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LETTER TO THE EDITOR

Conserving the Chinese caterpillar fungus under climate change

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The conservation of fungi is often less studied and considered in conservation initiatives despite its wide recognition of importance (Willis 2018). The Chinese caterpillar fungus, *Ophiocordyceps sinensis* has been proposed as a flagship species for fungal conservation for its ecological and economical importance (Cannon 2011). It parasitizes larvae of ghost moths (Hepialidae) and plays a key role in maintaining the stability of the world's largest alpine ecosystem on the Tibetan Plateau. Being widely used as a tonic and dietary supplement, it is now amongst the world's most precious fungi, valued up to 998,000 RMB (~US$ 145,000) per kilogram for the top-rated products in 2017 by Tongrentang Pharmaceutical Co., the most well-known pharmacy shop that sells traditional Chinese medicine. Collection of the fungus provides a critical household income for more than one million people, accounting for up to 90–100% in the core production areas and 20–60% in the non-core regions (Winkler 2008; Weckerle et al. 2010).

A significant decrease in the population of *O. sinensis* has seen observed in recent years. In addition to human activities such as over-harvesting and over-grazing, it is notable that collectors across the production areas also attribute the decline to climate change, especially overall warming (Shrestha and Bawa 2015; Hopping et al. 2018). The historical records of 13 national weather stations in the production areas showed that the mean

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temperature of the wettest quarter (MTWQ), one of the predominant factors that could affect the distribution of the fungus (Yan et al. 2017), has increased significantly since 1979 by approximately 1.6 °C (Fig. 1d). Another main factor, precipitation of the warmest quarter, showed more heterogeneity among years and across regions (Fig. 1d). Although there might be conflicting predictions in different regions, the overall habitat suitability is predicted to decrease continually in the near future (Shrestha and Bawa 2014; Yan et al. 2017; Hopping et al. 2018). If the warming continues at the same speed, the projected future climate in the production areas would be close to the highest anthropogenic greenhouse gas emission scenario (RCP8.5) in the IPCC Fifth Assessment Report (Kirtman et al. 2013). Under such a scenario, 36% of the current habitats are predicted to be unfavorable in the next 50 years (Yan et al. 2017).

This fungus has long been listed as vulnerable under the Second-Class Category in China by the State Forestry Administration and Ministry of Agriculture since 1999. Nevertheless, the urgency to conserving the species needs to be emphasized both in the biggest consumption and production country, China, and worldwide. To draw the

