RESEARCH ARTICLE

Landscapes with different biodiversity influence distribution of small mammals and their ectoparasitic chigger mites: A comparative study from southwest China

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Abstract

From a previous field investigation in Yunnan, southwest China between 2001 and 2015, we selected two types of landscapes to make a retrospectively comparative study on the distribution of small mammals and their ectoparasitic chigger mites. One landscape is “mountainous uncultivated land (MUL)” with higher biodiversity, which is located in a famous “World Nature Heritage Site”, the Three-Parallel-Rivers Region in the northwest of Yunnan. The other is “cultivated flatland landscape (CFL)” with lower biodiversity, which is located in the south of Yunnan. The landscapes with different biodiversity apparently influenced the distribution of small mammals and their ectoparasitic chigger mites. Much more species of small mammals and mites were found in MUL than in CFL. A total of 3,177 small mammals captured from MUL were identified as 55 species, 30 genera and 10 families in five orders. From these small mammal hosts, 5,882 chigger mites were collected and identified as 127 species, 15 genera and 3 subfamilies in two families. A total of 1,112 small mammals captured from CFL were identified as 19 species, 12 genera and 5 families in three orders. From these hosts, 17,742 chiggers were collected and identified as 127 species, 15 genera and 3 subfamilies in two families. Both the species diversity (S = 55) and community diversity (H = 2.673) of small mammals in MUL were much higher than those in CFL (S = 19; H = 0.926). There were also higher values of β diversity in MUL than in CFL. Different main reservoir rodent hosts of zoonoses (including tsutsugamushi disease) were found in two types of landscapes. Rattus tanezumi (one main reservoir host) was most abundant in CFL, which accounted for 80.22% of all the small mammals. Another two main reservoir hosts, Eothenomys miletus and Apodemus chevrieri were the dominant species in MUL, but they were not as abundant as R. tanezumi in CFL. Different vector species of chigger mites also existed in MUL and CFL. Leptotrombidium deliense (a main and powerful vector of tsutsugamushi disease in China) and Ascoschoenga stia indica (a potential vector of tsutsugamushi disease) were the dominant species of chigger mites in CFL (Cr = 25.81% for A. indica; Cr = 23.47% for L. deliense). Leptotrombidium scutellare (also a main vector of tsutsugamushi...
disease in China) was the dominant chigger species in MUL (Cr = 26.09%). Higher infestation of vector mites on small mammals was found in the simple landscape with lower biodiversity (CFL) than in the complex landscape with higher biodiversity (MUL). The overall prevalence ($P$), mean abundance ($MA$) and mean intensity ($MI$) of chigger mites on small mammals were much higher in CFL than in MUL. The main vector mite species on their main rodent hosts also showed a higher $P$, $MA$ and $MI$ in CFL than in MUL.

### Introduction

Small mammals usually involve five orders, Rodentia, Insectivora, Scandentia, Lagomorpha and Chiroptera. Of the five orders, the majority of small mammals are rodents (rats, mice, voles and squirrels, etc.) with more than 2000 species recorded globally [1]. Small mammals are an important constituent part in natural ecosystems and food webs (food chains). They are of great significance in maintaining the integrity of ecosystem and ecological equilibrium [1, 2]. Besides destroying crops in agriculture, some rodents can be reservoir hosts for zoonotic diseases and play a crucial role in maintaining and transmitting diseases [3, 4]. The Asian house rat, *Rattus tanezumi* (also called *Rattus flavipectus*), for example, is the main animal host and infection source of scrub typhus, plague and some other zoonoses in the foci [5, 6].

Chigger mites (trombiculid mites) are a large group of arthropods, which belong to two families (Trombiculidae and Leeuwenhoekiidae) in Acari [7]. There are several stages in the life cycle of chigger mites, but only the larva lives as ectoparasitic stage on a host’s body. Rodents and other small mammals are the most common hosts of the larvae of chigger mites [7, 8]. The larvae of chigger mites can transmit the pathogen of scrub typhus, *Orientia tsutsugamushi*, through their biting activity [7, 9, 10]. Besides transmitting scrub typhus, some chigger mites have been proven to be the potential vectors of hemorrhagic fever with renal syndrome caused by hanta virus [11–13].

Because of the medical importance of small mammals and their ectoparasitic chigger mites, it is worth understanding their distribution in different geographical regions and landscapes with different biodiversity. There have been some studies reporting the relationship between biodiversity and human health. Some reports suggested that simplified landscapes and biodiversity loss could increase the incidence of some infectious diseases [14–24]. Some experts pointed out that urban green space could increase the biodiversity of a city and its surrounding areas, and this could combat many urban ills [25–27]. Based on previous studies, we hypothesize that landscapes with different degrees of biodiversity would influence the distribution of small mammals and their ectoparasitic chigger mites. In comparison with complex landscapes, the species diversity of small mammals and chigger mites would be lower in the simple landscapes, but the individual abundance of some reservoir rodent species and vector chigger mite species would be higher in simple landscapes. To test the hypotheses, we selected two types of landscapes in Yunnan province, southwest China from our previous field investigation and made a retrospectively comparative study on the distribution of small mammals and their ectoparasitic chigger mites. One type of landscape is the mountainous uncultivated land (MUL) with higher biodiversity, a complex landscape, which is located in a famous “World Nature Heritage Site”, the Three-Parallel-Rivers Region in the northwest of Yunnan. The Three-Parallel-Rivers Region where MUL was selected is also known as a “biological gene bank of the world” [28]. The other type of landscape is the cultivated flatland (CFL) with lower biodiversity, a simple landscape, which is in the south of Yunnan. The south of Yunnan where
CFL was selected have a wide scope of flatland-type farmlands, which is far from the northwest of Yunnan where MUL was selected. Yunnan province in southwest China, where the above MUL and CFL were selected, is an ideal place to study biodiversity, because the acreage of the province accounts for less than 0.4% of the whole China, but it has more than 20% of higher plants and 25% of animal species of the whole country [29–31].

In the present study, the original data in both MUL and CFL came from a part of the previously accumulated field investigation between 2001 and 2015 [32–34]. In each landscape of MUL and CFL, six counties were selected for the study. The analysis of the present paper by using a part of the previous investigation data belongs to the “data mining” process, which aims to elucidate some new phenomena and distribution patterns within some existed data.

