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ORIGINAL ARTICLE

Collembola associated with edible mushrooms in China

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Abstract Collembola, a common pest of mushrooms, could reduce the yield and quantity of edible mushroom and causes great economic losses in their production. During the investigation of Collembola in the main edible mushroom production areas in China, 27 species belonging to five families and 16 genera, hosted by more than ten species of edible mushrooms have been revealed by morphological and molecular evidence. The most diverse genus was the genus *Ceratophysella* with five species reported. Fourteen of the 27 species were distributed only in China, while others were widely distributed all over the world. Fifteen species on mushrooms have been barcoded; the results of the species delimitation by mitochondrial *COI* marker confirmed the results by morphology, with low intra-specific divergences (0–8%). Two *Thalassaphorura* species, with the only difference being in the presence of parapseudocelli on the anterior ventral head, were clearly differentiated by the molecular markers.

Key words Distribution, edible fungi, list of species, mitochondrial maker, springtails.

1 Introduction

Edible mushrooms have been widely treated as delicious and nutritious food sources, being low in energy and fat but high in protein, carbohydrate, and dietary fibre (Cheung, 2010). The production of edible mushrooms has greatly increased during the past half-century, and the cultivation becomes a substantial key to food security in the world (Pandey *et al.*, 2018). Especially in the main producing country China, the mushroom industry is currently ranked the sixth among the country's agricultural products (Zhang *et al.*, 2014a). However, cultivated mushrooms are subject to attack by a variety of pests, and this reduces the yield and quantity of mushroom that causes great economic losses (Oyebamiji *et al.*, 2018). Springtails, are regarded as one of the main pests which are injurious to mushrooms, often brought into the greenhouse with mushrooms culture in the compost of which cultivated beds are composed (Popenoe, 1917). Besides directly eating fungus strains, both hyphae and fruiting bodies, Collembola can also carry and spread diseases to various species of edible mushrooms and are difficult to control (Yang & Zhang, 1981; He *et al.*, 2004; Sun & Wang, 2012).

Researches of collembolan species on mushrooms began at the beginning of the 20th century. Popenoe (1917) summarised the damage and control of Collembola, but only mentioned one species, *Ceratophysella armata* (Nicolet, 1842),

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from the United States. Later, Thomas (1939) gave a comprehensive list of more than 20 species which were associated with edible mushrooms in the United States and in England. In recent years, researches on Collembola on edible mushrooms have been carried out in other countries; for example, more than 30 species have been recorded in Mexico, Spain, and Australia (Palacios-Vargas & Gómez, 1991; Mateos *et al.*, 1996; Greenslade *et al.*, 2002). The results from both Mexico and Spain showed that Hypogastruridae (the genus *Ceratophysella*) was the most abundant group of Collembola, they eat fungi and may live in huge number on cultivated fungi, which raises the problem of their potential harmfulness (Palacios-Vargas & Gómez, 1991; Mateos *et al.*, 1996). In Australia, the species of Brachystomellidae, as well as Hypogastruridae, were found to be abundant on fungal fruit bodies (Greenslade *et al.*, 2002; Greenslade & Clift, 2004). Interestingly, Brachysomellidae species were only found as the potential endamicbasidiospore feeders in the southern hemisphere but not in the northern hemisphere (Greenslade *et al.*, 2002). The research of Collembola on edible mushrooms in China started in 1981 and the results were reported at the family level only (Yang & Zhang, 1981). Subsequently, five new species were reported from southern China (Guangdong Province) (Lin & Xia, 1983, 1985; Lin, 1985). Afterward, no comprehensive reviews on mushroom Collembola have been completed. Some reports on Collembola concerned as edible fungi pests listed no more than ten species (Zhang, 1989; Jiang, 1996; He *et al.*, 2004; Luo & Zhuang, 2006; Sun & Wang, 2012). Still, these references are doubtful as names and distributions of species were rarely given, or names were wrongly cited. Moreover, DNA barcoding, which was used to complement morphological characters to allow species characterization in several groups of Collembola (Pan, 2015; Sun *et al.*, 2017; Yu *et al.*, 2017), has never been employed in the taxonomy of mushroom springtails.

In fact, hard data about the harmfulness of Collembola to fungi are lacking. The aim of our study is to give an overview of our knowledge on Collembola species living on edible mushrooms in China, and to improve the taxonomic characterisation of some of them, based on combined morphological and barcode approaches. On this basis, a second step will be to evaluate the suspected harmfulness of Collembola to cultivated fungi.

2 Materials and methods

2.1 Taxon sampling

The collections were implemented on mushrooms inhabited by Collembola in the main edible fungi production areas of China, including Jilin, Shandong, Henan, Zhejiang, Fujian, Sichuan, and Tibet (Figs 1 and S1, Table S1). Specimens of

