)\) | Cassie index \((C_f)\) |
|--------------------------|-----------------------------|----------------|-------------------|
| Leptotrombidium scutellare | 32.52                       | 118.67          | 31.52             |
| Leptotrombidium sinicum   | 41.47                       | 87.88           | 40.47             |

Table 4

Analysis on interspecific association between dominant chigger species on large Chinese voles (E. miletus) in the five provincial regions of Southwest China (2001–2019).

| Dominant chigger species | Leptotrombidium scutellare (Chigger species Y) |
|--------------------------|-----------------------------------------------|
|                         | +     | –     | Total |
| Leptotrombidium sinicum (Chigger species X) | 220 (a) | 50 (b) | 273 (a+b) |
|                         | 238 (c) | 2150 (d) | 2388 (c + d) |
| Total                   | 458   | 2203 (b + d) | 2661 (a) |
| Chi-square                | 857.46 |
| Significance           | P < 0.001 |

Annotation: In the above table, \(n\) = the total number of animal hosts (E. miletus), \(a\) = the host individuals simultaneously infested with chigger species X and Y, \(b\) = the host individuals only infested with chigger species X, \(c\) = the host individuals only infested with chigger species Y, and \(d\) = the host individuals without the infestation of chigger species X and Y.

Table 5

Niche breadths of 18 main chigger species on large Chinese voles (E. miletus) in five provincial regions of Southwest China (2001–2019).

| Chigger species | Codes | Individuals | Constituent ratios (%) | Niche breads |
|----------------|-------|-------------|------------------------|--------------|
|                |       |             | \(B_1\) | \(B_2\) | \(B_3\) | \(B_4\) |
| Leptotrombidium scutellare | 1     | 10019       | 19.17 | 0.47 | 0.28 | 0.68 | 0.87 |
| Leptotrombidium sinicum      | 2     | 5778        | 11.06 | 0.25 | 0.05 | 0.48 | 0.55 |
| Heleniuma simera             | 3     | 4398        | 8.42  | 0.39 | 0.14 | 0.55 | 0.69 |
| Leptotrombidium euhomonymsis | 4     | 3929        | 7.52  | 0.15 | 0.39 | 0.58 | 0.72 |
| Leptotrombidium densipunctatum | 5   | 3336        | 6.38  | 0.66 | 0.69 | 0.85 | 1.28 |
| Herpetotrichus hastochlasus  | 6     | 3160        | 6.05  | 0.25 | 0.00 | 0.47 | 0.53 |
| Leptotrombidium biemorale    | 7     | 3066        | 5.87  | 0.02 | 0.49 | 0.53 | 0.72 |
| Leptotrombidium rusticum     | 8     | 1804        | 3.45  | 0.30 | 0.16 | 0.56 | 0.65 |
| Walchia koi                  | 9     | 1425        | 2.73  | 0.51 | 0.47 | 0.65 | 0.95 |
| Trombiculidus yunnanus       | 10    | 1187        | 2.27  | 0.17 | 0.01 | 0.41 | 0.45 |
| Gahrliepia longipenis       | 11    | 1182        | 2.26  | 0.42 | 0.08 | 0.32 | 0.53 |
| Leptotrombidium bambicola    | 12    | 986         | 1.89  | 0.37 | 0.20 | 0.23 | 0.36 |
| Gahrliepia linguipelta      | 13    | 938         | 1.79  | 0.53 | 0.04 | 0.47 | 0.71 |
| Walchia ewingii             | 14    | 763         | 1.46  | 0.50 | 0.40 | 0.59 | 0.87 |
| Heleniuma saui               | 15    | 746         | 1.43  | 0.03 | 0.63 | 0.69 | 0.94 |
| Leptotrombidium jimnai      | 16    | 698         | 1.34  | 0.14 | 0.04 | 0.64 | 0.66 |
| Leptotrombidium wurgi       | 17    | 634         | 1.21  | 0.09 | 0.14 | 0.73 | 0.75 |
| Leptotrombidium gongshanganense | 18   | 555         | 1.06  | 0.46 | 0.12 | 0.67 | 0.82 |

Annotation: \(B_1\) = the niche breadths along different altitudes; \(B_2\) = the niche breadths along different latitudes; \(B_3\) = the niche breadths along different habitats; \(B_4\) = the niche breadths along the combined environment series (multidimensional environment series).
Table 6
Constituent ratios (Cᵣ) of the 18 main chigger species on large Chinese voles (E. miletus) along different environment series (altitudes, latitudes and habitats) in the five provincial regions of Southwest China (2001–2019).

