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Research article

Large-scale interviews and plot-based data reveal declining yields of the prized matsutake mushrooms in the major producing areas of China

Yingfeng Bi [a,b,1], Bin Liu [c,1], Guangli Chen [d], Ti Bu [e], Pengwan Zhang [e], Qinghong Zhou [f], Liqin Mu [f], Yao Fu [a,b], Yinxian Shi [a,b], Xuefei Yang [a,b,*], Deli Zhai [g,**]

[a] Key Laboratory of Economic Plants and Biotechnology, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, 650201, China
[b] Southeast Asia Biodiversity Research Institute, Chinese Academy of Sciences, Menglun, Mengla, 666303, China
[c] School of Ecology and Environmental Sciences & Yunnan Key Laboratory for Plateau Mountain Ecology and Restoration of Degraded Environments, Yunnan University, Kunming, 650021, China
[d] Kunming Institute of Science and Technology Information, Kunming, 650021, China
[e] Administration and Protection Bureau of Yunnan Baima Snow Mountain National Nature Reserve, Deqin, 674500, China
[f] Chuxiong Research Institute of Forestry Science, Chuxiong, 675000, China
[g] Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla, 666303, China

A B S T R A C T

Matsutake mushroom (Tricholoma matsutake), one of the most prized mushrooms, has been a luxury food for millennia. China is the leading producer and exporter of this mushroom. Although variations in matsutake yield have been reported at two locations in China, there is still a lack of data on changes in matsutake yield over recent decades at national scale. Here, we employed ethnobiological interviews and plot-based monitoring to assess changes in matsutake yield and the driving factors. We validated the reliability of the interviews by comparing matsutake yield trends obtained from interviews with those obtained from 26-year plot-based data across four villages. This plot-based dataset represents the longest and largest observations on matsutake yield in China. We found 94.64 % collectors reported a decline in matsutake yield, which matches the significant declining trend observed from plot-based data. We, then, extended our interviews to 20 villages, and found 86.28 % collectors perceived a decline in matsutake yield. Collectors attributed this decline to climate change, shiros disturbance, and increased forest density, with the impacts of the latter two varying by forests access rights. In common access forests, 50.87 % collectors attributed this decline to shiros disturbance, whereas in private access forests, 62.16 % collectors identified increased forest density, mainly induced by Chinese forest protection policies, as key factor. These findings highlight the need for sustainable managements, such as reducing disturbance in shiros or thinning dense forests, to mitigate matsutake yield declining in China. They also underscore the importance of integrating community-based knowledge into future wild resource management.

1. Introduction

Matsutake (*Tricholoma matsutake*) is an ectomycorrhizal fungus that forms symbiotic relationships with certain plant species, primarily pine (*Pinus sp.*) and oak (*Quercus sp.*). The host plants provide carbohydrates to the fungus, while the matsutake in turn enhances the host plants' access to water and soil nutrients, and provides some protection against diseases and environmental stresses (Gong et al., 1999). Matsutake has a discontinuous distribution across Asia (Bhutan, China, Japan, and the Korean Peninsula) and Europe (Finland, Norway, and Sweden) (Michael, 2022). Economically, matsutake is among the most expensive wild edible mushrooms (Hall et al., 2003), with top-quality fresh mushrooms reaching USD 1500 per kilogram (Statistics bureau of Japan, 2024), and the annual market value being estimated between 0.50 and 1.00 billion USD (Suzuki, 2005; Pérez-Moreno et al., 2021a,b). This value represents approximately 10.00–29.76 % of the total global market value of wild edible mushrooms, which is estimated to be between 3.62 and 5.00 billion USD (Royse et al., 2017; Pérez-Moreno et al., 2021a,b; Niego et al., 2023). During the collecting season, over one million people worldwide are engaged in matsutake collection and trade every day (Michael, 2022). Matsutake has therefore become crucial in supporting local livelihoods, contributing 6.00–90.00% of the cash income in rural households in matsutake-producing regions globally (Martinez-carrera et al., 2002; Arora, 2008; Yang et al., 2008; Brooks

* Corresponding author. Key Laboratory of Economic Plants and Biotechnology, Chinese Academy of Sciences, Kunming, 650201, China.
** Corresponding author. Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla, 666303, China.
E-mail addresses: xuefei@mail.kib.ac.cn (X. Yang), zhaideli@xtbg.ac.cn (D. Zhai).
[1] **Joined-first author:** Yingfeng Bi and Bin Liu are joint first authors.

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and Tshering, 2010; Van Gevelt, 2014). In southwest China, two decades ago, households in matsutake highly productive villages could generate revenues of 7,000–8,000 USD during a harvesting season (July–October) (Yeh, 2000). Our recent interview data reveals that this figure has increased two-to threefold, with seasonal incomes now reaching 15, 000–29,000 USD. From the perspective of global supply and demand, Japan is the largest consumer of matsutake, while China is the leading producer and exporter, supplying around 70 % of Japan's matsutake imports (Vaario et al., 2017). Consequently, fluctuations in matsutake yield in China could have a profound impact on the global wild mushroom market, as well as on the livelihoods of the millions of local collectors (Michael, 2022).

Currently, all matsutake is collected directly from the wild, because artificial cultivation is not yet possible (Yamanaka et al., 2020; Yamada, 2022). Given this high reliance on wild collection, assessing changes in matsutake yield in China is essential for the sustainable use and management of this high-value resource, as well as for future market planning. However, researches into this valuable mushroom in China have primarily focused on its taxonomy (Zang, 1990; Liu et al., 2011), artificial propagation techniques aimed at enhancing yield (Wang and Su, 2003; Gong et al., 1999; Su and Wang, 2006; Su and Zhao, 2007; Brown et al., 2018), ecological niche modeling and spatial distribution pattern (Guo et al., 2017), localized access rights to matsutake-producing forests and the corresponding forest management strategies (Yeh, 2000; Yang et al., 2009), commodification (He, 2010; He et al., 2014), and benefit-sharing mechanism among stakeholders along the commodity chain in Yunnan Province(He, 2010; Yang et al., 2008; Zhang et al., 2017; Li et al., 2024). To date, only two studies have addressed matsutake yield. One employed ethnobiological interviews to assess the local collectors' perception of matsutake yield and the reasons driving the observed changes in Shangri-La, Yunnan Province (Amend et al., 2010), while the other study explored the relationship between climatic variables and matsutake yield using 11-years of plot-based data in Baoshan, Yunnan Province (Yang et al., 2012). Both studies were conducted before the year of 2010, and were limited to Yunnan Province in southwestern China. In China, matsutake are found from the southwest (Yunnan, Tibet, Guizhou, Gangsu, Guangxi and Sichuan province) to the northeast (Jilin and Heilongjiang province) of the country, and across large elevational belts (Yang et al., 2008; Guo et al., 2017). For example, matsutake can be found in regions where the elevation ranges from 2, 000 m a.s.l to 4,000 m a.s.l. Fluctuations in matsutake yield at localized sites within a small region are therefore unlikely to represent yield changes at a national scale. To assess overall fluctuations in the Chinese matsutake yield, it is necessary to investigate at a larger scale, such as at the national level, and to explore the reasons behind any observed changes.