Materials and methods

Study sites

As mentioned above, two types of landscapes (MUL and CFL) in Yunnan province of southwest China were selected from our previous field investigation between 2001 and 2015 [32–34]. In each landscape of MUL and CFL, six counties were selected for the study. The distribution of small mammals and their ectoparasitic chigger mites was retrospectively studied between these two landscapes, MUL and CFL.

The mountainous uncultivated land (MUL) with higher biodiversity, a complex landscape in the Three-Parallel-Rivers Region of northwest Yunnan, involved a complex type of wild habitats with various kinds of plants and higher biodiversity, including bush fallows, second growth woodlands, wild grasslands and some other wastelands. From low latitude to high latitude, the following six counties (each county with only one selected investigation site) in MUL were selected for the study: Fugong, Lijiang, Weixi, Gongshan, Xianggelila and Deqin.

The cultivated flatland (CFL) with lower biodiversity, a simple landscape in the south of Yunnan mainly involved a simple type of habitats, farmlands (paddy fields and non-irrigated farmlands) with lower biodiversity. From low latitude to high latitude, the following six counties in CFL were selected for the study: Mengla, Menghai, Jinghong, Puer, Ninger and Yuanjiang. There was only one selected investigation site in each of five counties (Mengla, Menghai, Puer, Ninger and Yuanjiang) in CFL, but two investigation sites in Jinghong (Jinghong site and Jingha site) which is an exception (Fig 1).

Collection and identification of chigger mites and their hosts

In our previous field investigation between 2001 to 2015, small mammals (mainly rodents) were sampled from each study site in two types of landscapes, MUL and CFL (Fig 1). The small mammals were mainly trapped with mousetraps (Guixi Mousetrap Apparatus Factory, Guixi, Jiangxi, China) from different habitats of each study site. Mousetraps (18cm×12cm×9cm) baited with corns, peanuts or some other food baits, were set in different types of habitats (bush fallows, woodlands, grasslands, paddy fields and some other farmlands) in the evening and checked the following morning. A total of 3000 traps were accumulatively placed in various types of habitats in each investigation site (about 200 traps/per night), which usually lasted about 15 days for each site of investigation.

The trapped rodents and other small mammals (hosts) were separately placed in premarked white cloth bags and then transferred to the laboratory for the collection of chigger mites. In the laboratory, each trapped host was anaesthetized with ether (cotton balls soaked with ether) within a close container. Most harmful rodents to agriculture (pests) were euthanized to death in deep anesthesia (euthanasia). (ether was used as a form of euthanasia in our manuscript). Some non-pest small mammals (weasels and moles, for example), however, were
anaesthetized only for two to five minutes according to their body size, and these hosts were marked with yellow dye under the anesthesia (fur staining method)\cite{35}. Most rodents were considered "pests" in agriculture and the local government encourage people to kill and eradicate them. All the "pests" rodents were euthanized to death according to the above methods. (Please see the Appendix at the end of the paper about the full list of species that were considered "pests" and the number that were euthanized). The systematic collection of chigger mites was done under the anesthesia of the hosts. The marked hosts were released to the wild after they waked up. Over a large white tray and with the help of a magnifier, the larvae of chigger mites were mainly collected by a curette (or earpick) and lancet from the auricles and external auditory canals of the host ears, which are the most common parasitic places of chigger larvae \cite{4, 7}. In addition, the groin, perineal and axillary regions of the hosts were also examined as

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Fig 1. The study sites in the mountainous uncultivated areas (Three Parallel Rivers Region) (MUL) and the cultivated flatlands (CFL) from 2001 to 2015.

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well, where the larvae are probably attached. Few recaptured hosts previously marked were not repeatedly examined. The collected chigger mites from each host were separately marked in labeled vials containing 70% ethanol [4, 7, 8]. After collection, the white plate and other instruments were cleaned with disposable paper towels to reduce the chance of cross-contamination. The collected chiggers were made into glass slide specimens before identification. Chigger mites were rinsed with clean water to remove the ethanol and mounted on glass slides with Hoyer's medium. All the mounted chigger specimens were finally identified to species under a microscope [4, 7]. The capturing of small mammals was officially permitted by the local authority of wildlife service in Yunnan Province, China. The use of animals (including rodent euthanasia) for research was also officially approved by Ethics Committee of Dali University. The specimens of voucher chigger mites and representative small mammals are deposited in the specimen repository of the Institute of Pathogens and Vectors, Dali University, China.

**Statistical analysis**

For each species of small mammal hosts and their ectoparasitic chigger mites, the constituent ratio \((Cr)\), prevalence \((P)\), mean abundance \((MA)\) and mean intensity \((MI)\) were calculated [36]. Species richness \((S)\) and Shannon-Wiener diversity index \((H')\) were adopted to analyze community structure of small mammals and chigger mites [37–39]. The Cody diversity index was used to measure the Beta-diversity (β diversity) estimation of hosts and chiggers [40]. The calculation formulae are as follows.

\[
Cr = \left( \frac{N_i}{N} \right) 
\times 100\%; \quad P = \left( \frac{H_i}{H} \right) \times 100\%; \quad MA = \frac{N_i}{H_i}; \quad MI = \frac{N_i}{H_i};
\]

\[
S = \sum S_i; \quad H' = -\sum_{i=1}^{S} \left( \frac{N_i}{N} \right) \ln \left( \frac{N_i}{N} \right); \quad \beta_C = \frac{g(h) + l(h)}{2}
\]

In the above formulae, \(N_i\) represents the individuals of host species (small mammal) \(i\) or chigger mite species \(i\). \(N\) represents the total individuals of all species of small mammals or chigger mites. \(H\) represents the total number of individual small mammal hosts. \(H_i\) represents the number of individual hosts infested by chigger mite \(i\). \(S_i\) represents the number of small mammal species \(i\) or chigger mite species \(i\). The \(g(h)\) is the number of species that increase along the habitat gradient \(h\). The \(l(h)\) is the number of species that decrease along the habitat gradient \(h\). The Chi-square test was adopted to analyze the percentages of rodent species and individuals in two types of landscapes.