Table 7
Niche overlaps (cosine similarity, cosθᵢⱼ) of the 18 main chigger species on large Chinese voles (E. miletus) along the combined environment series (multidimensional environment series) in the five provincial regions of Southwest China (2001–2019).

Fig. 2. Niche breaths of the 18 main chigger species on large Chinese voles (E. miletus) along the combined environment series (multidimensional environment series) in the five provincial regions of Southwest China (2001–2019).
higher infestation of chiggers on the male *E. miletus* than the females may be partially due to the relatively low resistance of the males. It is claimed that the males of rodents and other mammals usually have a lower resistance against parasites than the females because of the negative influence of androgen (male sex hormone) and the consumptive competition in mating activity (Folstad and Karter 1992; Xiang et al., 2021).

### 4.2. Dominant chigger species and their spatial distribution pattern and interspecific relationship on *E. miletus*

*Leptotrombidium scutellare* and *L. sinicum* were two dominant chigger species on *E. miletus* in Southwest China, which accounted for 30.23% (Cᵢ = 30.23%) of the total 185 chigger species. It has been proved that there are six main vectors of scrub typhus in China, and these six vector chigger species are *L. deliense, L. scutellare, L. rubellum, L. sialkotense, L. wenense* and *L. insulare* (Li et al., 1997; Wu et al., 2013; Xiang and Guo 2021; Xiang et al., 2022). The occurrence of *L. scutellare* with the highest Cᵢ on large Chinese voles (*E. miletus*) in Southwest China would increase the potential risk of chiggers’ transmitting the pathogen of scrub typhus, *O. tsutsugamushi*, from voles to humans in the region. There is no evidence that *L. sinicum* can transmit *O. tsutsugamushi* effectively, and therefore we are not able to determine the epidemiological significance of *L. sinicum* in the present paper.

The spatial distribution pattern is an important issue in ecological practice with a lot of methods to measure it. The patchiness index (m*), clump index (f) and Cassie index (C₄) used in the present study are the commonly used methods (Liu et al., 2019; Ding et al., 2021). The calculated values of m*, f and C₄ for two dominant chigger species...
**4.3. Niche characteristics of main chigger species in different environments**

As two important ecological concepts and parameters, the niche width and niche overlap are often used to evaluate the extent to which a certain species uses a series of resources and the overlapped degree to which different species use the same series of resources (Futuyma and Moreno 1988; Yu et al., 2022; Zhang et al., 2022). When a group of different species of animal hosts are regarded as a certain series of host resources, the niche breadth can be used to compare the host specificity of different species of chiggers and other ectoparasites, and the niche overlap can be used to evaluate the overlapped extent of different species in the selection of different host species (Krasnov et al., 2005; Peng et al., 2017). The present study, however, involved only one species (E. miletus), and the niche breadth was used to compare the utilized extent of different chigger species along different environment gradients (environment series) instead of comparing their host specificity. Most chigger species have low host specificity. A certain chigger species can parasitize different animal hosts and a certain host species can harbor different chigger species as well (Li et al., 1997; Peng et al., 2016a; Xiang and Guo 2021). The distribution of chiggers is often influenced by a series of factors including animal hosts and environments, and the host and environment selection of chiggers are different from species to species (Chen et al., 2021b, 2022; Ding et al., 2021). On the same host species, the niche breadths of different chigger species can reflect their different ecological adaptability to different environments. The species with wide niche breadths usually have strong adaptability to their environments. On the contrary, the species with narrow niche breadths often have weak adaptability to their environments, and the weak adaptability and fragile competition can easily cause the extinction of the species (Yang et al., 2019; Chen et al., 2021a). The high niche breadths of L. densipunctatum, W. koi, H. hsui, L. scutellare and W. ewingi (Table 5, Fig. 2) suggest that these chigger species have a high adaptability to their environments with a wide distribution scope. The high adaptability of L. scutellare (a main vector species in China) to the environments would increase the potential risk of transmitting scrub typhus in different regions. In the clustering dendrogram, the 18 main chigger species were classified into 4 groups, and the different chigger species within the same group had a high degree of niche overlaps (Table 7, Fig. 3). The high niche overlaps suggest that these chigger species tend to choose the same or similar environments with similar environmental adaptability. The results further imply that some chigger species can coexist not only on the same species of host, but also in the same environment, and this may be an interspecific cooperation (Peng et al., 2016a; Zhang et al., 2022).