Long-term plot-based monitoring data with daily or yearly resolution is commonly employed to assess fluctuations in the yield of wild edible plants and mushrooms. However, collecting long-term plot-based data is labor-intensive, time-consuming, and costly, and is therefore often restricted to small areas with limited sites. Recent studies have highlighted the potential of ethnobiological interviews with local collectors as a complementary method for capturing yield changes in wild edible mushrooms and plants across larger spatial scales (Amend et al., 2010; Bélanger and Pilling, 2019; Schunko et al., 2022). This approach is less time- and budget-intensive, and offers a practical means of gathering data from multiple sites over broad geographic spaces. Despite these advantages, ethnobiological interviews have received limited attention as a potential method for assessing yield changes in wild edible plants and mushrooms.

Here, we employed ethnobiological interviews together with plot-based monitoring to assess changes in matsutake yield and to identify the factors driving these changes across its major producing areas in China. First, we validated the reliability of ethnobiological interviews by comparing the matsutake yield trends derived from interview data with those observed from long-term plot-based data across four villages. Following this validation, we extended the ethnobiological interviews to 20 villages across different major matsutake-producing areas in China. Our objectives are threefold: 1) to determine whether matsutake collectors could accurately capture those changes in matsutake yield that

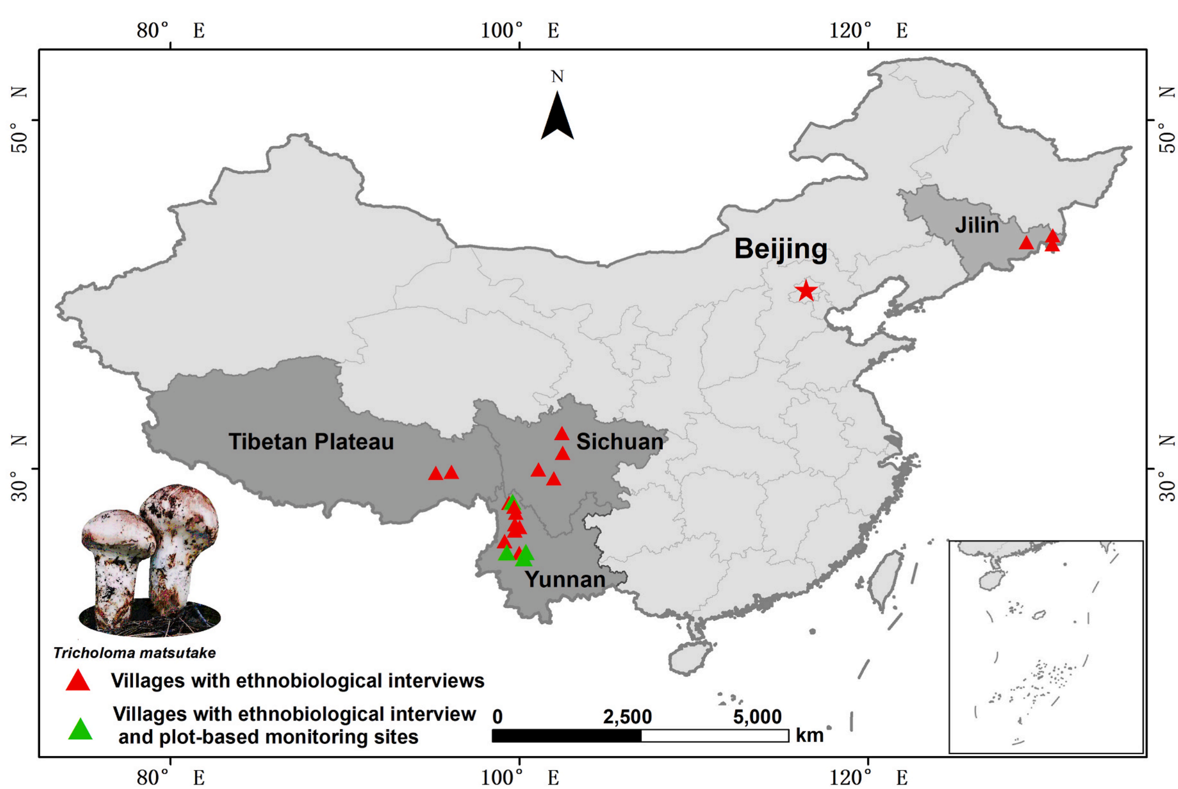

Fig. 1. Geographical locations of the 20 surveyed villages in major matsutake (*Tricholoma matsutake*) producing areas of China.

also observed from long-term plot-based data; 2) to identify the most cited changes in matsutake yield over recent decades by collectors; 3) to explore the factors driving these yield changes.

2. Materials and methods

2.1. Study area and selection of study villages

There are two largest matsutake-producing regions in China: the southwest and the northeast of the country (Fig. 1). We, thus, selected these two regions as our study area. Southwestern China has higher matsutake production and larger matsutake-producing forests than the northeastern China (Yang et al., 2008; Guo et al., 2017). The habitats and host trees of matsutake also differ significantly between these two regions. In the southwestern China, the matsutake is distributed across a large elevational range (2,100–4,100 m a.s.l.), and the matsutake-producing forests are also diverse including pine, oak, and mixed oak-pine forests. In the northeast of the country, matsutake is distributed within a smaller elevational range (350–900 m a.s.l.), and is primarily found in pine forests.

To ensure the selected villages were able to adequately represent the major matsutake-producing regions of China, we followed a multi-step village selection process. Firstly, we selected Yunnan and Sichuan Provinces and the Tibet Autonomous Region in southwestern China, and Jilin Province in northeastern China as our target regions, which collectively encompass the entire natural distribution range of matsutake in China (Guo et al., 2017). Secondly, we listed all counties within these four regions that produced this species. Thirdly, we ranked these counties based on their matsutake yields, and then selected those counties with higher yields as candidate counties. Fourthly, we projected those counties onto the natural distribution range of matsutake in China, and removed any counties that were geographically close to each other. Fifthly, we selected at least one village with high matsutake yield within those selected counties, which guided by recommendations from primary matsutake buyers. Moreover, Chinese matsutake-producing forests are also subject to two main forms of access rights: common access forests and private access forests (Yang et al., 2009), and we also ensured that our selection included both types of access rights.