**Results**

**Species composition and diversity of small mammals in two types of landscapes**

The results showed that the species composition and diversity of small mammals were very different in two types of landscapes. In MUL with higher biodiversity in the Three Parallel Rivers region of Yunnan, a total of 3,177 small mammals were captured between 2001 and 2015, and they were identified as 55 species, 30 genera and 10 families in five orders: Rodentia, Insectivora, Scandentia, Lagomorpha and Carnivora (Table 1). In CFL with lower biodiversity in the south of Yunnan, a total of 1,112 small mammals were captured in the same period of time (2001–2015) and they were identified as 19 species, 12 genera and 5 families in three orders: Rodentia, Insectivora and Scandentia (Tables 2 and 3). As showed in Table 3, both the species
Table 1. Small mammal hosts captured in MUL from 2001 to 2015.

| Taxonomic taxa of small mammal hosts | Captured species and individuals of small mammal hosts (The figures in the brackets are the collected individuals for each host species) |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Rodentia                            | Total hosts: 2,766 individuals; 39 species, 18 genera, 4 families                                                             |
| Muridae                             | Apodemus draco (641); A. chevrieri (410); A. denissi (104); A. sylvaticus (15); A. lutronum (233); A. agrarius (4); Rattus tanezumi (89); R. nitidus (98); R. norvegicus (69); R. sladeni (28); R. bowersi (12); Niviventer confucianus (231); N. fulvescens (101); N. andersoni (10); N. ehu (1); N. excelso (2); Mus caroli (1); M. pahari (4); M. musculus (4); Micromys minutus (1); Vernaya fulva (1); Vandeleuria oloracea (1); Bandicota indica (1); Leopoldamys edwardsi (3). |
| Sciuridae                           | Callosciurus erythraeus (2); C. quinquestriatus (4); Tamipos swinhoei (7); Dremomys perayi (20). |
| Petauristidae                       | Petaurista clarki (6); P. albiventer (4); P. xanthotis (7); Trogopterus xanthipes (12); Pteropus volans (11); Hylopotis alboniger (4); Belomys pearsonii (2). |
| Insectivora                         | Total hosts: 369 individuals; 12 species, 9 genera, 3 families                                                               |
| Erinaceidae                         | Neotetraeus sinensis (1).                                                                                                    |
| Soricidae                           | Suncus murinus (21); Crocidura attenauata (10); C. dracula (2).                                                             |
| Scandentia                          | Total hosts: 1 individual; 1 species, 1 genera, 1 family                                                                     |
| Tupaiidae                           | Tupai belangeri (1).                                                                                                          |
| Lagomorpha                          | Total hosts: 40 individuals; 2 species, 1 genera, 1 family                                                                    |
| Ochotona                            | Ochotona thibetana (36); O. roylei (4).                                                                                         |
| Carnivora                           | Total hosts: 1 individual; 1 species, 1 genera, 1 family                                                                     |
| Mustelidea                          | Mustela kathiah (1).                                                                                                          |

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diversity ($S = 55$) and community diversity ($H = 2.673$) of small mammals in MUL were much higher than in CFL ($S = 19; H = 0.926$).

Distribution difference of reservoir rodents in two types of landscapes

Of the captured small mammals (55 species and 3,177 individuals) in MUL, rodents accounted for 70.91% of species (39/55) and 87.06% of individuals (2766/3177) (Table 1). Of 19 species and 1,112 individuals of small mammals in CFL, the constituent ratios of rodent species and

Table 2. Small mammal hosts captured in CFL from 2001 to 2015.

| Taxonomic taxa of small mammal hosts | Captured species and individuals of small mammal hosts (The figures in the brackets are the collected individuals for each host species) |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Rodentia                            | Total hosts: 1,069 individuals; 14 species, 8 genera, 2 families                                                             |
| Muridae                             | Rattus tanezumi (892); R. nitidus (6); R. norvegicus (19); R. sladeni (68); R. bowersi (4); Niviventer confucianus (14); N. fulvescens (48); Mus pahari (7); M. musculus (4); Apodemus chevrieri (1); Micromys minutus (2); Leopoldamys edwardsi (1); Berlmys berdmorei (2). |
| Cricetidae                          | Eothenomys eleusis (1).                                                                                                    |
| Insectivora                         | Total hosts: 35 individuals; 4 species, 3 genera, 2 families                                                               |
| Erinaceidae                         | Neotetraeus sinensis (2);                                                                                                   |
| Soricidae                           | Suncus murinus (21); Crocidura attenauata (10); C. dracula (2).                                                             |
| Scandentia                          | Total hosts: 8 individuals; 1 species, 1 genera, 1 family                                                                     |
| Tupaiidae                           | Tupai belangeri (8).                                                                                                         |

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individuals reached 73.68% (14/19) and 96.13% (1069/1112) (Table 2). The percentages of rodent species and individuals in CFL were higher than those in MUL ($P < 0.05$, $P < 0.01$).

Different main rodent species of reservoir hosts of zoonoses were found in two types of landscapes. As one main reservoir host of tsutsugamushi disease and some other zoonoses, the Asian house rat (R. tanezumi) was the most abundant species of small mammals in CFL, which accounted for 80.22% of all the captured small mammals. Another two main reservoir hosts, the Yunnan red-backed vole (E. miletus) and Chevrier’s field mouse (A. chevrieri) were the dominant species in MUL, which accounted for 15.93% and 12.91% of all the captured small mammals, but they were not as abundant as R. tanezumi in CFL.

**Species composition and diversity of chigger mites in two types of landscapes**

In MUL with higher biodiversity in the Three Parallel Rivers region of Yunnan, a total of 5,882 chigger mites were collected from 3,177 small mammal hosts, and they were identified as 127 species (not including 90 chigger mites unidentified), 15 genera, 3 subfamilies (Trombiculinae, Gahrliepiinae, Leeuwenhoekiinae) in two families (Trombiculidae and Leeuwenhoekiidae). The subfamily Trombiculinae had the most abundant species and individuals (96 species in 8 genera with 4,482 individuals), and Gahrliepiinae came next (27 species in 4 genera with 1,283 individuals). Leeuwenhoekiinae had the least species and individuals (4 species in 3 genera with 27 individuals) (Table 4). As shown in Table 5, three species of chigger mites (L. scutellare, G. fimbriata and L. densipunctatum) were the most dominant in MUL and their constituent ratios ($C_r$) were 26.10%, 13.47% and 9.01% respectively.

In CFL with lower biodiversity in the south of Yunnan, a total of 17,742 chigger mites were collected from 1,112 small mammal hosts, and they were identified as 86 species, 12 genera and 3 subfamilies in two families. The subfamily Trombiculinae had the most abundant species and individuals (59 species in 8 genera with 14,472 individuals), and Gahrliepiinae came next (26 species in 3 genera with 2,886 individuals). Leeuwenhoekiinae had the least species and individuals (one species in one genus with only 16 individuals) (Tables 5 and 6). Three species of chigger mite (A. indica, L. deliense and W. micropelta) were the most dominant species, and their constituent ratios ($C_r$) were 25.81%, 23.47% and 12.15% respectively (Table 5). As showed in Table 5, both the species diversity ($S = 127$) and community diversity ($H = 3.057$) of chigger mites in MUL were much higher than in CFL ($S = 86$; $H = 2.506$).