**4.4. Species abundance distribution and total expected species of chiggers on E. miletus**

In ecological studies, the species abundance distribution is to illustrate the relationship between the individuals and species in a certain community, and Preston’s lognormal model is often used to fit the theoretical curve of the species abundance (McGill et al., 2007; Ding et al., 2021). In the present study, the species abundance distribution of chiggers on E. miletus was successfully fitted with Preston’s lognormal model and the theoretical equation was \( S(R) = 34e^{-0.27R-2} \) (Table 8, Fig. 4). The curve tendency of the species abundance distribution showed a gradual descending tendency from log interval 2 to log interval 8 and 9. Log interval 2 corresponded to the highest number of chigger species with 5–13 individuals, and log interval 8 and 9 corresponded to the few dominant chigger species with abundant individuals (Table 8, Fig. 4). The result is highly consistent with the previous study, which indicates that the majority of chigger species belong to rare or uncommon species with few individuals and few species are dominant ones with abundant individuals (McGill et al., 2007; Liu et al., 2019; Ding et al., 2021).

In community ecology, how to scientifically estimate the total number of expected species is often necessary and important, but it is very difficult to make an accurate estimation. There are a lot of methods to estimate the total expected species, and one of them is the formula \( S_T = \frac{S_V(\bar{x})}{\alpha} \) based on Preston’s model (Preston 1948; Ding et al., 2021). According to the calculated result, the expected total species of chiggers on E. miletus was estimated to be 223 species \((S_T = 223)\), 38 more than actually collected species (185 species). The estimated result implies that 38 species have been probably missed in the actual field investigation. In fact, some rare species are unavoidable to be missed in field investigations because they are too few to be collected in sampled investigations (Balstanás 1992; Ding et al., 2021).

**5. Conclusions**

The large Chinese vole (E. miletus) has a great potential to harbor lots of chiggers with high species diversity and infestation in the five provincial regions of Southwest China. The male voles have higher infestation than the females with sex-bias. *Leptotrombidium scutellare* and *L. sinicum* are two dominant chigger species on E. miletus and they are of aggregated distribution among different individuals of E. miletus. A positive association exists between two dominant chigger species. *Leptotrombidium densipunctatum, W. koi, H. hsui, L. scutellare* and *W. ewingi* have a strong adaptability to their environments with high niche breadths and some chigger species tend to coexist in similar environments with obvious niche overlaps. Based on the theoretical curve fitting of species abundance, the expected total number of chigger species can be roughly estimated.

**Declaration of competing interest**

All the authors declare that there is no conflict of interest.
Acknowledgements

We would like to express our sincere thanks to the following people who contributed to the field investigations and laboratory work: Yun-Ji Zou, Zong-Yang Luo, Qiao-Hua Wang, Ai-Qing Niu, Shu-Xin Hou, Wen-Ge Dong, Yin-Zhu Zhan, Peng-Biao Yang, Peng Hou, Rong Xiang, Yong Zhang, Cong-Hua Gao, Nan Zhao, Jian-Chang He, Guo-Li Li, Yan-Liu Li, Xue-Song He, De-Cai Ouyang, Shuang-Lin Wang, Jun Zhao, Ji-Wei Guo, Chang-Ji Pu, Xing-Shun Zhu, A-Si Di, Cheng-Wei He, He Sha, Long Zhou, some colleagues and college students. The present study was supported by the National Natural Science Foundation of China (Nos. 81960380 and 82160400) and Major Science and Technique Programs in Yunnan Province (No. 202102AA310055-X) to Xian-Guo Guo. We would like to express our sincere thanks to the above financially supports.

Appendix. The captured large Chinese voles (*Eothenomys miletus*) from each of 91 investigation sites in the five provincial regions of Southwest China (2001–2019)