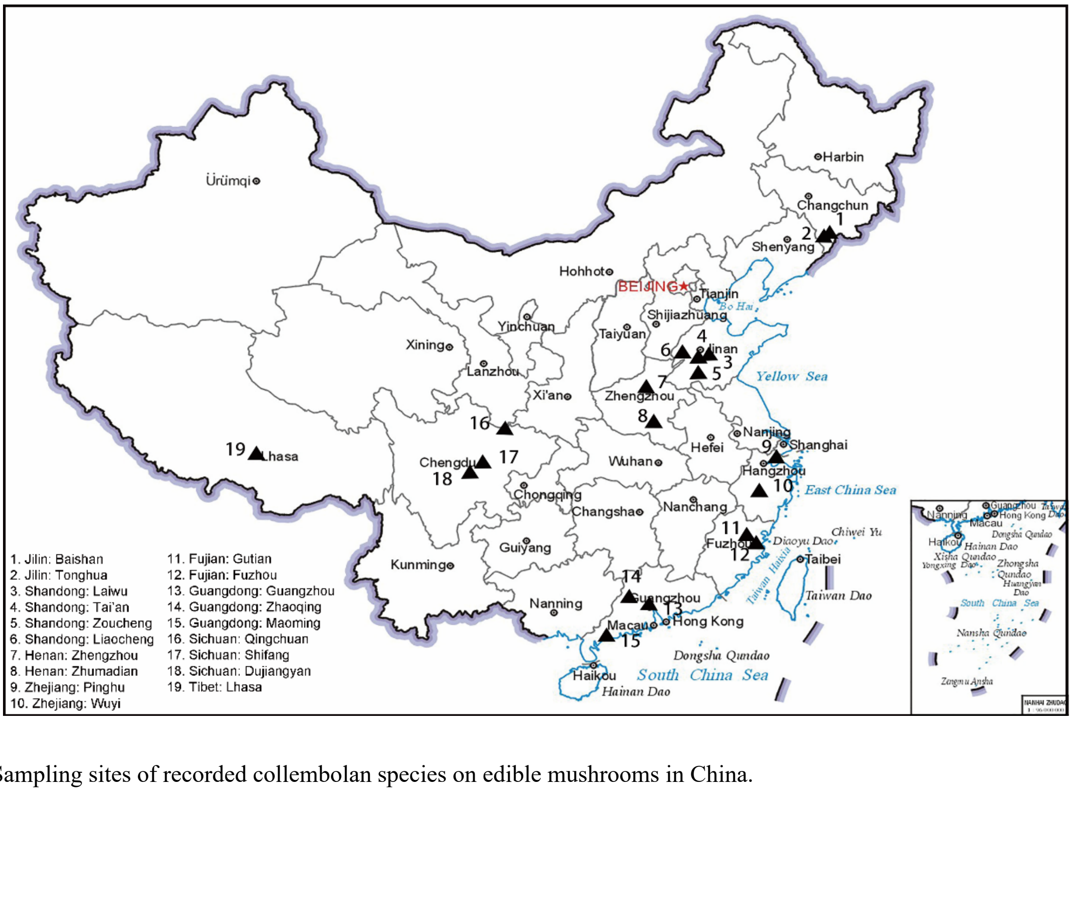

Figure 1. Sampling sites of recorded collembolan species on edible mushrooms in China.

Collembola were collected by aspirator or by hand using a brush and stored in 99% ethanol at -20°C. One hundred and sixty-one individuals were selected for molecular analysis. The samples were in the Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, China and the Department of Entomology, College of Plant Protection, Nanjing Agricultural University, Nanjing, China.

2.2 Morphological identification

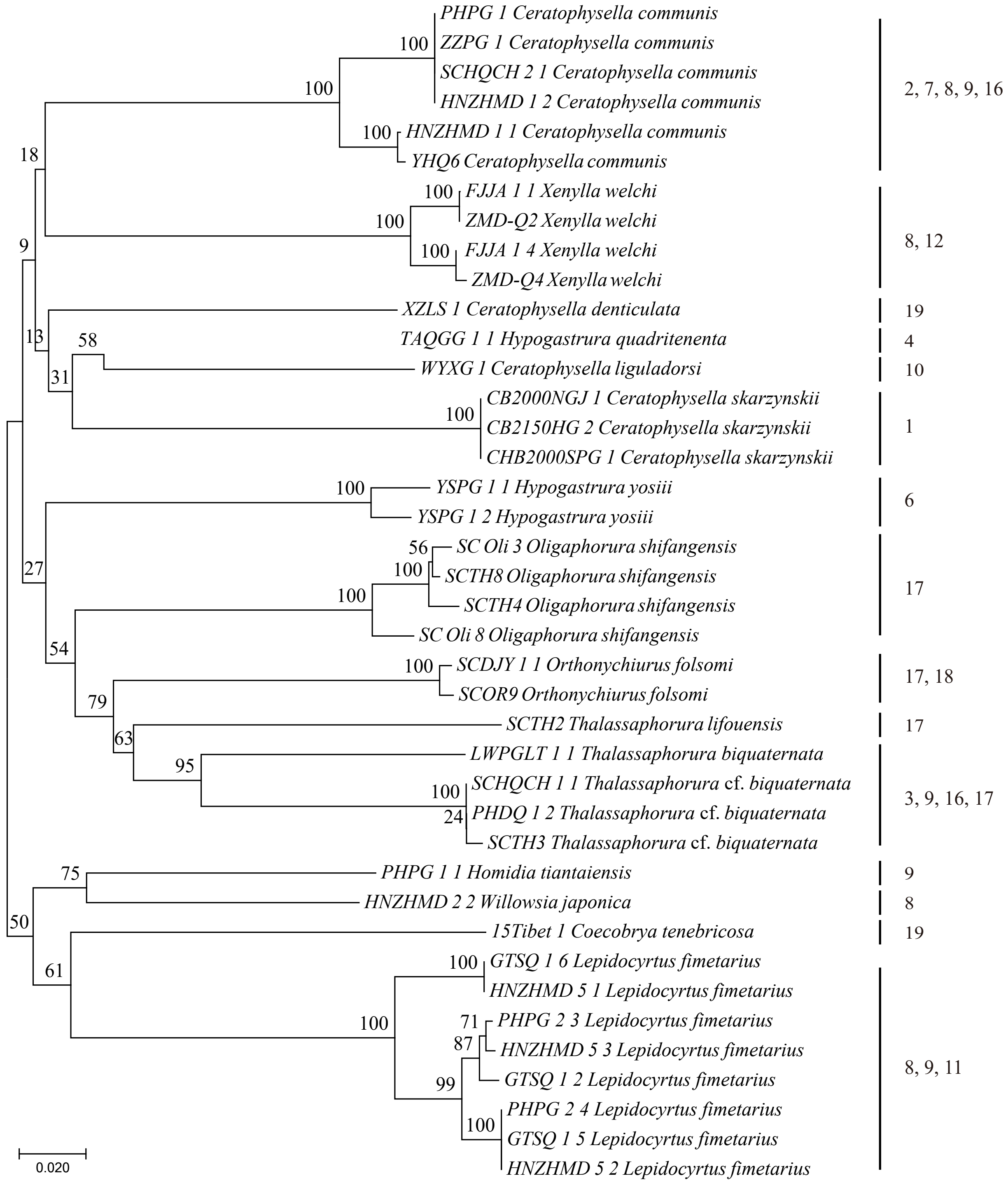

Figure 2. Reconstructed phylogenetic tree based on mitochondrial *COI* marker. Maximum-likelihood bootstrap support values are shown in the branches. The codes of sampling sites are referred in Fig. 1. The codes inserted before the species name are named for distinguishing samples from different collection locations in molecular experiments and the information in detail is listed in Table S2.