**Distribution difference of vector mites in two types of landscapes**

As showed in Tables 4 and 6, the species of chigger mites marked with “**” are some main vectors of scrub typhus in China, and the other mite species marked with “*” are some potential
Table 4. Chigger mites collected and identified in MUL from 2001 to 2015.

| Taxonomic taxa of chigger mites | Collected individuals and species of chigger mites (The figures in the brackets are the collected individuals for each mite species) |
|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Trombiculidae                   | 5,765 individuals; 123 species, 12 genera, 2 subfamilies                                                                                                                                       |
| Trombiculinae                   | 4,482 individuals; 96 species, 8 genera                                                                                                                                                    |
| Leptotrombidium                | Leptotrombidium scutellare** (1,535); L. sinicum (151); L. parapalpale (19); L. eothenomydis (114); L. hiemalis (1); L. rusticum (74); L. shaqiu (1); L. wangii (102); L. densipunctatum (530); L. yonghehengense (32); L. yui (67); L. xiaguanaense (1); L. imphalum (6); L. gonghanense (58); L. spicatetum (1); L. cuonae (1); L. deplanoscutatum (1); L. langhense (13); L. kaushense** (16); L. qingense (5); L. dianchi (6); L. jinhai (1); L. longmedium (12); L. akamushi** (2); L. alpinum (107); L. trapezoidum (1); L. allosatum (3); L. pallidum* (5); L. sinotquatium (1); L. hsui (2); L. robustisetatum (12); L. bluoxueshanense (20); L. cangjiangen (15); L. hupeicium (1); L. apodemi (4); L. intermedium (3); L. biji (5); L. apodevrleri (3); L. suense (12); L. kitaai (1); L. huangdi (1); L. zhongsianense (30); L. bhishanense (5); L. yuilingense (219); L. eijinghanense (5); L. baohui (68); L. laojianhanense (285); L. caudatum (1); L. xinjiangense (1); L. jianghanense (3); L. sultuosum (15); L. sexetum (1); L. rupestre* (41); L. bamicola (4); L. myrtis (1); L. subintermedium (4); L. liaoji (16); L. dihumerale (22); L. rattitae (1); L. linhuakongense (5); L. myajinami (1); L. fujianense (4); L. burnsi (1); L. insulare** (3); L. gemictulum (4); L. yunnanense (11); L. rufoanum (1); L. huangchuanense (11); L. hayanense (6). |
| Trombiculindus                  | Trombiculindus alpinus (1); T. yunnanus (3); T. cianetius (1); T. bambusoides (13); T. nieujiange (9).                                                                                     |
| Neotrombicula                  | Neotrombicula deqinensis (11); N. japonica (5); N. tongtianhans (65); N. aeretes (212); N. vulgaris (5); N. microtomic (72); N. microti (255); N. pomeranzori (1); N. sinica (1). |
| Microtrombicula                | Microtrombicula nadchatrami (4).                                                                                                                                                    |
| Dolosisa                       | Dolosisa brachyapus (2); D. taishanensis (2); D. furcipelta (1).                                                                                                                        |
| Ascoschoengastia               | Ascoschoengastia indica (1); A. yuannanensis (69); A. leeci (13); A. rattinorvgeci (1); A. menghaensis (4).                                                                                       |
| Herpetacarbus                  | Herpetacarbus aristoletus (1); H. spinosetosus (7); H. tenuiculus (8).                                                                                                                   |
| Euschoengastia                 | Euschoengastia weifangensis (1).                                                                                                                                                    |
| Gahrliptineae                  | 1,283 individuals; 27 species, 4 genera                                                                                                                                                    |
| Walchia                        | Walchia pacifica (2); W. parapacifica (4); W. micropelta (20); W. chinensis* (7); W. kor (6); W. enode (7); W. sheens (4); W. ewingi (66).                                                                 |
| Schoengastiella               | Schoengastiella ligula (195).                                                                                                                                                    |
| Gahrlepia                      | Gahrlepia zhongwei (2); G. longipeda (32); G. radiopunctata (2); G. octosetosa (1); G. latscutata (2); G. lenghui (8); G. yangehencnsis (27); G. deqinensis (6); G. tenuiculav (1); G. tenella (1); G. chekiangen (16); G. yunnanensis (5); G. chungkingkensis (6); G. megascuta (21); G. madun (3); G. linguelpeta (38); G. fimbrriata (792). |
| Intermediailla                | Intermediailla hugo (9).                                                                                                                                                                  |
| Leeuwenhoekidae                | 27 individuals; 4 species, 3 genera, 1 subfamily                                                                                                                                             |
| Leeuwenhoekiinae               | 27 individuals; 4 species, 3 genera                                                                                                                                                         |
| Odontacarbus                  | Odontacarbus tetradetosus (12).                                                                                                                                                           |
| Chatia                         | Chatia maoyi (2); C. alpine (1).                                                                                                                                                           |
| Shunseennia                    | Shunseennia scabristetosa (12).                                                                                                                                                            |
| Unidentified species           | 90 individuals                                                                                                                                                                              |
| Total chigger mites            | 5,882 individuals; 127 species, 15 genera, 3 subfamilies, 2 families                                                                                                                          |

** Main vectors of scrub typhus in China
* Potential vectors of scrub typhus and hemorrhagic fever with renal syndrome (caused by hanta virus; also called “epidemic hemorrhagic fever, EHF” in China)

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Table 5. The comparative analysis of chigger mites collected from small mammal hosts in MUL and CFL areas (2001–2015).

| Dominant chigger mite species | MUL | CFL |
|------------------------------|-----|-----|
| Name                        |     |     |
| L. scutellare                |     |     |
| G. fimbriata                 |     |     |
| L. densipunctatum            |     |     |
| A. indica                    |     |     |
| L. deliens                   |     |     |
| W. micropelta                |     |     |

Table 6. Chigger mites collected and identified in CFL from 2001 to 2015.