Based on this multi-step village selection process, we selected a total of 20 villages for our ethnobiological interviews, comprising 17 villages (85 %) from southwestern China and 3 villages (15 %) from the northeastern China (indicated by red and green triangles, in Fig. 1). Of these 20 selected villages, 15 villages (75 %) have common access forests, while 5 villages (25 %) have private access forests. Additionally, four of these 20 selected villages (20 %) had long-term plot-based monitoring plots (indicated by green triangles, Fig. 1), with three having private access forests and one having common access forests.

Table 1
Basic information of 20 villages for ethnobiological interview across China and of plot-based monitoring sites for matsutake (*Tricholoma matsutake*).

No.	Village Name	Location: county, province	Latitude (°N) /Longitude (°E)	Elevation (m a.s.l)	Name of plot-based monitoring sites
1	Shimen (SM)	Antu, Jilin	42.99/ 129.07	350.00	NA
2	Songlin (SL)	Hunchun, Jilin	42.89/ 130.56	500.00	NA
3	Miaoling (ML)	Hunchun, Jilin	42.91/ 130.59	500.00	NA
4	Mazuzhai (MZZ)	Xiaojin, Sichuan	31.10/ 102.50	3114.06	NA
5	Heshang (HS)	Xiaojin, Sichuan	37.34/ 108.86	3006.41	NA
6	Mazishi (MZS)	Yanjiang, Sichuan	29.99/ 101.09	3719.00	NA
7	Egu (EG)	Yanjiang, Sichuan	29.62/ 101.06	3400.00	NA
8	Gangba (GB)	Bomi, Xizang	29.83/ 96.11	3256.00	NA
9	Duoge (DG)	Bomi, Xizang	29.76/ 96.09	3215.00	NA
10	Yeri (YR)	Deqin, Yunnan	28.38/ 99.23	3400.00	Yeri1 and Yeri2
11	Sihua (SH)	Lijiang, Yunnan	29.17/ 102.09	2002.36	NA
12	Heping (HP)	Shangri-La, Yunnan	28.03/ 100.36	3200.55	NA
13	Jidi (JD)	Shangri-La, Yunnan	28.10/ 99.63	3300.00	NA
14	Laza (LZ)	Shangri-La, Yunnan	27.83/ 99.70	3276.00	NA
15	Bushihua (BSH)	Lijiang, Yunnan	26.82/ 99.74	2901.84	NA
16	Qincaitang (QCT)	Chuxiong, Yunnan	25.17/ 99.00	2486.00	Qincaitang1and Qincaitang2
17	Songhe (SH)	Dali, Yunnan	26.09/ 99.90	2981.90	NA
18	Bupeng (NP)	Dali, Yunnan	25.17/ 99.00	2500.00	NA
19	Miheimen (MHM)	Chuxiong, Yunnan	25.17/ 99.00	2386.00	Miheimeng
20	Haitang (HT)	Baoshan, Yunnan	25.22/ 99.30	2350.00	Haitang

2.2. Plot-based matsutake yield data and climatic data at the local scale

We had a total of six plot-based monitoring sites (Table 1; see Appendix Part-1 for details for each site), distributed across four villages: Haitang, Miheimen, Qingcaitang, and Yeri. Specifically, Yeri and Qingcaitang each have two monitoring plots, while Haitang and Miheimen each have one monitoring plot. The matsutake-producing forests in Haitang, Miheimen, and Qingcaitang are predominantly pine forests. In contrast, in Yeri, those at higher elevations are primarily oak forests, while at middle elevations, they are mixed oak-pine forests. In Haitang, Miheimen, and Qingcaitang, the matsutake-producing forests were contracted to local villagers for sustainable management of matsutake, while those in Yeri are located within the Baima Snow Mountain National Nature Reserve. Therefore, we worked with one to two local villagers in Haitang, Miheimen, and Qingcaitang to record matsutake yield. In Yeri, we collaborated with the Baima Snow Mountain National Nature Reserve to record the matsutake yield.

These six plots are named according to the nearby village: “Haitang” (1.00 ha (ha), 2350 m a.s.l., 26-year observation period), “Miheimen” (23.30 ha, 2386 m a.s.l., 5-year observation period), “Qincaitang1” (0.67 ha, 2410 m a.s.l., 7-year observation period), “Qincaitang2” (4.00 ha, 2396 m a.s.l., 5-year observation period), “Yeri1” (0.10 ha, 3400 m a.s.l., 5-year observation period), and “Yeri2” (0.022 ha, 3900 m a.s.l., 5-year observation period). During the matsutake collection season, the collectors visit each plot daily to collect mushrooms. The yield data from “Haitang”, “Yeri1”, and “Yeri2” were recorded as individual mushroom counts, while in “Miheimen”, “Qincaitang1”, and “Qincaitang2” were recorded as weight measurements in kilograms. This monitoring dataset represents the largest and longest-running records on matsutake yield in China to date. We used this dataset to analyze matsutake yield trends over recent decades, and then compared this yield trend with those derived from interview data from the same villages to validate the reliability of the ethnobiological interview method.

From our primary analysis, and from previous research (Amend et al., 2010), most matsutake collectors cited climate change as one of the most important factors causing fluctuation in matsutake yield in China. We, therefore, wanted to test whether climate factors really do affect matsutake yield, and we assessed the relationships between certain climate variable and matsutake yield from our plot-based dataset. These climatic data, including temperature and precipitation, were recorded at the nearest meteorological stations, and were downloaded from the National Meteorological Information Center of China (http://data.cma.cn/data/cdcdetail/dataCode.html).

2.3. Interview data on matsutake yield changes and underlying reasons in major producing areas of China

In China, the primary matsutake buyers usually visit villages with matsutake-producing forests daily during the collection season to purchase fresh matsutake. The collectors typically sell their daily collection directly to these buyers. Therefore, in order to conduct our interviews, we accompanied buyers to the villages. Our interviewees were matsutake collectors who had recently returned from mountains. For each family that voluntarily participated in the interviews, we selected one family member to do an interview. The selection prioritized individuals with the longest matsutake collecting experience. We interviewed a total of 301 collectors from 20 villages across the major matsutake-producing regions in China (Fig. 1). These collectors belonged to seven ethnic groups: Korean, Tibetan, Lisu, Bai, Naxi, Yi, and Han. Of these, Tibetans accounted for 62.25 % (n = 301) of the total number of collectors. The average age was 44.09 years old with the youngest being 17 years old and oldest of 84 (Fig. A3a). Approximately 70.76 % (n = 301) of the interviewed collectors had been engaged in matsutake collecting for more than 21 years (Fig. A3b and see Table A1 in the appendix). The mean collection duration for these collectors was 67.42 days per year, with the shortest period being 20 days in northeastern China, and the longest being 130 days in parts of southwestern China (Fig. A3c).