| Site abbr. | Names of investigation sites | Captured voles | Site abbr. | Names of investigation sites | Captured voles | Site abbr. | Names of investigation sites | Captured voles | Site abbr. | Names of investigation sites | Captured voles |
|-----------|-------------------------------|---------------|-----------|-------------------------------|---------------|-----------|-------------------------------|---------------|-----------|-------------------------------|---------------|
| A1*       | Anyue                         | 0             | JY*       | Jiangyang                     | 0             | SM        | Simao                         | 0             |
| B*        | Binchuan                      | 34            | KR*       | Karuo                         | 0             | SN*       | Sinan                         | 0             |
| B1*       | Bayi                          | 0             | LC*       | Longchuan                     | 131           | SZ*       | Shizhu                        | 0             |
| C*        | Changshou                     | 0             | LHI*      | Lianghe                       | 129           | SZH*      | Shizhong                      | 0             |
| CY*       | Cangyuan                      | 2             | LIH*      | Lahuoo                        | 0             | TN*       | Tongnan                       | 0             |
| DC*       | Daocheng                      | 0             | LL*       | Liliang                       | 2             | TZ*       | Tongzhi                       | 0             |
| DJ*       | Dali                          | 1081          | LP*       | Laping                        | 13            | WS*       | Wusheng                       | 0             |
| DL*       | Deqin                         | 52            | LS*       | Lushui                        | 0             | WX*       | Weixi                         | 430           |
| DP*       | Daying                        | 0             | LA*       | Luxian                        | 0             | WY*       | Weiyuan                       | 0             |
| DY*       | Duyun                         | 68            | LZ*       | Lezhi                         | 0             | WZ*       | Wanzhou                       | 0             |
| FC*       | Fucheng (Mianyang)            | 0             | MEK*      | Maerkang                      | 0             | XC        | Xiangcheng                    | 0             |
| FG*       | Fugong                        | 0             | MG        | Maguan                        | 0             | XGGL      | Xianggella                    | 0             |
| FK*       | Fuling                        | 0             | MH        | Menghai                       | 0             | XH*       | Xishan                        | 0             |
| FY*       | Fuyuan                        | 12            | MK*       | Mangkang                      | 0             | XX*       | Xixiu                         | 32            |
| GD*       | Guiding                       | 23            | ML*       | Mengla                        | 0             | XZ*       | Xuzhou                        | 0             |
| GL*       | Guanling                      | 1             | MLI*      | Muli                          | 85            | Ya*       | Yajiang                       | 0             |
| GM*       | Gengma                        | 3             | MNI**     | Minanning                     | 12            | YD*       | Yongde                        | 106           |
| GS*       | Gongshan                      | 18            | MY*       | Miyi                          | 19            | YJ        | Yuanjiang                     | 0             |
| GZ*       | Ganzi                         | 0             | MZ         | Mengzi                        | 0             | YL*       | Yulong                        | 19            |
| HK*       | Hekou                         | 0             | NE        | Ninger                        | 0             | YoY**     | Youyang                       | 2             |
| HS*       | Huishui                       | 4             | PA**      | Puan                          | 103           | YU*       | Yunyang                       | 0             |
| HX*       | Huaxi (Guizhou)               | 48            | PC*       | Pingchong                     | 0             | YY*       | Yanyuan                       | 30            |
| HY*       | Hongya                        | 0             | PS*       | Pingshan                      | 0             | ZA*       | Zhangen                       | 0             |
| JC*       | Jianchuan                     | 83            | QB        | Qiebei                        | 0             | ZF*       | Zhenfeng                      | 0             |
| JH*       | Jinhong                       | 0             | QJ        | Qiaojia                       | 0             | ZJ*       | Zhijin                        | 50            |
| JI*       | Jiangjin                      | 0             | QW*       | Qianwei                       | 0             | ZS*       | Zhongshan                     | 17            |
| JK*       | Jiangkou                      | 0             | RI*       | Rongjiang                     | 0             | ZX*       | Zhongxian                     | 0             |
| JP*       | Jingping                      | 4             | RL*       | Ruli                          | 36            | ZZ*       | Zizhong                       | 0             |
| JS*       | Jimha                         | 0             | RS*       | Renhousu                      | 0             |          |                               |               |
| JT*       | Jintang                       | 0             | SJ        | Suijiau                       | 0             |          |                               |               |

(Annotation: Site abbr. = the name abbreviations of the investigation sites. The investigation sites marked “*” were newly increased sites after 2013 and those marked “**” were the sites where large Chinese voles, *Eothenomys miletus*, were captured.)

References

Balntasis, A., 1992. On the use of some methods for the estimation of species richness. Oikos 484–492.

Chaisiri, R., Gill, A.C., Stekolnikov, A.A., Hinjopy, S., McGarry, J.W., Darby, A.C., Morand, S., Makepeace, B.L., 2019. Ecological and microbiological diversity of chigger mites, including vectors of scrub typhus, on small mammals across stratified habitats in Thailand. Anim. Microbiome. 1 (1), 18. https://doi.org/10.1590/s0103-901620100500008.