| Taxonomic taxa of chigger mites | Collected individuals and species of chigger mites (The figures in the brackets are the collected individuals for each mite species) |
|---------------------------------|---------------------------------------------------------------------------------------------------------------|
| Trombiculidae                   |                                                                                                              |
| Microtrombicula                 |                                                                                                              |
| Eutrombicula                   |                                                                                                              |
| Hellenicula                    |                                                                                                              |
| Dolosia                        |                                                                                                              |
| Acsoschoengastia               |                                                                                                              |
| Walchiella                     |                                                                                                              |
| Gahrlietinae                   |                                                                                                              |
| Walchia                        |                                                                                                              |
| Schoengastiella                |                                                                                                              |
| Gahrlietia                     |                                                                                                              |
| Leeuwenhoekiidae               |                                                                                                              |
| Chatia                         |                                                                                                              |
| Unidentified species           |                                                                                                              |

** Main vectors of scrub typhus in China
* Potential vectors of scrub typhus and hemorrhagic fever with renal syndrome (caused by hanta virus; also called "epidemic hemorrhagic fever, EHF" in China)
vectors of scrub typhus and hemorrhagic fever with renal syndrome (caused by hanta virus) in China. Of the six main vectors of scrub typhus in China, five vector species were found in the two landscapes of Yunnan province. These five species are *L. scutellare*, *L. deliense*, *L. rubellum*, *L. kaohuense* and *L. insulare*. Of these five vector species, *L. scutellare* and *L. deliense* are the dominant mite species (Figs 2 and 3). The only exception was *L. jishoum* (one main vector of tsutsugamushi disease in China) which was not collected from the two landscapes in this investigation. A total of 10 vector species or potential vector species of chigger mites were found in each landscape, but the dominant vector species and their distribution were very different. As
a main and powerful vector (*L. deliense*) or an important potential vector (*A. indica*) of tsutsugamushi disease in China, *L. deliense* and *A. indica* were the dominant chigger mites in CFL (Cr = 25.81% for *A. indica*; Cr = 23.47% for *L. deliense*). Another vector of tsutsugamushi disease and hemorrhagic fever with renal syndrome in some parts of China, *L. scutellare* was the dominant chigger mite in MUL (Cr = 26.09%). The total percentage of *L. deliense* and *A. indica* (Cr = 25.81% + 23.47% = 49.28%) in CFL was much higher than that of *L. scutellare* (Cr = 26.09%) in MUL (Table 5).

**Fig 3.** The photos of *Leptotrombidium deliense*. (a) Complete picture (under microscope: 10×20); (b) Scutum and dorsal setae (under microscope: 10×40).

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Infestation difference of vector mites on small mammal hosts in two types of landscapes

The overall infestations of chigger mites on all the small mammals were different in two types of landscapes. There were much more individuals of chigger mites collected in CFL (17,742) than in MUL (5,882). The overall prevalence ($P = 38.40\%$), mean abundance ($MA = 15.96$ mites/per host) and mean intensity ($MI = 41.55$ mites/per host) in CFL were much higher than those in MUL ($P = 19.96\%, MA = 1.85$ mites/per host, $MI = 9.28$ mites/per host) (Table 7). The main vector species of chigger mites on their main rodent hosts also showed a higher prevalence ($P$), mean abundance ($MA$) and mean intensity ($MI$) in CFL than in MUL. As showed in Table 7 for example, the prevalence ($P = 14.57\%$), mean abundance ($MA = 4.30$) and mean intensity ($MI = 29.49$) of \textit{L. deliense} on its dominant host species (\textit{R. tanezumi}) were high in CFL. In comparison with \textit{L. deliense} on \textit{R. tanezumi} in CFL, the prevalence ($P$) of \textit{L. scutellare} was lower on one of its dominant host species \textit{A. chevrieri} ($P = 3.41\%$) in MUL. The mean abundance ($MA$) and mean intensity ($MI$) of \textit{L. scutellare} on its two dominant host species (\textit{E. miletus} and \textit{A. chevrieri}) were all lower in MUL ($MA = 2.47$ and $MI = 9.77$ on \textit{E. miletus}; $MA = 0.13$ and $MI = 3.71$ on \textit{A. chevrieri}). The prevalence ($P$) of \textit{L. scutellare} on \textit{E. miletus} (one of its dominant host species), however, was higher ($P = 25.30\%$) than that of \textit{L. deliense} on \textit{R. tanezumi} in CFL ($P = 14.57\%$) and this is an exception.

Beta-diversity measurement of small mammal hosts and chigger mites in two types of landscapes

Cody diversity index was used to analyze the beta-diversity ($\beta$ diversity) of small mammal hosts and chigger mites in MUL and CFL landscape. From low latitude to high latitude of investigation counties in MUL and CFL landscape, the $\beta$ diversity of small mammal hosts and chigger mites in MUL landscape were higher than that in CFL landscape (Table 8).

Discussion

Small mammals usually involve five orders: Rodentia, Insectivora, Scandentia, Lagomorpha and Chiroptera. Of the five orders, Rodentia (rodents) are the major part with about 2000 species recorded in the world [1]. Different from other categories of small mammals, the majority of rodents (rats, mice and voles, etc.) are pests and they are harmful to agriculture and forestry. Besides destroying crops and forests in agriculture and forestry, some rodents are of medical importance and they can be reservoir hosts and infection sources of some zoonoses [3–6]. Although many rodent species can be the potential reservoir hosts of some zoonoses, \textit{R. tanezumi} is the most important reservoir host and infection source of some zoonoses (such as plague, hemorrhagic fever with renal syndrome, scrub typhus and leptospirosis, etc.) in Yunnan province, and \textit{E. miletus} and \textit{A. chevrieri} come next [3–6]. Six species of chigger mites

| MUL | CFL |
|-----|-----|
| Overall infestation of chiggers | Overall infestation of chiggers |
| L. scutellare on E. miletus | L. deliense on R. tanezumi |
| $P$ | 19.96% | 38.40% |
| $MA$ | 1.85 | 15.96 |
| $MI$ | 9.28 | 41.55 |

$P =$ Prevalence; $MA =$ Mean abundance; $MI =$ Mean infestation

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(L. deliense, L. scutellare, L. rubellum, L. kaohuense, L. insulare, L. jishoum) have been proven to be the main vectors of tsutsugamushi disease in China [13, 41–44], and two of them (L. deliense and L. scutellare) are very abundant and wide distributed in Yunnan province [43, 45] (Figs 2 and 3). Besides L. scutellare has been proved to be the potential vector of hanta virus [12, 46].