We conducted both questionnaires (Figure A1a) and semi-structured interviews (for details on the ethnobiological interview, see Part-2 in the appendix). The questionnaires were designed to collect basic information pertaining to the collectors, including their age, education level, ethnicity, the year they began collecting, and the number of days they spend per year engaged in matsutake collection. This information served as a foundation for our analysis. The semi-structured interviews were designed to collect data on three specific questions: (1) What is your perception of the changes in matsutake yield since you began collecting them? (2) What are the underlying causes of these changes? (3) What measures should be taken to increase the yield of matsutake in the future?

2.4. Statistical analysis

2.4.1. Validation of the reliability of the ethnobiological interview method

To assess whether matsutake collectors were able to capture changes in matsutake yield accurately, we compared the yield trends derived from interview data with those from long-term plot-based data across four villages. The yield trends over the past 26 years from the six monitoring plots were analyzed using a linear regression model (for details on the linear regression models see Part-3 in the appendix). After taking the interviews, we categorized collectors' perceptions of yield trends into four categories: decrease, increase, unchanged, and unknown. We then calculated the proportion of collectors at each village in each category. This was done by dividing the number of collectors reporting each category by the total number of collectors interviewed in that village. A match between the perceived trends and those observed in the long-term plot-based data would indicate that the ethnobiological interview method can reliably capture changes in matsutake yield. Based on this successful validation, we next applied the ethnobiological interview to assess changes in matsutake yield in the major producing areas of China.

2.4.2. Collector' perception of matsutake yield over recent decades in major producing areas of China

We then expanded our ethnobiological interviews to 20 villages across the major matsutake-producing regions in China to assess changes in matsutake yield over recent decades. For each village, we calculated the proportion of collectors reporting each trend (increase, decrease, unchanged, and unknown). This was done as before by dividing the number of collectors reporting each trend by the total number of collectors interviewed in that village. We then conducted an Analysis of Variance to determine whether there were significant differences among these four trends. We also used logistic regression to explore whether collectors' perceptions of yield changes were further influenced by factors including province, age, ethnicity, years of collecting experience, and annual collecting duration.

2.4.3. Collectors' perceptions of reasons for the declines in matsutake yield

Matsutake collectors were asked to explain the underlying causes of the changes in matsutake yield they reported. Most collectors interviewed in this study reported a widespread decline in matsutake yield, prompting us to focus our further analysis on those collectors who observed a decline in matsutake yield. To identify the main reasons for this decline, we first listed all the reasons reported by collectors for the observed decline in matsutake yields. Then, we merged reasons that could be grouped into the same category, and treated those that couldn't be categorized as an independent reason. Finally, we obtained a list of 10 distinct reasons cited by collectors (Fig. 4). Of these, four were categorized reasons and the remaining six were independent reasons. Independent reasons included "Collection of undersized mushrooms", "Increased number of collectors", "Increased artificial rainfall", "Increased collecting hours", "Increased market price", and "Pollution". The four categorized reasons are "Disturbance of shiros ", "Deforestation", "Increased forest density", and "Climate change". Since a shiro is a solid and tightly aggregated underground structure of mycelium and mycorrhiza, from which the mushrooms (fruiting bodies) are produced (for details on shiros see Fig. A4 in the appendix). Therefore, "Disturbance of shiros" refers to all disturbance relating to improper collection techniques, such as collectors failing to re-cover the collection area after gathering matsutake, or "digging" or "raking" the deep soil during the matsutake search process, or removing the humus layer without replacing it when no matsutake is found. "Deforestation" refers to disturbances to plant communities, such as cutting or burning of the host trees. "Increased forest density" covers reasons associated with increased forest density, such as dense forests induced by large numbers of shrubs. "Climate change" encompasses reasons related to changed climate, such as prolonged periods of drought, low precipitation, untimely precipitation, low winter snow, and high temperatures. Of these 10 reasons, one is related to climate and the other nine are related to forest management practices. The proportion of collectors citing each reason was calculated by dividing the number of collectors who reported it by the total number of collectors who reported a decline in matsutake yield in that village. The effect of forest access rights (common access forests or private access forests) on the proportions of these 10 reasons was then calculated. The reasons reported by the highest proportion of collectors were considered to be the primary factors contributing to the observed declines in matsutake yield.

Since a high proportion of collectors cited climate change as a key factor for matsutake decline in China, we investigated the impact of climate change on matsutake yield using our long-term plot-based data. We used multiple linear regression models to assess the relationships between matsutake yield and critical climate periods (for details on the multiple linear regression model see Part-5 in the appendix). The critical climate factors are temperatures (Tem-1, Tem-2 …, and Tem-5) and precipitation (Pre-1, Pre-2 …, and Pre-5) over the one to five months prior to fruiting onset, and temperature (Temfd) and precipitation (Prefd) during the fruiting season (for details on the selection of critical climate periods see Part-4 in the appendix).

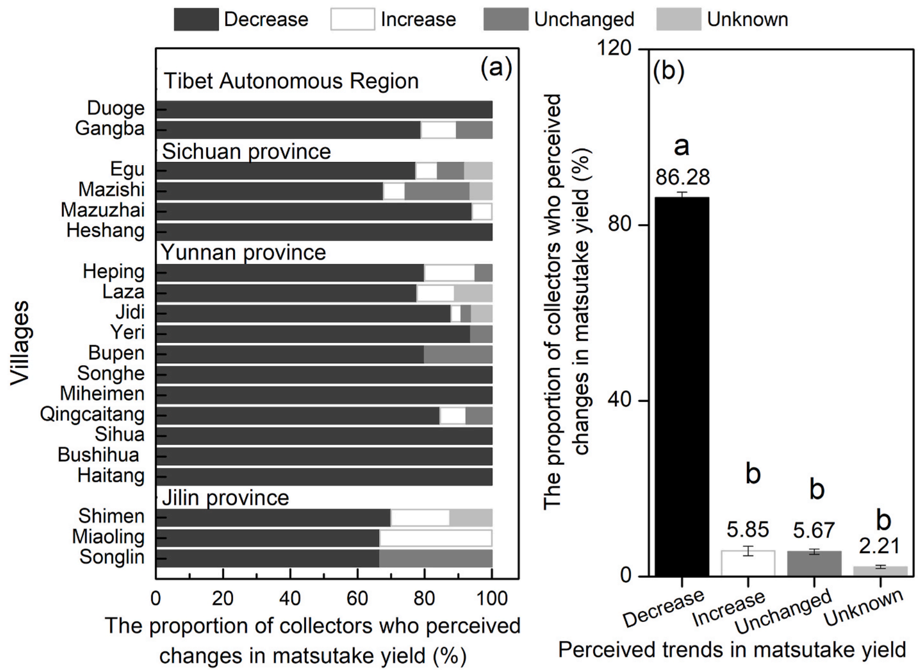

Fig. 2. Perceived trends in matsutake yield. The proportion of perceived trends (decrease, increase, unchanged and unknown) in matsutake (*Tricholoma matsutake*) yield since collectors began this collecting activity across 20 villages in the major producing areas of China (a). Analysis of variance among the proportion of perceived trends in matsutake yield. Bars marked with the same letter indicates no significant difference between them, while those marked with different letters indicates significantly different (b).