Table 1. The information of recorded collembolan species on edible mushrooms in China (dubious records with insufficient descriptions in former references were not included).

Family	Species	Collection sites and host mushrooms	Record references	Identification literature	Distribution*
Dicyrtomidae	*Dicyrtoma balicrura* Lin & Xia, 1985	South China: Guangdong: Zhaoqing (*Auricularia auricula*)	Lin & Xia, 1985		China
Entomobryidae	*Coecobrya tenebricosa* (Folsom, 1902)	West China: Tibet: Lhasa (*Ganoderma* sp.)	the present study	Jordana, 2012	China, South Korea, Hawaii, Central America, Europe
Entomobryidae	*Entomobrya proxima* Folsom, 1924	North China: Shandong: Zoucheng (*Stropharia rugosoannulata*), Tai'an (*Pleurotus citrinopileatus*)	the present study	Jordana, 2012	China, Japan, Singapore, Indonesia, New Guinea
Entomobryidae	*Homidia dianbaiensis* (Lin, 1985)	South China: Guangdong: Maoming (*Auricularia auricula*)	Lin, 1985		China
Entomobryidae	*Homidia socia* Denis, 1929	East China: Zhejiang: Pinghu (*Pleurotus ostreatus*)	the present study	Jordana, 2012	China, USA
Entomobryidae	*Homidia tiantaiensis* Chen & Lin, 1998	East China: Zhejiang: Pinghu (*Pleurotus ostreatus*)	the present study	Jordana, 2012	China
Entomobryidae	*Lepidocyrtus fimetarius* Gisin, 1964	South China: Fujian: Gutian: Shangqiancun (*Volvariella volvacea*); East China: Zhejiang: Pinghu (*Pleurotus ostreatus*); North China: Henan: Zhumadian (*Pleurotus ostreatus*), Shandong: Zoucheng *(Ganoderma* sp.)	the present study	Gisin, 1964	Europe, Asia, Australia
Entomobryidae	*Sinella curviseta* Brook, 1882	North China: Shandong: Zoucheng (*Stropharia rugosoannulata*)	the present study	Jordana, 2012	Cosmopolitan
Entomobryidae	*Willowsia japonica* (Folsom, 1898)	North China: Shandong: Zoucheng (*Ganoderma* sp.), Henan: Zhumadian (*Pleurotus ostreatus*)	the present study	Zhang *et al.*, 2011	China, Hawaii, Japan
Hypogastruridae	*Ceratophysella communis* (Folsom, 1898)	Southwest China: Sichuan: Qingchuan (*Morchella vulgaris, Pleurotus ostreatus*); East China: Zhejiang: Pinghu (*Pleurotus ostreatus*); Northeast China: Jilin: Tonghua (*Morchella vulgaris*); North China: Henan: Zhumadian (*Pleurotus ostreatus, Morchella vulgaris*), Zhengzhou (*Pleurotus ostreatus*)	Weiner *et al.*, 2019; the present study	Weiner *et al.*, 2019	Cosmopolitan
Hypogastruridae	*Ceratophysella denticulata* (Bagnall, 1941)	West China: Tibet: Lhasa (*Ganoderma* sp.)	Weiner *et al.*, 2019; the present study	Weiner *et al.*, 2019	Cosmopolitan
Hypogastruridae	*Ceratophysella flectoseta* Lin & Xia, 1983	South China: Guangdong: Guangzhou (mushroom species was not mentioned)	Lin & Xia, 1983		China
Hypogastruridae	*Ceratophysella liguladorsi* (Lee, 1974)	East China: Zhejiang: Wuyi (*Lentinus edodes*)	Weiner *et al.*, 2019; the present study	Weiner *et al.*, 2019	Asia
Hypogastruridae	*Ceratophysella skarzynskii* Weiner & Sun, 2019	Northeast China: Jilin: Baishan (*Melanoleuca* sp., *Boletus* sp., *Russulaceae* sp.)	Weiner *et al.*, 2019; the present study	Weiner *et al.*, 2019	China

Table 1 (continued)

Family	Species	Collection sites and host mushrooms	Record references	Identification literature	Distribution[*]
Hypogastruridae	*Hypogastrura quadritenenta* Jiang & Chen, 2008	North China: Shandong: Tai'an (*Stropharia rugosoannulata*), Zoucheng (*Ganoderma* sp.)	the present study	Jiang & Chen, 2008	China
Hypogastruridae	*Hypogastrura yosiii* Stach, 1964	North China: Shandong: Liaocheng (*Pleurotus ostreatus*)	the present study	Stach, 1964	China
Hypogastruridae	*Xenylla welchi* Folsom, 1916	North China: Henan: Zhumadian (*Morchella vulgaris*); South China: Fujian: Fuzhou (*Agrocybe aegerita*)	the present study	Thibaud *et al.*, 2004	Cosmopolitan
Onychiuridae	*Allonychiurus shandongensis* Sun & Li, 2015	North China: Shandong: Tai'an (*Pleurotus ostreatus*), Laiwu (*Pleurotus ostreatus*)	Sun & Li, 2015; the present study	Sun & Li, 2015	China
Onychiuridae	*Oligaphorura shifangensis* Liu & Sun, 2019	Southwest China: Sichuan: Shifang (*Morchella vulgaris*)	Liu *et al.*, 2019		China
Onychiuridae	*Onychiurus qingchuanensis* Liu & Sun, 2019	Southwest China: Sichuan: Shifang (*Morchella vulgaris*)	Liu *et al.*, 2019		China
Onychiuridae	*Orthonychiurus folsomi* (Schäffer, 1900)	Southwest China: Sichuan: Shifang (*Morchella vulgaris*), Dujiangyan (*Morchella vulgaris*)	the present study	Sun & Huang, 2014	Cosmopolitan
Onychiuridae	*Thalassaphorura biquaternata* Sun & Li, 2015	North China: Shandong: Laiwu (*Pleurotus ostreatus*), Liaocheng (*Pleurotus ostreatus*)	Sun & Li, 2015; the present study	Sun & Li, 2015	China
Onychiuridae	*Thalassaphorura* cf. *biquaternata* Sun & Li, 2015	Southwest China: Sichuan: Qingchuan (*Morchella vulgaris*), Shifang (*Morchella vulgaris*); East China: Zhejiang: Pinghu (*Stropharia rugosoannulata*)	the present study	Sun & Li, 2015	China
Onychiuridae	*Thalassaphorura encarpata* (Denis, 1931)	North China: Shandong: Tai'an (*Pleurotus ostreatus*), Zoucheng (*Pleurotus ostreatus*)	Sun & Li, 2015; the present study	Sun *et al.*, 2017	Cosmopolitan
Onychiuridae	*Thalassaphorura lifouensis* (Thibaud & Weiner, 1997)	Southwest China: Sichuan: Shifang (*Morchella vulgaris*); North China: Shandong: Laiwu (*Pleurotus ostreatus*)	Sun & Li, 2015; the present study	Thibaud & Weiner, 1997	Cosmopolitan
Paronellidae	*Salina auriculae* Lin, 1985	South China: Guangdong: Maoming (*Auricularia auricula*)	Lin, 1985		China
Paronellidae	*Salina sinensis* Lin, 1985	South China: Guangdong: Maoming (*Auricularia auricula*)	Lin, 1985		China