About six mite species (A. indica, L. yui, L. imphalum, L. akamushi, L. pallidum, L. rupestre) are suspected to be the potential vectors of tsutsugamushi disease [44, 47, 48].

The distribution of small mammals and their ectoparasitic chigger mites, especially the reservoir hosts and vectors of zoonoses, would influence the spread and incidence of the related zoonoses [49, 50]. As showed in the results of this paper, the species diversity of small mammals was much higher in MUL than in CFL, but more rodents were found in CFL with a higher percentage (Tables 2 and 3). The percentage of the main zoonosis reservoir host (R. tanezumi) in CFL was much higher than the reservoir hosts (E. milietus and A. chevrieri) in MUL (Table 3). Much more species of chigger mites were collected in MUL with a higher species diversity (S = 127) than in CFL (S = 86) (Tables 4, 5 and 6). Although there were a total of 10 vector species or potential vector species of chigger mites found in each type of landscapes, but the dominant vector species and their percentage were different (Tables 4, 5 and 6). As two dominant species of chigger mites in the cultivated landscape, the total percentage of L. deliense and A. indica (Cr = 25.81% + 23.47% = 49.28%) in CFL was much higher than that of L. scutellare (Cr = 26.09%) in MUL (Table 5). The infestation of vector mite species on small mammal hosts was more severe in CFL with higher prevalence (P), mean abundance (MA) and mean intensity (MI) than that (infestation) in MUL. The results of the present paper suggest that landscapes with different biodiversity influence the distribution of small mammals and their ectoparasitic chigger mites. A complex landscape with higher biodiversity seems to decrease the intensity of the main reservoir hosts and vector species, and a simple landscape with lower biodiversity may benefit the occurrence of the main reservoir hosts and vector species [15, 18, 19].

In the present investigation, MUL is situated in the famous “Three Parallel Rivers Region” on the eastern Tibetan Plateau, where three rivers (Jinshajiang, Lancangjiang, and Nujiang rivers) are parallel to each other, flowing from the northwest towards the southwest. The Three Parallel Rivers Region has been attracting a great attention of the world because of its unique geological history on the Asian continent, rich biodiversity and fascinating ethnic cultures [28, 30]. The MUL in the Three Parallel Rivers Region is a typically complex landscape with higher biodiversity. Far from MUL, the selected six counties in the south of Yunnan province have a wide realm of flat-like farmlands with abundant crops, which forms CFL, a typically simple

Table 8. Comparison on Beta-diversity of small mammal hosts and chigger mites between MUL and CFL.

| County (low to high latitude) | MUL | CFL |
|------------------------------|-----|-----|
|                              | Hosts | Chigger mites | Hosts | Chigger mites |
| M1                           | 10.5 | 20 | C1 | 6.5 | 14 |
| M2                           | 14.5 | 27.5 | C2 | 5 | 23.5 |
| M3                           | 14 | 31 | C3 | 2 | 24 |
| M4                           | 10.5 | 18.5 | C4 | 5 | 22.5 |
| M5                           | 9.5 | 26 | C5 | 5 | 27 |
| X                            | 11.8±2.2804 | 24.6±5.2369 | X | 4.7±1.6432 | 22.2±4.8811 |

M1: Fugong—Lijiang; M2: Lijiang—Weixi; M3: Weixi—Gongshan; M4: Gongshan—Xianggelila; M5: Xianggelila—Deqin. C1: Mengla—Menghai; C2: Menghai—Jinghong; C3: Jinghong—Puer; C4: Puer—Ninger; C5: Ninger—Yuanjiang.

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landscape with lower biodiversity. Besides a simple landscape and lower biodiversity, CFL in the south of Yunnan have warm and humid climate, which may be beneficial to the growth and reproduction of chigger mites [7].

Beta diversity is an important component of biological diversity, measuring compositional change in species assemblages across temporal and spatial scales. Beta diversity concerns not only a number of ecological and evolutionary issues [51], but can also guide the selection of protected areas and help to optimize conservation networks [52]. It has thus become a hot topic in biodiversity research in recent years. Researchers have used various measures and analytical methods to investigate patterns of beta diversity and its underlying mechanisms for various taxa and in different regions. Whittaker introduced the term beta diversity in 1960, but defined it vaguely [53]. As the concept of beta diversity evolved, a high variety of measures were developed to quantify the concept. In present paper, we used Cody diversity index to analyze the beta diversity of small mammal hosts and chigger mites [40]. The results of the beta diversity further supported that there was lower species diversity of small mammals and their ectoparasitic chigger mites, but higher individual abundance of main rodent reservoir species and main vector mite species in the simple landscape (CFL) in comparison with in the complex landscape (MUL) (Table 8).

According to the results in the present paper, the species diversity of small mammals and their ectoparasitic chigger mites in the simple landscape (CFL) was much lower, but the percentage of reservoir rodent hosts and vector mites of zoonoses were prominently higher and the infestation of vector mites on their hosts were much more severe in comparison with those in the complex landscape (MUL). The simple landscape with lower biodiversity, together with warm and humid climate, seems to have caused the quantity increase of some reservoir rodent hosts and vector chigger mites with the decrease of their species diversity. By contrast the complex landscape with higher biodiversity seems to have depressed some reservoir rodent hosts and vector chigger mites. The decrease of species diversity and the quantity increase of reservoir rodent hosts and vector chigger mites would likely increase the potential risk of the spread of tsutsugamushi diseases and some other related zoonoses.

Some studies have previously revealed that there are some links between ecological environments (including landscapes and biodiversity, etc.) and human health. The fragmentation of forests, wetlands destruction and some other habitat destruction or modification would lead to the loss of biodiversity. The destruction of ecological environment and biodiversity loss would increase the human contact rates with various pathogens and disease vectors, which can finally increase the spread and incidence of some diseases [14–24]. The results in our study revealed that there were much more individuals and higher percentage of the main zoonosis reservoir rodent hosts and the main vector chigger mites in the simple landscape with lower biodiversity (CFL) and this would likely increase the potential risk of the spread of the related zoonoses. Our results support the previous opinions related to the relationship between ecological environments and human health. The complex landscape with higher biodiversity may depress the reservoir rodent hosts and vector mites of zoonoses, and therefore it is of medical significance to preserve the biodiversity in the environments and prevent them from being destroyed.