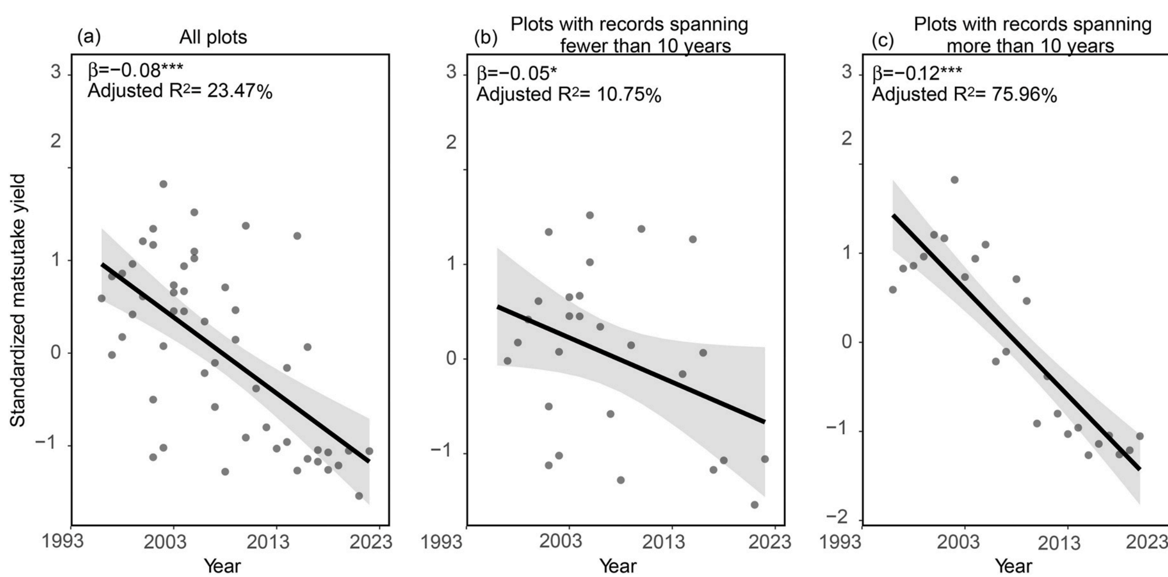

Fig. 3. Significant declines were observed in matsutake (*Tricholoma matsutake*) yields from six monitoring plots over recent decades. Yield data were standardized using the Z-scores method to remove the units in matsutake yield. The adjusted R^2 accounts for the proportion of variance in the response variable explained by all predictors. The significance of this relationship in the model is denoted by an asterisk, where $^*P < 0.05$ and $^{**}P < 0.01$.

3. Results

3.1. Declines in matsutake yield were the most frequently cited change by collectors in the major producing areas of China

Ethnobiological interviews with collectors in the villages of Haitang, Qingcaitang, Miheimen, and Yeri revealed that an average of 94.64 % (n = 57) of the collectors reported a decline in matsutake yields. Specifically, 100 % (n = 12) of collectors in Haitang, 84.62 % (n = 13) of collectors in Qingcaitang, 100 % (n = 16) of collectors in Miheimen, and 93.75 % (n = 16) of collectors in Yeri reported a decline in matsutake yield (Fig. 2a). Consistent with the declining trend reported in the interview data, our long-term plot-based data at six plots in the same villages also showed significant declines in matsutake yield over the past 26 years (Fig. 3 and Figure A4). This strong agreement between interview data and plot-based data suggests that matsutake collectors are able to capture changes in matsutake yield accurately. Therefore, ethnobiological interviews with collectors are a reliable method for assessing long-term changes in matsutake yield.

After confirming the reliability of the ethnobiological interview

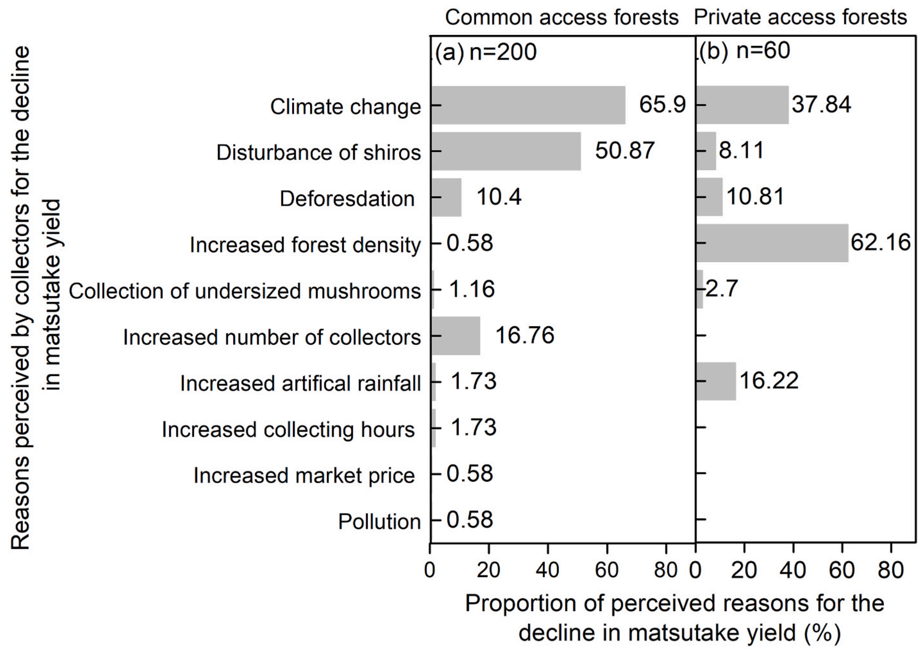

Fig. 4. Proportion of perceived reasons for the decline in matsutake (*Tricholoma matsutake*) yields in common access forests (a) and in private access forests (b) in the major producing areas of China.