[*]The distribution of the species was from in Bellinger, Christiansen, & Janssens (1996–2019).

Specimens for morphological identification were cleared in lactic acid, mounted in Hoyer's medium to permanent slides, and studied using a Nikon Eclipse 80i microscope.

2.3 DNA extraction, amplification, and sequencing

DNA was extracted using an Ezup Column Animal Genomic DNA Purification Kit (Sangon Biotech, Shanghai, China) following the manufacturer's standard protocols. Specimens were maintained in 75% ethanol for further morphological re-examination after the 1h-lysis buffer was transferred to the pipette column containing silica. Extractions were performed non-destructively allowing further morphological re-examination of the specimens (Porco *et al.*, 2010). Primers were LCO1490 and HCO2198 commonly used for metazoan (Folmer *et al.*, 1994). Amplification volume and procedure were followed and described in Zhang *et al.* (2014b). All PCR products were checked on a 1% agarose gel. Successful products were purified and sequenced in both directions by Majorbio (Shanghai, China) on the ABI 3730XL DNA Analyser (Applied Biosystems). Sequences were assembled in Sequencher 4.5 (Gene Codes Corporation, Ann Arbor, USA), and deposited in GenBank (Table S1). Sequences were blasted in GenBank and checked for possible errors, then were preliminarily aligned using MAFFT v7.149 by the G-INS-I strategy (Katoh & Standley, 2013). Alignments were checked and corrected manually, with a final 658 bp for Cytochrome c oxidase subunit I (COI).

2.4 Data analyses

Neighbour-joining (NJ) trees and genetic distances were calculated in MEGA version X (Kumar *et al.*, 2018), with the Kimura-2 parameter model (Kimura, 1980) and pairwise deletion for gaps. Node supports of the NJ tree were evaluated through 1000 bootstrap replications.

3 Results

Twenty-seven species of Collembola were revealed on more than ten species of edible mushrooms originating from eight provinces of China (Fig. 1, Table 1). Among them, twenty-two species were added by our investigation with the use of mainly morphological, but also molecular analyses (Table S2). The species belonged to five families and sixteen genera: Dicyrtomidae (one *Dicyrtoma* species), Entomobryidae (eight species in six genera), Hypogastruridae (eight species in two genera), Onychiuridae (eight species in four genera), Paronellidae (two *Salina* species), and the most diverse genus was *Ceratophysella* with five species.

Fourteen of the twenty-seven species were distributed only in China, while the others were reported from all over the world (Table 1). Four species, *Willowsia japonica* (Folsom, 1898), *Xenylla welchi* Folsom, 1916, *Thalassaphorura* cf. *biquaternata* Sun & Li, 2015 and *Thalassaphorura lifouensis* (Thibaud & Weiner, 1997), were found in two provinces, and two species, *Lepidocytrus fimetarius* Gisin, 1964 and *Ceratophysella communis* (Folsom, 1898), were found in three or more provinces. Additionally, the species *L. fimetarius* was found on the mushroom species *Pleurotus ostreatus* both in Zhejiang and Henan, while the species *C. communis* was found on *Pleurotus ostreatus* in Zhejiang, Henan, and Sichuan, on *Morchella vulgaris* in Henan, Sichuan, and Jilin. Moreover, eight species (*Dicyrtoma balicrura* Lin & Xia, 1985, *Homidia dianbaiensis* (Lin, 1985), *Ceratophysella flectoseta* Lin & Xia, 1983, *Ceratophysella skarzynskii* Weiner & Sun, 2019, *Oligaphorura shifangensis* Liu & Sun, 2019, *Onychiurus qingchuanensis* Liu & Sun, 2019, *Salina auriculae* Lin, 1985, and *Salina sinensis* Lin, 1985) are only known from mushroom, the other ones living as well in different microhabitats.

Fifteen species have been barcoded in the study (Fig. 2, Table S2). Two species, *T. biquaternata* and *W. japonica*, have 8% within species mean distance. Seven species, *C. communis*, *H. yosiii*, *L. fimetarius*, *O. shifangensis*, *O. folsomi*, *T. lifouensis*, and *X. welchi*, have 1%–3% within species mean distance. Other five species have no intra-specific divergence.

4 Discussion

Five new species were described recently (Sun & Li, 2015; Liu *et al.*, 2019; Weiner *et al.*, 2019), and the current number of collembolan species on edible mushrooms (27 species) has more than doubled comparing to previous records in China (Zhang, 1989; Jiang, 1996; He *et al.*, 2004; Luo & Zhuang, 2006; Sun & Wang, 2012). Exceeding expectations, as the country produces and consumes the highest quantity of mushrooms in the world (Li, 2008; Xing & Zhao, 2014), China has a moderate number of Collembola reported from edible mushrooms, compared to records in other countries, *e.g.*, more than 30 species in Mexico, Spain, and Australia (Palacios-Vargas & Gómez, 1991; Mateos *et al.*, 1996; Greenslade *et al.*, 2002). Only eight species recorded in China were found only on mushrooms while others were also found in other habitats which is consistent with the results in Mexico (Palacios & Gomez, 1991). Interestingly, during our investigation, Collembola were only found on cultivated mushrooms of farmland greenhouses, but not on those of factory greenhouses. Whether this is due to the use of protective measures and pesticides in the latter needs to be investigated.