Chaisiri, R., Stekolnikov, A.A., Makepeace, B.L., Morand, S., 2016. A revised checklist of chigger mites (acari: Trombiculidae) from Thailand, with the description of three new species. J. Med. Entomol. 53 (2), 321–342. https://doi.org/10.1093/jme/ jtv244.

Chakraborty, S., Sarma, N., 2017. Scrub typhus: an emerging threat. Indian J. Dermatol. 62 (5), 478–485.

Chen, X., Liu, Z.X., Duan, X.D., Shao, Z.T., Pu, E.N., Su, C., Du, C.H., Li, Y.Q., Gao, Z.H., 2021a. Niche characteristics of parasitic fleas on the body surface of small mammals in Deqin county, the Tibetan area of Northwestern Yunnan Plateau. Acta Ecol. Sin. 41 (13), 5476–5486 (in Chinese).

Chen, Y.L., Guo, X.G., Ren, T.G., Zhang, L., Fan, R., Zhao, C.F., Zhang, Z.W., Mao, K.Y., Huang, X.B., Qian, T.J., 2021b. A report of chigger mites on the striped field mouse, *Apodemus agrarius*, in Southwest China. Int. J. Parasitol. 59 (6), 625.

Chen, Y.L., Guo, X.G., Ren, T.G., Zhang, L., Fan, R., Zhao, C.F., Zhang, Z.W., Mao, K.Y., Huang, X.B., Qian, T.J., 2022. Infestation and distribution of chigger mites on Chevriers’s field mouse (*Apodemus chevrieri*) in Southwest China. Int. J. Parasitol. Parasit. Wildl. 17, 74–82.

Colwell, R.K., Futuyma, D.J., 1971. On the measurement of niche breadth and overlap. Ecology 52 (4), 567–584.

Costa, M.G., Barbosa, J.C., Yamamoto, P.T., Leal, R.M., 2010. Spatial distribution of *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) in citrus orchards. Sci. Agr. 67 (5), 546–554. https://doi.org/10.1590/s0103-901620100500008.
Ding, F., Jiang, W.L., Guo, X.G., Fan, R., Zhao, C.F., Zhang, Z.W., Mao, K.Y., Xiang, R., 2021. Infestation and related ecology of chigger mites on the Asian house rat (Rattus norvegicus) in Yunnan Province, southwest China. J. Parasitol. 59 (4), 377–392. https://doi.org/10.1515/jkpi-2021-0437.

Driver, H.E., Kroeker, A.L., 1932. Quantitative Expression of Cultural Relationships. University of California Press, Berkeley, pp. 211–256.

Fenton, A., Viney, M., 2010. Detecting deterministic macroparasite interactions from ecological data: patterns and process. Ecol. Lett. 13 (5), 605–615.

Folstad, I., Karter, A.J., 1992. Parasites, bright males, and the immunocompetence handicap. Am. Nat. 139 (3), 603–622.

Futuyma, D.J., Moreno, R.E., 1988. The evolution of ecological specialization. Annu. Rev. Ecol. Syst. 207–233.

Guo, X.G., 1999. Clusters of ectoparasitic gamasid mites and their small mammal hosts in chigger habitats in Western Yunnan. Syst. Appl. Acarol-UK 4 (19). 46.

Guo, X.G., Song, W.Y., Men, Y.Q., Jin, D.C., Dong, W.G., Qian, T.J., Qin, F., Song, W.W., 2013. Ectoparasitic insects and mites on Yunnan red-backed voles (Eothenomys miletus) from a localized area in southwest China. Parasitology. Res. 112 (10), 3543–3549. https://doi.org/10.1007/s00436-013-3537-5.

Huang, W., Xia, L., Yang, Q.S., Feng, Z.J., 2008. Distribution pattern and zoogeographical division of mites on the Qinghai-Tibet plateau. Acta Theriol. Sin. 28 (4), 375–394 (in Chinese).

Huang, W.J., Chen, X.Y., Wen, Y.X., 1995. Rodents of Fudan University Press, Shanghai, pp. 1–308 (in Chinese).

Jiang, Z.G., Jiang, J.P., Fan, R., Chen, X.D., Deng, H.Q., Jiang, Y.L., Zhang, L.B., Shi, H.Y., 2021. Distribution and host selection of Tropical rat mite, Ornithonyssus bacoti, in yunnan province of Southwest China. Biologia 72 (9), 1031–1040. https://doi.org/10.1515/biolog-2017-0119.