Table 2
Relationship between climatic variables and matsutake (*Tricholoma matsutake*) yield from six monitoring plots over past decades.

	All plots	Plots with records spanning more than 10 years	Plots with records spanning fewer than 10 years
Intercept	−1.15***	15.27***	−0.83ns
Tem-2	×	−0.53 **(EV=29.41 %)	×
Tem-4	×	−0.35 **(EV14.70 %)	×
Pre-1	0.008** (EV=19.02 %)	0.006*(EV=17.73 %)	0.006*(EV=12.01 %)
Pre-4	0.011* (EV=4.59 %)	×	×
Observation sites	6	1	5
Adjusted R-squared (%)	23.61 %	61.84 %	12.01 %
F-statistic	8.88	11.34	4.55
Degrees of freedom	49	21	25
Residual standard error	0.82	0.66	0.85
p-value	<0.01	<0.01	<0.05

Note: Tem-2 and Tem-4 indicate temperatures for two months and four months prior to the month of fruiting onset, respectively; Pre-1 and Tem-4 indicate precipitation for one month and four months prior to the month of fruiting onset. The significance of relationships between the fruiting body production of matsutake (*Tricholoma matsutake*) and climatic variables in a model is denoted by an asterisk, where **P < 0.01, *P < 0.05. The symbol " × " indicates a predictor variable that has been excluded from the model. The EV is the abbreviation for 'explained variance,' and indicates the proportion of variance in the response variable that is explained by the predictor. The adjusted R^2 accounts for the proportion of variance in the response variable explained by all predictors.

method, we expanded our interviews to the major producing areas of China. Our large-scale interviews also revealed four distinct trends in matsutake yield changes: decrease, increase, unchanged, and unknown (Fig. 2). Although the proportions of these four trends varied by village, the most frequently reported trend in yield was a decline (Fig. 2a). Specifically, 86.28 % (n = 301) of the collectors interviewed reported a decrease in matsutake yields. This proportion was significantly higher than those for the other three trends (Fig. 2b). There were only 5.85 % (n = 301) reported an increase, 5.67 % (n = 301) observed no change, and 2.21 % (n = 301) were uncertain about the trend (Fig. 2b). Our logistic regression analysis found no significant differences between collectors' perceptions of yield declines and demographic factors, including province, age, ethnicity, years of collecting experience, or annual collection duration of each collector.

3.2. *Climate change, disturbance of shiros and increased forest density were cited as the primary reasons for observed declines in matsutake yields*

Climate change was listed as one of the main factors contributing to the decline in matsutake yields in the major producing areas of China, regardless of the access rights to the matsutake-producing forests (Fig. 4). In common access forests, approximately 65.90 % (n = 200) of collectors identified climate change as the primary reason for the declines in matsutake yields, compared to 37.84 % (n = 60) in private access forests (Fig. 4a–b). Consistent with the collectors' identification, our multiple regression analysis also revealed that climatic variables, specifically temperature and precipitation, explained 23.61 % of the variance in matsutake yield, with the range of explained variance being between 12.01 % and 61.84 % (Table 2). This strong agreement between collector perception and plot-based data suggests that collectors can reliably assess certain factors contributing to the observed declines in matsutake yield. Furthermore, our multiple regression analysis demonstrates that precipitation over the month prior to fruiting onset (Pre-1) was the most important climatic variable, explaining the largest proportion of variance (12.01 %–19.02 %) in matsutake yield over the past 26 years (Table 2). Higher precipitation during this period was associated with increased matsutake yield (Table 2). Moreover, higher temperature during two months (Tem-2) and four months (Tem-4) prior to fruiting onset also reduced matsutake yield (Table 2).

Disturbance of shiros and increased forest density were two other factors identified as contributing to the decline in matsutake yields in China. The impact of these two factors was found to vary with the type of forest access rights. In common access forests, approximately 50.87 %

(n = 200) of the collectors cited disturbance of shiros as the main factor (Fig. 4a), whereas in private access forests, increased forest density was identified as the key factor by 62.16 % (n = 60) of the collectors (Fig. 4b).

4. Discussion

4.1. Collectors were able to perceive changes in matsutake yield reliably

Our study demonstrates that the collectors' perceptions of recent declines in matsutake yields are consistent with the significant declines observed over a 26-year period at plot-based sites across four villages in southwestern China. Similar patterns have also been reported in other studies on matsutake within the region, including Amend et al. (2010), who found that collectors' observation of matsutake yield trends were consistent with those of the scientific community (Amend et al., 2010). In Bhutan, most collectors reported a decline in matsutake yields, which also aligns with the downward trend observed in national records on yields of this species (Brooks and Tshering, 2010). Moreover, a systematic review revealing local communities' perceptions of a decline in abundance of wild edible plants and mushrooms aligns with the global assessment, which also documents a significant decrease in the abundance of most species (Schunko et al., 2022; Bélanger and Pilling, 2019). These findings together suggest that collectors are able to capture changes in the yields of wild edible plants and mushrooms accurately. The high ability of collectors to perceive fluctuations in wild edible plant and mushroom yields is mainly driven by the high economic or nutritional values of those species. Fluctuations in the abundances or yields of those wild species could directly affect their household incomes (Arora, 2008; Yang et al., 2008) or nutritional requirements (Schunko et al., 2022). Through sustained interaction with their natural environment, collectors have gained a deep understanding of the local ecology of those wild edible plant and mushroom, including species phenology, habitat requirements, and productivity drivers such as weather conditions, forest health, and human activities. This intimate knowledge allows them to perceive even subtle changes in the abundance or yields of wild edible plants and mushrooms. All in all, this finding further suggests that ethnobiological interviews with local collectors could serve as a reliable method for assessing long-term changes in natural resources, particularly in regions where ecological records are sparse. By integrating local expertise with scientific data, we can bridge temporal and spatial gaps in traditional monitoring frameworks.

4.2. Declines in matsutake yield were the most cited changes in the major producing areas of China

Both our interview data and long-term plot-based data indicated that matsutake yields have decreased over recent decades in the major producing areas of China. This declining trend is not unique to China. In Bhutan, a decline in matsutake yields was reported by the majority of collectors (82 %, n = 100) and is also evident in national yield records (Brooks and Tshering, 2010). The regional and national matsutake production also significantly decreased in Japan since the 1940s (Vaario et al., 2017; Michael, 2022; Furukawa et al., 2024) and in South Korean since the 1980s (Van Gevelt, 2014). These findings together suggest a widespread decline in matsutake yields across the main production regions in Asia, highlighting the need for implementing sustainable management for this high-value mushroom.