The family Hypogastruridae was found to be the most abundant group that was associated with various edible mushrooms, and this is similar to the results of research in Australia (Greenslade *et al.*, 2002) and Mexico (Palacios-Vargas & Gómez, 1991). However, a few families reported in the above studies were not found in China. For example, the common family reported in both countries, Brachystomellidae, was not found in the present study. The absence of this family in our studies can be explained by its biogeographical distribution: most genera and species are distributed in the southern hemisphere. The family Brachystomellidae was recorded in Australia as hosting on *Agaricus bisporus* (Greenslade *et al.*, 2002). However, the cultivation of this mushroom species in China nowadays is mostly in industry and we did not find any individual of Brachystomellidae, nor of Collembola on it during the investigation. Three of those cosmopolitan species, *Ceratophysella denticulata* (Bagnall, 1941), *Orthonychiurus folsomi* (Schäffer, 1900), and *Xenylla welchi* Folsom, 1916, were shared with the fauna on edible mushrooms in Australia, Mexico, and United States (Thomas, 1939; Palacios-Vargas & Gómez, 1991; Greenslade *et al.*, 2002). However, the hosting mushroom of the same collembolan species varied in different countries. For instance, as the species *C. denticulata* was found on *Ganoderma* species in China, but on *Agaricus* species in other countries. Certain species of Collembola on mushrooms in China were widely distributed, for example, *L. fimetarius* Gisin, 1964, *C. communis* (Folsom, 1898) and *T.* cf. *biquaternata* Sun & Li, 2015. Large distributions of this kind were also found in Australia and Mexico by Greenslade *et al.* (2002) and Palacios-Vargas & Gómez (1991), respectively. We suggest that these widely distributed species may be introduced to different provinces by human activities during edible mushroom plantations.

The results of the species characterization by mitochondrial *COI* markers conformed to the results by morphology, with low intra-specific divergences (0–8%) and high between-species divergences (18%–30%). Unexpectedly, in our study, the species *Xenylla welchi* is the sister clade to *Ceratophysella communis* and then the monophyly of the genus *Ceratophysella* was not supported (Fig. 2). This is inconsistent with the results from Greenslade *et al.* (2011) using both mitochondrial (*COI*) and nuclear (*28S*) markers. Future studies based on more molecular genes need to be carried out to confirm the phylogenetic relationship of these two genera. Interestingly, the two *Thalassaphorura* species close in morphology, *T. biquaternata* Sun & Li, 2015 from Shandong and *T.* cf. *biquaternata* Sun & Li, 2015 form Sichuan and Zhejiang, were clearly separated by the molecular analysis. The value of inter-specific divergence (16%) between the two species is in agreement to the inter-specific divergence in other non-intertidal *Thalassaphorura* species (Sun *et al.*, 2018). However, the two species have only one morphological difference, *i.e.* the presence of anterior parapseudocelli on the ventral side of the head in *T.* cf. *biquaternata* versus its absence in *T. biquaternata* (Sun Xin pers. obs.). This result confirms parapseudocelli arragement as a valuable taxonomic character, that has been shown to be stable, without variations at the intraspecific level in several genera of Onychiuridae (Sun & Li, 2015; Sun *et al.*, 2017, 2019), such as *Protaphorura*, *Oligaphorura,* and *Thalassaphorura*. *T.* cf. *biquaternata* and *T. biquaternata* are the first species of the large genus *Thalassaphorura* to be associated with mushrooms, calling for further taxonomical and molecular studies as other species of the genus have different ecology.

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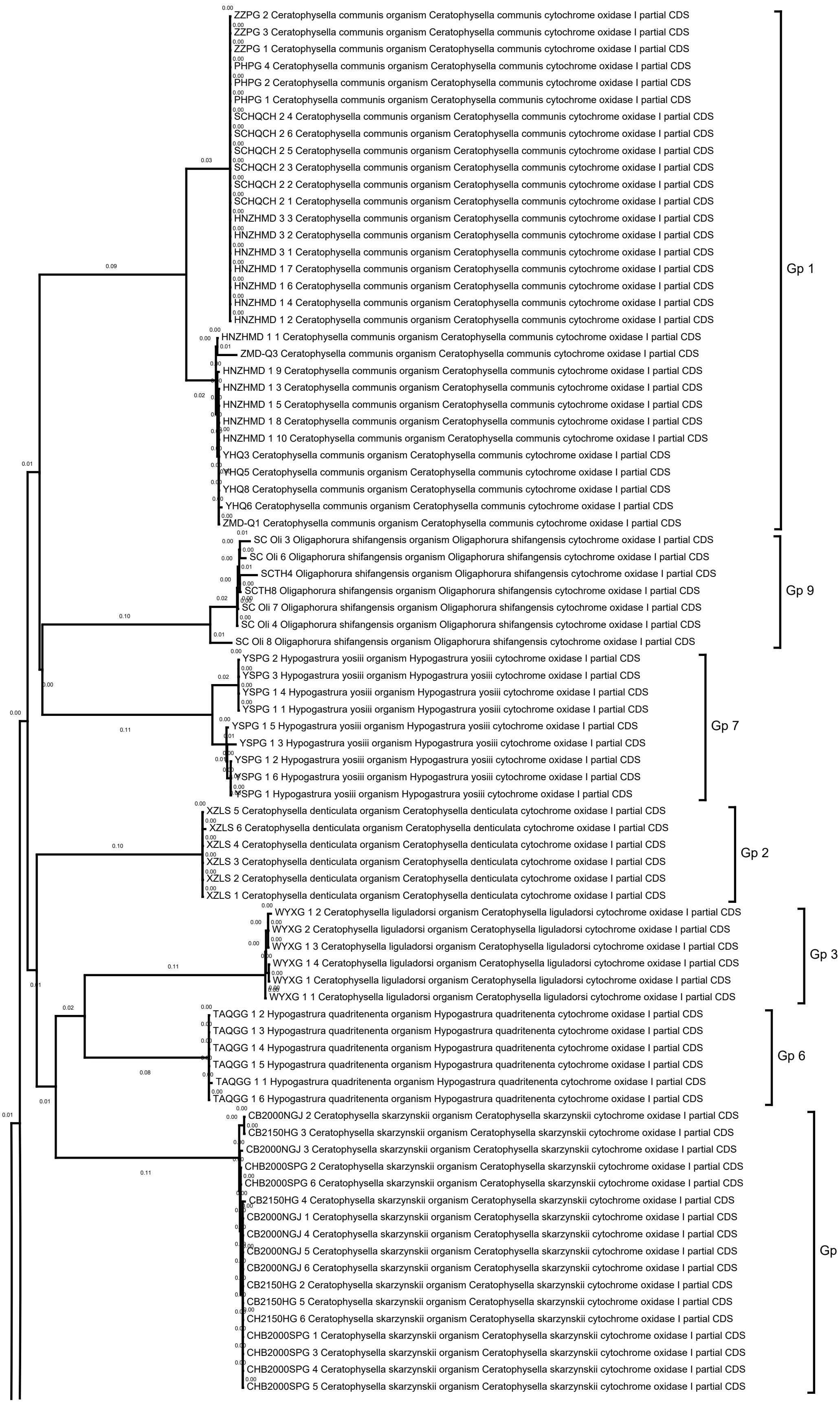