Kaplan, I., Denno, R.F., 2007. Interspecific interactions in phytophagous insects analyze various aspects of plant interspecific associations. Acta Ecol. Sin. 36 (24), 1325–1336. https://doi.org/10.2478/s11765-015-0033-z.

Lloyd, M., 1967. Mean crowding. J. Anim. Ecol. 36 (1), 1–9.

Mao, K.Y., Huang, X.B., 2007. Geographical range within an ecological framework. Ecol. Lett. 10 (10), 995–1002.

Williams Hooper Foundation, University of California, San Francisco, p. 1061.

Wang, X.G., Wang, S.Y., Li, J.T., Feng, Z.J., Wang, Y., Wang, B., Li, C., Song, X.L., Cai, L., Cao, L., Zheng, G.M., Dong, L., Zhang, Z.W., Ding, P., Liu, Z., Guo, X.G., 2021. Distribution pattern and related ecological analyses of mites on Mole shrews (Talpidae, Anourosorex squamipes, in Southwest China and ecological analysis. Parasite 29, 39.

Williams Hooper Foundation, University of California, San Francisco, p. 1061.

Xiang, R., Guo, X.G., 2021. Research advances of Leptotrombidium scutellare in China. Kor. J. Parasitol. 59 (1), 1–8. https://doi.org/10.2478/kjparasitol-2021-0014.

Xiang, R., Guo, X.G., Fan, R., Mao, K.Y., Zhang, Z.W., Huang, X.B., 2011. Infestation and distribution of gamasid mites on Himalayan field rat (Rattus musculus) in Yunnan Province of Southwest China. Biologia 76 (19), 1325–1336. https://doi.org/10.2478/s11765-015-0033-z.

Xiang, R., Guo, X.G., Fan, R., Mao, K.Y., Zhang, Z.W., Huang, X.B., 2011. Infestation and distribution of gamasid mites on Himalayan field rat (Rattus musculus) in Yunnan Province of Southwest China. Biologia 76 (19), 1325–1336. https://doi.org/10.2478/s11765-015-0033-z.

Yu, X.J., Tesh, R.B., 2014. The role of mites in the transmission and maintenance of hantavirus (Bunyaviridae) in ecosystems in a developing city. Mar. Freshw. Res. 70 (5), 615–624 (in Chinese).

Zhang, Y.D., Zhang, X.H., Liu, S.Y., 2011a. Correlation analysis on normalized difference vegetation index (NDVI) of different vegetation and climatic factors in Southwest China. J. Appl. Ecol. 48 (7), 1335–1340 (in Chinese).

Zhang, Y.Z., Whitmore, H., 1998. The commonness, and rarity, of species. Ecology 29 (63), 254–283.

Zhou, J.H., Chen, J.H., Zeng, C.H., Gao, C., Huang, G.H., Li, G., 2021. Geographical distribution and specificity in ectoparasitology: a case study with Amblyomma flarae and rodent hosts. J. Biogeogr. 40 (10), 1679–1690.

Zhu, Q., in: Schwartz, M.W., 2007. Interspecies interactions in phytophagous insects analyze various aspects of plant interspecific associations. Acta Ecol. Sin. 36 (24), 1325–1336. https://doi.org/10.2478/s11765-015-0033-z.

Zhuang, Z., Wang, X.P., Sheng, L.J., Zhu, Z.L., Wang, C.A., 2006. Models for niche breadth and niche overlap of species or populations. Sci. Silva Sin. 42 (7), 95–103 (in Chinese).

Zoological Society of London. 2013. Leptotrombidium (Acari: Trombiculidae) of the world. Zootaxa 3728 (1), 1–173. https://dx.doi.org/10.11646/zootaxa.3728.1.1.

Zoological Society of London. 2013. Leptotrombidium (Acari: Trombiculidae) of the world. Zootaxa 3728 (1), 1–173. https://dx.doi.org/10.11646/zootaxa.3728.1.1.

Zoological Society of London. 2013. Leptotrombidium (Acari: Trombiculidae) of the world. Zootaxa 3728 (1), 1–173. https://dx.doi.org/10.11646/zootaxa.3728.1.1.

Zoological Society of London. 2013. Leptotrombidium (Acari: Trombiculidae) of the world. Zootaxa 3728 (1), 1–173. https://dx.doi.org/10.11646/zootaxa.3728.1.1.