Similar patterns of yield or abundance decreases have also been observed in most other assessed wild edible mushrooms and plants (Perez-Moreno et al. 2021a; Pérez-Moreno et al., 2021b). For example, the production of black truffle (*Tuber melanosporum*) has also been decreased significantly in France, Italy and Spain (Büntgen et al., 2012a, b; Büntgen et al., 2019). A meta-analysis of 78 case studies shows that most wild edible wild species experienced similar declines in abundance (Schunko et al., 2022). A recent global assessment of wild edible plants revealed that in 63 % (n = 1039) of the species assessed, the abundance is decreasing (Bélanger and Pilling, 2019). These findings indicate that declines in the production or abundance of wild edible species are frequently occurring phenomena globally. Consequently, the conservation and sustainable management of these wild species, especially those with high economic value, is vital and has become an urgent issue.

4.3. Climate change, disturbance of shiros and increased forest density have been cited as the primary reasons for matsutake yield declines

Our interview data suggested that climate change was perceived as a critical factor for the declines in matsutake yields. This finding further consistent across different forests access rights. To test whether the climate in these areas had actually changed or not, we further analyzed the temperature and precipitation data recorded by the local meteorological stations (for details on the stations see Table A2 in the appendix) surrounding the 20 villages. Consistent warming trends were detected at both annual and seasonal scales, with the most pronounced increase seen in spring temperatures (warming rate: 0.30–0.50 °C/decade, Fig. A6). The annual and seasonal total precipitation showed a mixed trend with both significant increases and decreases, with these changes being particularly significant over the most recent two decades (Fig. A7). Multivariate analysis of long-term plot data further revealed that climate factors (temperature and precipitation) explained 23.61 % (range: 12.01–61.84 %; Table 2) of variance in matsutake yield on average. These results together suggest that climate change could be a major factor contributing to the decline in matsutake yield, as suggested by the collectors.

Our finding aligns with regional and global findings on climate-matsutake (or mushroom) linkages. In northwestern Yunnan, climate change was perceived as the primary cause of yield declines (Amend et al., 2010), and specifically, optimal August precipitation and temperature could enhance matsutake productivity in Baoshan (Yang et al., 2012). Similarly, Japanese studies also attributed matsutake yield variability to summer-autumn precipitation (Furukawa et al., 2016), and a Finnish study has noted that high matsutake yield were associated with a certain amount of precipitation prior to fruiting onset (Vaario et al., 2015). Moreover, the broader mycological literature reinforces this climatic sensitivity of mushroom yield (Boddy et al., 2014). Mushroom yields were modulated by temperature and precipitation globally, with summer precipitation often positively correlated with autumn productivity (Büntgen et al. 2012a, 2012b, 2015a, 2019; Steidinger et al., 2022). In arid ecosystems such as the Pyrenees and Mediterranean, water availability also constrains mushroom growth (Bonet et al., 2010; Olano et al., 2020). Experimental irrigation supports these field observations, showing that moderate irrigation can increase mushroom yield in those dry ecosystems (Büntgen et al., 2015b). Furthermore, high temperatures can negatively impact mushroom yields, especially in drier areas with high evapotranspiration rates (Boddy et al., 2014). Lastly, our findings also largely dovetail with global assessments of the drivers of decline in wild foods (Bélanger and Pilling, 2019), threatened plant and animal species (Maxwell et al., 2016), and life on earth in general (Diaz et al., 2019).

In common access forests, disturbance of shiros (Fig. A8) was identified as the primary cause of matsutake yield declines. Disturbance of shiros occurs largely due to unsustainable collection practices. Collectors typically locate matsutake by stripping the humus layer, and then dig into the deep soil layers within the shiro. Ideally, post-harvest restoration, backfilling of excavated soil and re-covering of the shiro with litterfall, should always follow collection to mitigate shiro disturbance. The matsutakes that grow in the common access forests of a village are open to all villagers (Yang et al., 2009). Therefore, collectors frequently neglect this restorative step after collection because the insecure ownership of matsutake leads them to increase their collection within a given time to maximize their own short-term economic benefits (Yang et al., 2009; He et al., 2014). The shiro is a solid and tightly aggregated underground structure composed of mycelium and mycorrhizae (a symbiotic structure between matsutake mycelium and the fine roots of its host trees), from which mushrooms emerge (Yang et al., 2012). Consequently, the quality of the shiros directly governs future matsutake productivity (Gong et al., 1999). Current unsustainable collection practices inevitably expose the mycelium and mycorrhizae to the air, resulting in their death (Su and Zhao, 2007). This mortality reduces both mycelial biomass and mycorrhizal numbers, thereby disrupting and damaging the structure and function of the shiros. Such damage not only reduces matsutake yield in that year, but also in subsequent years. It has been reported that once a shiro is damaged, it takes at least three to five years to recover its vitality and regrow. If severely damaged, the shiro may even face the risk of permanent loss of vitality (Gong et al., 1999). Therefore, we suggest the local forestry department should intensify its publicity efforts on raising awareness among local collectors about the long-term risks that their current collection practices pose both to their livelihoods and to the matsutake populations. We also advocate that the local forestry department should take the lead in or intervene to form a government-community co-management approach, integrating collectors' knowledge and regulations and conventions of village (Yang et al., 2009; He et al., 2014) with current forestry policies, to sustainably manage matsutake resources.

In private access forests, increased forest density (Fig. A9) was identified as the main reason for matsutake yield declines. These dense forests are largely induced by the Chinese government's Natural Forest Protection Program, which was launched in 1998 to conserve China's national forests by banning forest logging (Arora, 2008). This program leads to an increase in forest coverage and density. Our field surveys and communication with collectors suggest that the increased forest density is largely due to a significant rise in the number of shrubs, which are not matsutake host plants. As an ectomycorrhizal fungus, matsutake establishes a mutualistic relationship with its host trees. The growth of matsutake mycelium and the formation of this mushroom depend on carbohydrate fluxes from host tree roots (Egli et al., 2010). Increases in the numbers of shrubs may suppress host tree fine-root development through resource preemption (Ito and Ogawa, 1979). In Japan, a 41-year thinning experiment demonstrated that root biomass of non-host-trees in the control plot was more than twice that in the managed plot, where non-pine trees were removed and parts of host trees were thinned (Furukawa et al., 2024). This elevated root biomass of non-host-trees may intensify competition for nutrients between matsutake host trees and non-host-trees, potentially inhibiting host tree growth, and, in turn, significantly reducing matsutake yield in control plot. While matsutake yield remained high in the managed plot (Furukawa et al., 2024). Parallel study from Swiss forests also showed that reducing forest density through thinning can promote the growth of host plants, thereby increasing the production of mycorrhizal fungi (Egli et al., 2010). In addition, as suggested by Furukawa et al. (2024), reducing forest density by removing non-host trees and thinning parts of host trees has significantly increased the number of shiros over the past 41 years. Each of these new shiros will be able to survive and produce mushrooms for more than half a century if conditions remain favorable (Furukawa et al., 2024). Therefore, we recommend that private forest owners should first apply for a forest thinning permit, and then implement scientific thinning practices under the guidance of regional forestry governance, such as removing parts of shrubs, to improve matsutake yields in China.