Figure S1. Neighbour-joining tree based on COI for 161 specimens with node bootstrap values and species grouping shown.

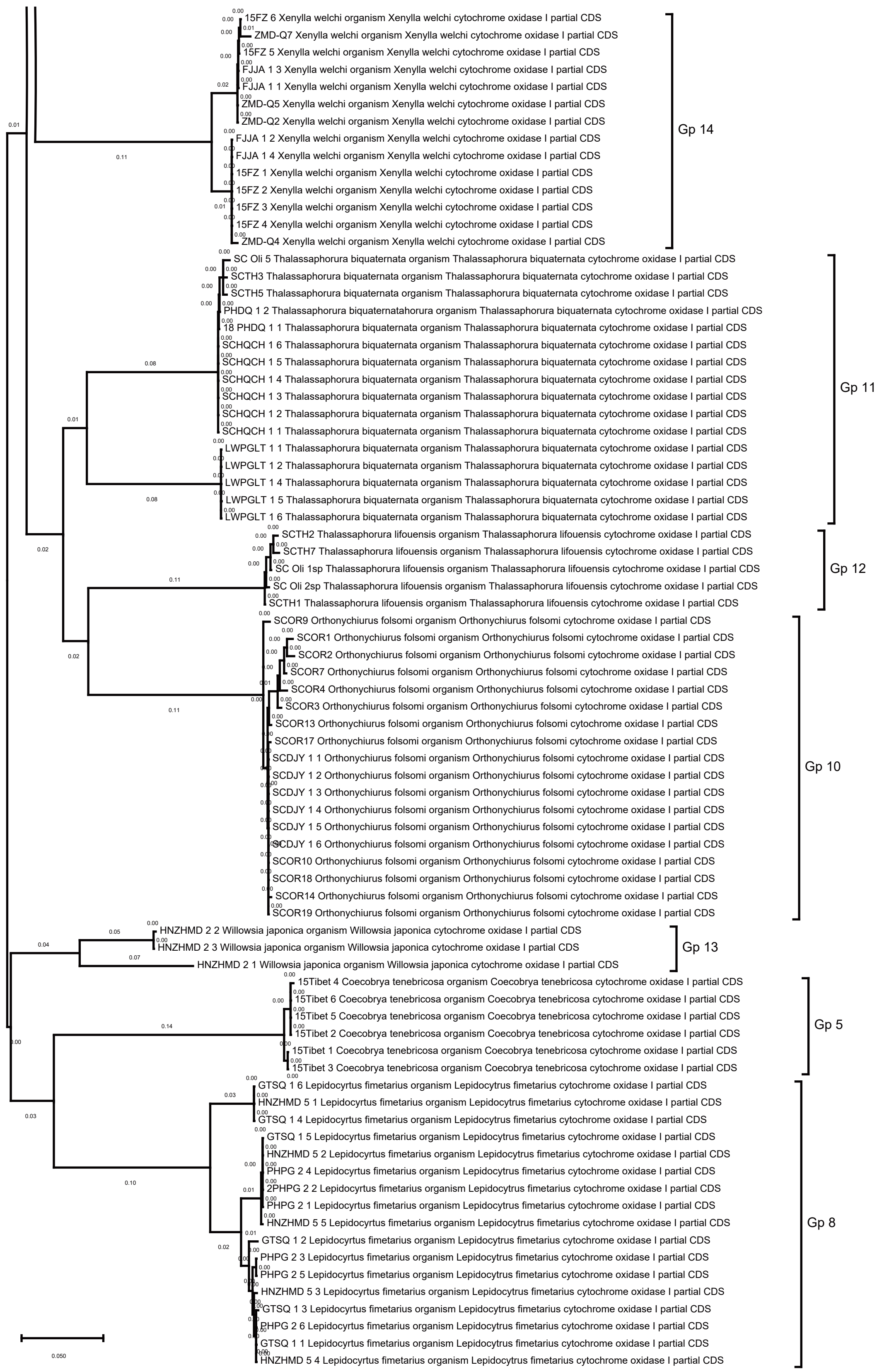

Figure S1 (continued).

Figure S2. Photos of mushroom Collembola. A. *Ceratophysella communis* in the soil and feeding on the hyphae of morels (the dark purple region), taken on 14.XI.2017 in Zhumadian, Henan; B. Mushroom (*Lentinus edodes*) infested by *Ceratophysella liguladorsi*, taken on 08.XII.2014 in Wuyi, Zhejiang; C. *Ceratophysella communis* on *Pleurotus ostreatus* (black dots), taken on 07.XII.2014 in Pinghu, Zhejiang; D. *Hypogastrura yosiii* in alcohol extracted from *Pleurotus ostreatus*, taken on 06.V.2014 in Liaocheng, Shandong; E. *Hypogastrura quadritenenta* in alcohol extracted from *Stropharia rugosoannulata*, taken on 07.V.2014 in Tai'an, Shandong; F. *Thalassaphorura biquaternata* in alcohol extracted from *Pleurotus ostreatus*, taken on 08.V.2014 in Laiwu, Shandong.