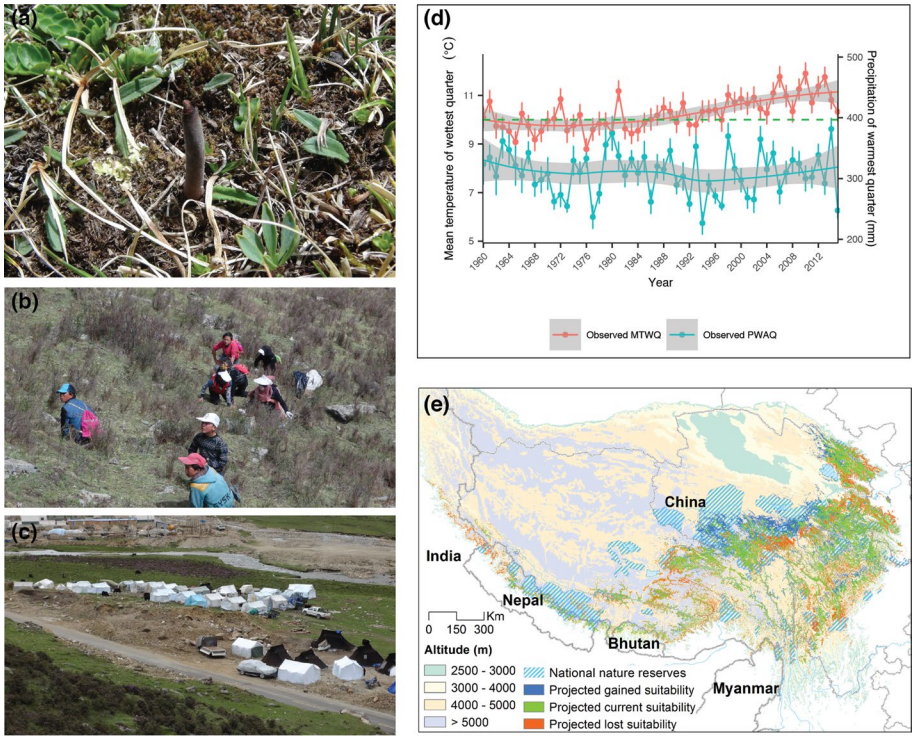

Fig. 1 **a** Specimen of *Ophiocordyceps sinensis* in natural habitat. **b** Children engaged in the fungus collection during the growing season in Maqên, Qinghai. **c** A collectors' camp in Gyaca, Tibet. **d** Historical records and loess curve of the mean temperature of the wettest quarter (MTWQ, in red) and precipitation of the warmest quarter (PWAQ, in blue) from 1960 to 2015 based on data from 13 national weather stations in the production areas, the green dash line represents the predicted optimum MTWQ (10 °C) and PWAQ (400 mm) for the species. **e** Predicted range shifts of *O. sinensis* under RCP 8.5 scenario in 2050 and the locations of National Nature Reserves of China. Photos by Yi Li. Data used in **d** obtained from National Meteorological Information Center (http://data.cma.cn/data/cdcindex/cid/0b9164954813c573.html, data accessed in October 2019). Data of the National Nature Reserves obtained from Zhao et al. (2013). Modeled range data obtained from Yan et al. (2017)

attention of researchers, policymakers and the public, the species has been classified as Vulnerable in a recent IUCN Red List assessment of macro-fungi in China as a start (Yao et al. 2020). It was also listed as a vulnerable species in the recent IUCN Red List of Threatened Species (Yang 2020).

To effectively conserving the species, it is crucial to identify priority settings and accumulate knowledge about the relationships between the species and the environment. Local governments of the core production areas (Qinghai and Tibet in China) have implemented various policies on the conservation of the species, including restricting the collection period, limiting the number of collectors and designating specific areas of harvest (Cannon 2011), but these policies have been less considered by the governments in the periphery of production regions. However, when combining the predicted range shifts under future climate change and the distribution of the genetic diversity, non-core production regions at low elevations and/or on the edge of the Tibetan Plateau (i.e., Gansu, Yunnan, and Sichuan provinces of China) were identified as conservation priorities. Most of the projected suitability loss would happen in these regions, indicating that populations there would face higher climate-induced extinction risks (Fig. 1e, Yan et al. 2017). Moreover, those areas harbor a higher genetic diversity of the fungus and its host insects than core regions (Quan et al. 2014; unpublished data).

The established National Nature Reserves in China could reduce the impact of human activities to some extent, given that 17% of the modeled current distribution is covered by the reserves (Fig. 1e) and harvesting is prohibited in the reserves. For priority areas not covered by the reserves, we suggest the same managing approaches implemented in the core areas to be employed. Facilitated human activities, such as culturing and inoculating insect hosts, is also possible to increase populations of both host insects and the fungus. Because the habitats in priority areas of the fungus are usually highly fragmented, we propose establishing several reserves with reasonable sizes in these areas rather than a single large one to protect the species and its natural habitats.

About 15% of the predicted habitat loss due to climate change would happen in the current established National Nature Reserves of China (Fig. 1e). These reserves serve as ideal places to conduct pilot conservation studies, such as local-scale studies of the impact of climate change and human activities, and the efficacy of different conservation measures. Additional investigations are also needed to gain knowledge on intraspecific diversity distribution, diversity of the host caterpillars, and the biology of the interactions between the fungus and its host insects.

Apart from China, conservation and management of this species have also been proposed or started in other countries that harbor the fungus, including Nepal (Shrestha and Bawa 2015), India (Negi et al. 2015), and Bhutan (Cannon et al. 2009). For example, Nepal has started organizing harvesting permits and royalties (Baral et al. 2015). The conservation strategies we proposed here could be adopted in those countries, and more importantly, be recommended to the conservation of other threatened fungal species.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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