4.4. Potential socio-economic and ecological consequences of matsutake yield declines

Declines in matsutake yield may have substantial socio-economic consequences. Globally, every day during the fruiting season (from June to October), more than one million people are engaged in matsutake collection and trade (Michael, 2022). The majority of these collectors are marginalized and impoverished people who reside in remote mountainous regions across various countries (Tsing, 2015). These collectors include immigrants from Southeast Asia and Latin America, European descendants, Vietnam War veterans, unemployed loggers, and various ethnic groups in North America (Tsing, 2015), mountain villagers in Japan (Faier, 2011), Korea (Van Gevelt, 2014), and Bhutan (Brooks and Tshering, 2010), as well as diverse ethnic groups along the border of China. Cash from matsutake sale has become crucial to their livelihoods, contributing between 6 % and 90 % of household cash income in these communities worldwide (Martinez-Carrera et al., 2002; Arora, 2008; Yang et al., 2008; Brooks and Tshering, 2010; Van Gevelt, 2014), with the contribution reaching as high as 50 %–80 % in parts of southwestern China (Arora, 2008; Yang et al., 2008). In general, a short-term decrease in matsutake yield might not affect the livelihoods of those collectors, as the negative impact could be mitigated by rising prices. However, a prolonged decrease would severely impact their livelihoods. A continued drop in matsutake availability would reduce the number of mushrooms that collectors can collect, leading to a decline in their overall income. This, in turn, would reduce their ability to support their families, such as affording education, purchasing food, and alleviating poverty (Arora, 2008), and ultimately affecting regional stability.

In addition to the socio-economic effects, declines in matsutake yield also reflect declining matsutake populations. Matsutake generally rely on non-human animals to disperse their spores (Michael, 2022). This process is crucial for the formation of new shiros (Fig. A2). A decrease in the number of mushrooms is likely to result in reduced spore dispersal, which could then lead to fewer new shiros forming. This, in turn, might cause a decrease in future matsutake yields. Moreover, as the yield declines, collectors might intensify their collecting efforts by spending more time for collecting (Dong et al., 2012). This increased collection time, exacerbated by economic pressures, could damage the old shiros, thereby reducing their ability to support future matsutake yields. For example, from our interviews during the year of 2023 in the village of Jidi, collectors usually spent 10–12 h per day searching for matsutake in the rugged mountains and traveling to market 10 years ago (Yang et al., 2009). Now, they spend around 12–14 h solely on searching matsutake. These collectors typically leave to begin the matsutake search at 4–5 o'clock am. Around 12 o'clock, they have lunch and give the collected matsutake mushrooms to a family member whose main job is cooking and selling the mushroom. Then, at about 14–15 o'clock, the collectors continue searching for matsutake and generally return to the village around 19–20 o'clock.

4.5. Advantages and limitations of ethnobiological interview method

As demonstrated by this study and previous research (Amend et al., 2010; Brooks and Tshering, 2010; Bélanger and Pilling, 2019; Schunko et al., 2022), ethnobiological interviews with local collectors are a reliable method for assessing long-term changes in wild edible plants and mushrooms, particularly for those with high economic value. Through the interviews, we can gather data on changing trends in the yields of wild mushrooms and plants, and the underlying reasons for these perceived changes across large geographic areas, even with limited time and financial resources. These broad trends are essential for the sustainable use and management of wild resources, especially for species like matsutake, whose ecology and ecological consequences are not yet well understood. Furthermore, the drivers suggested through interviews also can be used to guide future research into sustainable management strategies. However, although ethnobiological interviews provide valuable insights, they have limitations in providing detailed information on changes in wild edible mushrooms and plants, such as specific rates of change over defined time periods. Plot-based data with daily or annual resolution can provide such detailed information, however, collecting this data is labor-intensive, time-consuming, and costly. Therefore, integrating these two methods could offer a more comprehensive understanding of the long-term fluctuations in high-valued wild edible species like matsutake.

5. Conclusion

This study, for the first time, integrated long-term plot-based monitoring data with data from ethnobiological interviews to assess changes in matsutake yield and the factors driving yield changes. Both datasets consistently revealed a pattern of decreases in matsutake yield over recent decades in the mian producing areas of China, which has the potential to negatively affect the livelihoods of marginalized collectors, and the sustainability of matsutake populations. The decline in matsutake yield is attributed to climate change, disturbance of shiros in common access forests and increased forest density in private access forests by collectors in the major producing areas of China. These findings suggest the critical importance of incorporating local ecological knowledge into conservation frameworks. Local collectors demonstrated sophisticated understanding of resource dynamics that aligns with scientific observations, particularly regarding microhabitat requirements and anthropogenic impacts. This finding shows the potential for co-developed management strategies that engage collectors as key stakeholders, especially in common-access forests where open-access conditions frequently lead to resource overexploitation (Yang et al., 2009; He, 2010; He et al., 2014). To address disturbance of shiros in common-access forests, we advocate implementing a government-community co-management approach, that integrates collector's knowledge and village regulations and conventions with current forestry policies, to sustainably manage matsutake resources. For private forests, owners could apply a permit to conduct adaptive thinning practices under the guidance of regional forestry governance, such as removing parts of shrubs, to achieve sustainable management of matsutake resources. All in all, these interventions will not only help maintain the ecological balance but also provide economic benefits to local communities. Furthermore, the integrated approach of long-term plot-based monitoring and ethnobiology interviews not only provides a novel perspective for assessing the impact of global environmental changes on fungal ecology but also highlights the importance of incorporating local ecological knowledge into conservation strategies.

Credit author statement

Yingfeng Bi: Writing – review & editing, Writing – original draft. **Bin Liu:** Formal analysis, Data curation. **Guangli Chen:** Investigation. **Ti Bu:** Data curation. **Pengwan Zhang:** Data curation. **Qinghong Zhou:** Investigation. **Liqin Mu:** Investigation. Yao Fu: Field ethnobotanical interviews. Yinxian Shi: Field ethnobotanical interviews. **Xuefei Yang:** Conceptualization. **Deli Zhai:** Conceptualization.

Declaration of competing interest

All authors have approved the manuscript and agree with submission to Journal of Environmental Management. On behalf of all the co-authors, I declare that there is no conflict of interest involved.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125305.

Data availability

The authors do not have permission to share data.

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