Table S1. Information of collection sites and host mushrooms of mushroom Collembola. Mushrooms: a—*Auricularia auricula*; b—*Ganoderma* sp.; c—*Stropharia rugosoannulata*; d—*Pleurotus ostreatus*; e—*Volvariella volvacea*; f—*Morchella vulgaris*; g—*Lentinus edodes*; h—*Melanoleuca* sp.; i—*Boletus* sp.; j—*Russulaceae* sp.; k—*Agrocybe aegerita*.

Family	Species	Mushrooms	Sites	Collection sites' location	Number of host fungi	Number of localities	Ref*
Dicyrtomidae	*Dicyrtoma balicrura* Lin & Xia, 1985	a	14	South China	1	1	2
Entomobryidae	*Coecobrya tenebricosa* (Folsom, 1902)	b	19	West China	1	1	1
Entomobryidae	*Entomobrya proxima* Folsom, 1924	c	5	North China	1	1	1
Entomobryidae	*Homidia dianbaiensis* (Lin, 1985)	a	15	South China	1	1	3
Entomobryidae	*Homidia socia* Denis, 1929	d	9	East China	1	1	1
Entomobryidae	*Homidia tiantaiensis* Chen & Lin, 1998	d	9	East China	1	1	1
Entomobryidae	*Lepidocytrus fimetarius* Gisin, 1964	b, d, e	5, 8, 9, 11	South China; East China; North China	3	4	1
Entomobryidae	*Sinella curviseta* Brook, 1882	c	5	North China	1	1	1
Entomobryidae	*Willowsia japonica* (Folsom, 1898)	b, d,	5	North China	2	1	1
Hypogastruridae	*Ceratophysella communis* (Folsom, 1898)	d, f	2, 7, 8, 9, 16	Southwest China; East China; Northeast China; North China	2	5	1
Hypogastruridae	*Ceratophysella denticulata* (Bagnall, 1941)	b	19	West China	1	1	1
Hypogastruridae	*Ceratophysella flectoseta* Lin & Xia, 1983	?	13	South China	?	1	4
Hypogastruridae	*Ceratophysella liguladorsi* (Lee, 1974)	g	10	East China	1	1	1
Hypogastruridae	*Ceratophysella skarzynskii* Weiner & Sun, 2019	h, i, j	1	Northeast China	3	1	1
Hypogastruridae	*Hypogastrura quadritenenta* Jiang & Chen, 2008	b, c	4	North China	2	1	1
Hypogastruridae	*Hypogastrura yosiii* Stach, 1964	d	4	North China	1	1	1
Hypogastruridae	*Xenylla welchi* Folsom, 1916	f, k	8, 12	North China; South China	2	2	1
Onychiuridae	*Allonychiurus shandongensis* Sun & Li, 2015	d	3, 4	North China	1	2	1
Onychiuridae	*Oligaphorura shifangensis* Liu & Sun, 2019	f	17	Southwest China	1	1	5
Onychiuridae	*Onychiurus qingchuanensis* Liu & Sun, 2019	f	17	Southwest China	1	1	5
Onychiuridae	*Orthonychiurus folsomi* (Schäffer, 1900)	f	17, 18	Southwest China	1	2	1
Onychiuridae	*Thalassaphorura biquaternata* Sun & Li, 2015	d	3, 6	North China	1	2	1
Onychiuridae	*Thalassaphorura cf. biquaternata* Sun & Li, 2015	c, f	9, 16, 17	Southwest China; East China	2	3	1
Onychiuridae	*Thalassaphorura encarpata* (Denis, 1931)	d	4, 5	North China	1	2	1
Onychiuridae	*Thalassaphorura lifouensis* (Thibaud & Weiner, 1997)	d, f	3, 17	Southwest China; North China	2	2	1
Paronellidae	*Salina auriculae* Lin, 1985	a,	15	South China	1	1	3
Paronellidae	*Salina sinensis* Lin, 1985	a	15	South China	1	1	3

[*]The references: 1—The present study; 2—Lin & Xia, 1985; 3—Lin, 1985; 4—Lin & Xia, 1983; 5—Liu *et al.*, 2019.

Table S2. Information on mushroom Collembola from China in molecular analysis.