Appendix

(The full list of species that were considered "pests" and the number that were euthanized in parentheses, MUL and CFL included)

Apodemus draco (641)
Apodemus chevrieri (411)
Apodemus deninsulae (104)
Apodemus sylvaticus (15)
Apodemus latronum (233)
Apodemus agrarius (4)
Rattus tanezumi (981)
Rattus nitidus (104)
Rattus norvegicus (88)
Rattus sladeni (96)
Rattus bowersi (16)
Niviventer confucianus (245)
Niviventer fulvescens (149)
Niviventer andersoni (10)
Niviventer eha (1)
Niviventer excelsior (2)
Mus caroli (1)
Mus pahari (11)
Mus musculus (8)
Micromys minutus (3)
Vernaya fulva (1)
Vandeleuria oleracea (1)
Bandicota indica (1)
Eothenomys miletus (506)
Eothenomys eleusis (2)
Eothenomys proditor (60)
Eothenomys custos (56)
Suncus murinus (38)
Crocidura attenuata (24)

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References

1. Zheng ZM, Jiang ZK, Chen AG. Rodents. Shanghai: Shanghai Jiaotong University Press; 2008. (In Chinese)

2. Huang WJ, Chen YX, Wen YX. Rodents of China. Shanghai: Fudan University Press; 1995. (In Chinese)

3. Oguge NO, Durden LA, Keirans JE, Balami HD, Schwan TG. Ectoparasites (sucking lice, fleas and ticks) of small mammals in southeastern Kenya. Med Vet Entomol. 2009; 23:387–392. https://doi.org/10.1111/j.1365-2915.2009.00820.x PMID: 19941604

4. Daniel M, Stekolnikov AA, Hakimitabar M, Saboori A. Chigger mites (Acarai: Trombiculidae) parasitizing small mammals in the Eastern Hindu Kush and some other Afghan areas. Parasitol Res. 2010; 107:1221–1233. https://doi.org/10.1007/s00436-010-1992-x PMID: 21140167

5. Zuo XH, Guo XG, Zhan YZ, Wu D, Yang ZH, Dong WG, et al. Host selection and niche differentiation in sucking lice (Insecta: Anoplura) among small mammals in southwestern China. Parasitol Res. 2011; 108:1243–1251. https://doi.org/10.1007/s00436-010-2173-7 PMID: 23471780

6. Huang LQ, Guo XG, Speakman JR, Dong WG. Analysis of gamasid mite (Acaii: Mesostigmata) associated with the Asian house rat, Rattus tanezumi (Rodentia: Muridae) in Yunnan Province, Southwest China. Parasitol Res. 2013; 112:1967–1972. https://doi.org/10.1007/s00436-013-3354-y PMID: 23471780

7. Li JC, Wang DQ, Chen XB. Trombiculid mites of China. Guangzhou: Guangdong Science and Technology Press; 1997. (In Chinese)

8. Daniel M, Stekol'nikov AA. Chigger mites (Acarai: Trombiculidae) from Makalu region in Nepal Himalaya, with a description of three new species. J Med Entomol. 2009; 46: 753–765. PMID: 19645277

9. Traub R, Wisseman CL Jr. The ecology of chigger-borne rickettsiosis (scrub typhus). J Med Entomol. 1974; 11: 237–303. PMID: 4212400

10. Takamura A, Tanaka H, Kawamura A. Tsutsugamushi diseases: an overview. Tokyo: University of Tokyo Press; 1995.

11. Zhang Y, Li XF, Zhu J, Tang JQ, Li YX, Wu GH, et al. Preliminary studies on proliferation of haemorrhagic fever with renal syndrome virus in Leptotrombidium (L.) scutellare. Chin J Exp Clin Virol. 1997; 11: 259–262. (In Chinese)

12. Song G. Epidemiological progresses of hemorrhagic fever with renal syndrome in China. Chinese Med J. 1999; 112: 472–477.

13. Yu J, Deng XZ, Yang ZQ, Yao PP, Zhu HP, Xiong HR, et al. Study on the transmission of Hantaan virus and Orientia tsutsugamushi by naturally dual infected Leptotrombidium scutellare through stinging. Chin J Prevent Med. 2010; 44: 324–328. (In Chinese)