Sequence_ID	Specie ID	GenBank accession numbers	Coll.	Collection date	Isolation source	Lat_Lon	Sampling code
PHPG_1_1–PHPG_1_4	*Homidia tiantaiensis*	MN387800–MN387803	X. Sun	01.XII.2014	*Pleurotus ostreatus*	30.7°N, 121.02°E	ZhejiangPinghu201412
FJJA_1_1–FJJA_1_4	*Xenylla welchi*	MN432692–MN432695	X. Sun	01.VI.2015	*Agrocybe aegerita*	26.08°N, 119.30°E	Fuzhoujin'an201506
HNZHMD_1_1–HNZHMD_1_10	*Ceratophysella communis*	MN432696–MN432705	Z.J. Xie	01.XI.2017	*Morchella vulgaris*	32.98°N, 114.02°E	HenanZhumadian201711
HNZHMD_2_2–HNZHMD_2_3	*Willowsia japonica*	MN432707–MN432708	Z.J. Xie	01.XI.2017	*Pleurotus ostreatus*	32.98°N, 114.02°E	HenanZhumadian201711
HNZHMD_3_1–HNZHMD_3_3	*Ceratophysella communis*	MN432709, MN432710–MN432711	Z.J. Xie	01.XI.2017	*Pleurotus ostreatus*	32.98°N, 114.02°E	HenanZhumadian201711
SCHQCH_1_1–SCHQCH_1_6	*Thalassaphorura biquaternata*	MN432712–MN432717	Z.J. Xie	01.III.2017	*Morchella vulgaris*	32.59°N, 105.24°E	SCQC201703
SCHQCH_2_1–SCHQCH_2_6	*Ceratophysella communis*	MN432718–MN432723	Z.J. Xie	02.III.2017	*Morchella vulgaris*	32.59°N, 105.24°E	SCQC201703
TAQGG_1_1–TAQGG_1_6	*Hypogastrura quadritenenta*	MN432724–MN432729	X. Sun	02.IV.2014	*Stropharia rugosoannulata*	36.11°N, 117.29°E	SDTA-140402
WYXG_1_1–WYXG_1_4	*Ceratophysella liguladorsi*	MN432730–MN432733	X. Sun	02.XII.2014	*Lentinus edodes*	28.90°N, 119.81°E	ZhejiangWuyi201412
YSPG_1_1–YSPG_1_6	*Hypogastrura yosiii*	MN432734–MN432739	X. Sun	02.X.2014	*Pleurotus ostreatus*	36.46°N, 115.99°E	ShandongYansi201410
LWPGLT_1_1, LWPGLT_1_2, LWPGLT_1_4, LWPGLT_1_6	*Thalassaphorura biquaternata*	MN432740–MN432743	X. Sun	01.IV.2014	*Pleurotus ostreatus*	36.22°N, 117.49°E	SDLW-140401Laiwu
PHPG_2_1, 2PHPG_2_2, PHPG_2_3–PHPG_2_6	*Lepidocytrus fimetarius*	MN432744–MN432749	X. Sun	01.XII.2014	*Pleurotus ostreatus*	30.7°N, 121.02°E	ZhejiangPinghu201412
GTSQ_1_1–GTSQ_1_6	*Lepidocytrus fimetarius*	MN432750–MN432755	X. Sun	02.VI.2015	*Volvariella volvacea*	26.58°N, 118.74°E	FujianShangqiancun201506
HNZHMD_5_1–HNZHMD_5_5	*Lepidocytrus fimetarius*	MN432756–MN432760	Z.J. Xie	01.XI.2017	*Pleurotus ostreatus*	32.98°N, 114.02°E	HenanZhumadian201711
18_PHDQ_1_1, PHDQ_1_2	*Thalassaphorura biquaternata*	MN432761–MN432762	X. Sun	01.XII.2014	*Stropharia rugosoannulata*	30.7°N, 121.02°E	ZhejiangPinghu201412
SCDJY_1_1–SCDJY_1_6	*Orthonychiurus folsomi*	MN432763–MN432768	Z.J. Xie	02.XI.2017	*Morchella vulgaris*	30.0°N, 103.61°E	SichuanDujiangyan201711
YSPG_1–YSPG_3	*Hypogastrura yosiii*	MN432769–MN432771	X. Sun	02.X.2014	*Pleurotus ostreatus*	36.46°N, 115.99°E	ShandongYansi201410
WYXG_1–WYXG_2	*Ceratophysella liguladorsi*	MN432772–MN432773	X. Sun	02.XII.2014	*Lentinus edodes*	28.90°N, 119.81°E	ZhejiangWuyi201412
PHPG_1, PHPG_2, PHPG_4	*Ceratophysella communis*	MN432774–MN432776	X. Sun	01.XII.2014	*Pleurotus ostreatus*	30.7°N, 121.02°E	ZhejiangPinghu201412
ZZPG_1–ZZPG_3	*Ceratophysella communis*	MN432777–MN432779	X. Sun	05.XII.2014	*Pleurotus ostreatus*	34.75°N, 113.62°E	HenanZhengzhou 201412

Table S2 (continued)

Sequence_ID	Specie ID	GenBank accession numbers	Coll.	Collection date	Isolation source	Lat_Lon	Sampling code
XZLS_1–XZLS_6	*Ceratophysella denticulata*	MN432780–MN432785	W.P. Xiong	27.III.2015	*Ganoderma* sp.	29.65°N, 91.113°E	Lasa20150327
CB2000NGJ_1–CB2000NGJ_6	*Ceratophysella skarzynskii*	MN432786–MN432791	X. Sun	15.IX.2015	*Boletus* sp.	42.05°N, 128.07°E	Changbai2000m201509
CB2150HG_2–CH2150HG_6	*Ceratophysella skarzynskii*	MN432792–MN432796	X. Sun	15.IX.2015	*Russulaceae* sp.	42.04°N, 128.07°E	Changbai2150m201509
CHB2000SPG_1–CHB2000SPG_6	*Ceratophysella skarzynskii*	MN432797–MN432802	X. Sun	15.IX.2015	*Melanoleuca* sp.	42.05°N, 128.07°E	Changbai2000m201509
15FZ_1–15FZ_6	*Xenylla welchi*	MN432803–MN432808	X. Sun	01.VI.2015	*Agrocybe aegerita*	26.08°N, 119.30°E	Fuzhoujin'an201506
15Tibet_1–15Tibet_6	*Coecobrya tenebricosa*	MN432809–MN432814	W.P. Xiong	27.III.2015	*Ganoderma* sp.	29.65°N, 91.113°E	Lasa20150327
SC_Oli_1sp–SC_Oli_2sp	*Thalassaphorura lifouensis*	MN432834–MN432835	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SC_Oli_5	*Thalassaphorura biquaternata*	MN432837	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SC_Oli_3, SC_Oli_6, SC_Oli_8	*Oligaphorura shifangensis*	MN432836, MN432838–MN432839	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SCOR10, SCOR13, SCOR14, SCOR17–SCOR19	*Orthonychiurus folsomi*	MN432817–MN432822	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SCOR1–SCOR4, SCOR7	*Orthonychiurus folsomi*	MN432840–MN432844	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SCTH1–SCTH2, SCTH7	*Thalassaphorura lifouensis*	MN432845–MN432846, MN432849	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SCTH3, SCTH5	*Thalassaphorura biquaternata*	MN432847–MN432848	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
SCTH4, SCTH8	*Oligaphorura shifangensis*	MN432824–MN432825	Z.J. Xie	08.XII.2018	*Morchella vulgaris*	31.07°N, 104.10°E	SCSF201812
YHQ3, YHQ5, YHQ6, YHQ8	*Ceratophysella communis*	MN432826–MN432829	Z.J. Xie	12.XI.2018	*Morchella vulgaris*	41.43°N, 125.56°E	THYH201811
ZMD-Q1, ZMD-Q3	*Ceratophysella communis*	MN432830, MN432850	Z.J. Xie	01.XI.2017	*Morchella vulgaris*	32.98°N, 114.02°E	HenanZhumadian201711
ZMD-Q2, ZMD-Q4–ZMD-Q5, ZMD-Q7	*Xenylla welchi*	MN432831–MN432832, MN432851–MN432852	Z.J. Xie	01.XI.2017	*Morchella vulgaris*	32.98°N, 114.02°E	HenanZhumadian201711