14. Chivian E. Global environmental degradation and biodiversity loss: implications for human health. Washington, D.C: Island Press; 1997.
15. Chivian E, Bernstein A. Sustaining life: how human health depends on biodiversity. New York: Oxford university press; 2008.
16. Ostfeld RS, Keesing F. Biodiversity and disease risk: the case of Lyme disease. Conserv Biol. 2000; 14: 722–728.
17. Loguидice K, Ostfeld RS, Schmidt KA, Keesing F. The ecology of infectious disease: effects of host diversity and community composition on Lyme disease risk. Ecology. 2003; 100: 567–571.
18. Pongsiri MJ, Roman J, Ezenwa VO, Goldberg TL, Koren HS, Newbold SC, et al. Biodiversity loss affects global disease ecology. BioScience. 2009; 59: 945–954.
19. Suzin G, Marce E, Giermakowski JT, Mills JN, Ceballos G, Ostfeld RS, et al. (2009). Experimental evidence for reduced rodent diversity causing increased hantavirus prevalence. PLoS ONE. 2009; 4: e5461. https://doi.org/10.1371/journal.pone.0005461 PMID: 19421313
20. Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, et al. Biodiversity loss and its impact on humanity. Nature. 2012; 486: 59–67. https://doi.org/10.1038/nature11148 PMID: 22678280
21. Johnson PTJ, Preston DL, Hoverman JT, Henderson JS, Paull SH, Richgels KLD, et al. Species diversity reduces parasite infection through cross-generational effects on host abundance. Ecology. 2012; 93: 56–64. PMID: 22486087
22. Johnson PTJ, Preston DL, Hoverman JT, Richgels KLD. Biodiversity decreases disease through predictable changes in host community competence. Nature. 2013; 494: 230–233. https://doi.org/10.1038/nature11883 PMID: 23407539
23. Young HS, Billeter S, Dirzo R, Helgen KM, Kosoy M, McCauley DJ, et al. Does habitat disturbance increase infectious disease risk for primates? Ecol Lett. 2013; 16: 656–683. https://doi.org/10.1111/ele.12094 PMID: 2348139
24. Wood CL, Lafferty KD, Deleo G, Young HS, Hudson PJ, Kuris AM. Does biodiversity protect humans against infectious disease? Ecology. 2014; 95: 817–832. PMID: 24933803
25. Jackson LE. The relationship of urban design to human health and condition. Landsc Urban Plan. 2003; 64: 191–200.
26. Lee ACK, Maheswaran R. The health benefits of urban green spaces: a review of the evidence. J Publ Health. 2010; 33: 212–222.
27. Wolch JR, Byrne J, Newell JP. Urban green space, public health, and environmental justice: The challenge of making cities ‘just green enough’. Landsc Urban Plan. 2014; 125: 234–244.
28. Yi SL, Luo P, Wang Q, Shi FS, Sun G, et al. Changes in livestock migration patterns in a Tibetan-style agropastoral system: A study in the Three-Parallel-Rivers Region of Yunnan, China. Mt Res Dev. 2007; 27: 138–145.
29. Wang JX, Peng XF, Yang SY. A primary analysis of tourist resources and environment fragility of three parallel river of Yunnan protected areas. J Yunnan Normal Univ. 2005; 25: 59–64. (In Chinese)
30. Gong ZD, Zhang LY, Duan XD, Feng XG, Ge JQ, Li DM, et al. Species richness and fauna of fleas along a latitudinal gradient in the three parallel rivers landscape, China. Biodivers Sci. 2007; 15: 61–69. (In Chinese)
31. Ou GL, Peng MC, Wang CY, Xiang L. Distribution of vegetation landscape in Gongshan county of Yunnan Province, the core area of the three parallel river belt. J Mt Sci. 2013; 31: 464–472. (In Chinese)
32. Peng PY, Guo XG, Ren TG, Song WY. Faunal analysis of chigger mites (Acari: Prostigmata) on small mammals in Yunnan Province, southwest China. Parasitol Res. 2015; 114: 2815–2833. https://doi.org/10.1007/s00436-015-4483-2 PMID: 25930112
33. Peng PY, Guo XG, Song WY, Hou P, Zou YJ, Fan R, He XS. Analysis of ectoparasites (chigger mites, gamasid mites, fleas and sucking lice) of the Yunnan red-backed vole (Eothenomys milleti) sampled throughout its range in southwest China. Med Vet Entomol. 2015; 29: 403–415. https://doi.org/10.1111/mve.12134 PMID: 26345365
34. Peng PY, Guo XG, Ren TG, Song WY, Dong WG, Fan R. Species diversity of ectoparasitic chigger mites (Acari: Prostigmata) on small mammals in Yunnan Province, China. Parasitol Res. 2016; 115: 3605–3618. https://doi.org/10.1007/s00436-016-5127-x PMID: 27212464
35. Wan XF, Zhang XJ, Liu W, Wang GH, Wang MJ, Zhong QW. Social hierarchy and its seasonal changes of marked Lasiosignum brandti population. Chin J Ecol. 2007; 26: 359–362. (In Chinese)
36. Men XY, Guo XG, Dong WG, Niu AQ, Qian TJ, Wu D. Ectoparasites of Chevrier’s field mouse, Apodemus chevrieri, in a focus of plague in southwest China. Med Vet Entomol. 2007; 21: 297–300. https://doi.org/10.1111/j.1365-2915.2007.00679.x PMID: 17897372
37. Simpson EH. Measure of diversity. Nature. 1949; 163: 688.
38. Zhao ZM, Guo YQ. Principle and methods of community ecology. Chongqing: Publishing house of Scientific and Technical Documentation (Chongqing Branch); 1990. (In Chinese)
39. Magurran AE. Measuring richness and evenness. Trends Ecol Evol. 1998; 13:165–166.
40. Cody ML. Towards a theory of continental species diversities: bird distributions over Mediterranean habitat gradients. In: Cody ML, Diamond JM, editors. Ecology and Evolution of Communities; 1975. pp. 214–257.
41. Wei JJ, Tong GZ, Shi SF. Study on Leptotrombidium gaohuensis sp. Nov. newly discovered vector of tsutsugamushi disease. Chin Med J. 1987; 100: 590–594. PMID: 3123167
42. Yang GR, Yu ZZ, Xie BO. Investigation studies on the biological behaviour of Leptotrombidium deliense in Yunnan Province. Chin J Pest Control. 1991; 7: 7–12. (In Chinese)
43. Wu GH, Zhang Y, Guo HB, Jiang KJ, Zhang JJ, Gan YH. The role of Leptotrombidium scutellare in the transmission of human diseases. Chin Med J. 1996; 109: 670–673. PMID: 9275333
44. Wu GH. Research on the media of scrub typhus in China. Chin J Vector Bio & Control. 2005; 16: 485–487.
45. Zhan YZ, Guo XG, Zuo XH, Wang QH, Wu D. Preliminary survey on the distribution of Leptotrombidium deliense in some areas of Yunnan province. Chin J Epidemiol. 2011; 32: 13–16. (In Chinese)
46. Wu GH, Zhang Y, Guo HB. Study on transovarian transmission of pathogen in Leptotrombidium scutellare. Chin J Vector Bio & Control. 2004; 15: 301–303.
47. Hou SX, Guo XG. The development of chigger mite and tsutsugamushi disease research. J Dali Univer. 2006; 5: 74–77. (In Chinese)
48. Lee IY, Kim HC, Lee YS, Seo JH, Lim JW, Yong TS, et al. Geographical distribution and relative abundance of vectors of scrub typhus in the Republic of Korea. Korean J Parasitol. 2009; 47: 381–386. https://doi.org/10.3347/kjp.2009.47.4.381 PMID: 19967086
49. Ostfeld RS, Keesing F. The function of biodiversity in the ecology of vector-borne zoonotic diseases. Can J Zool. 2000; 78: 2061–2078.
50. Huang TH, Liu L, Du CH, Hong M, Liu ZX, Gao ZH. The relationship between the distribution of small mammals, vectors and plague in different landscapes in Southwest Yunnan. Chin J Vector Biol & Control. 2016; 27: 112–116. (In Chinese)
51. Lennon JJ, Koleff P, Greenwood JJD, Gaston KJ. The geographical structure of British bird distributions: diversity, spatial turnover and scale. J Anim Ecol. 2001; 70: 966–979.
52. Jacquemyn H, Honnay O, Pailler T. Range size variation, nestedness and species turnover of orchid species along an altitudinal gradient on Réunion Island: implications for conservation. Biol Conserv. 2007; 136: 388–397.
53. Whittaker RH. Vegetation of the Siskiyou Mountains, Oregon and California. Ecol Monogr. 1960; 30: 279–338.