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Gastrodia elata production areas in China: climate and distribution changes (A.D. 25–2100)

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Introduction: *Gastrodia elata* is a prized traditional Chinese medicine with a long history of use, and its wild resources have progressively declined as its value has become increasingly apparent. Given the high dependence of *G. elata*'s growth on climate and the severe challenges posed by global warming, it is crucial to explore the historical shifts and future trends of its production areas.

Methods: This study systematically combed through ancient Chinese herbal and local chronicles, comprehensively documenting the geographical distribution of *Gastrodia elata*, a traditional precious medicinal herb in China, from the Eastern Han Dynasty to the Ming and Qing Dynasties (A.D. 25 - 1912). Based on contemporary geographical distribution data of *Gastrodia elata*, the MaxEnt model was used to simulate its suitable distribution areas in the present and future (2081–2100 AD).

Results: The study reveals that climate change and human activities significantly affect the distribution patterns of *Gastrodia elata* production areas. The expansion and transformation of *Gastrodia elata* production areas across different historical periods are closely related to climate fluctuations and social development. During the Eastern Han to Sui - Tang periods, it was mainly produced in the Yellow River Basin of China; during the Song, Jin, and Yuan dynasties, it expanded to the Huang - Huai Basin; during the Little Ice Age (LIA) of the Ming and Qing Dynasties, it continued to migrate southward into the Yangtze River Basin; and in recent years, there has been a trend of a decrease in coastal areas, which is consistent with the climate changes during the Little Ice Age and the current global warming trend.

Discussion: This study's discussion on the changes in *Gastrodia elata* distribution areas and high - quality production zones covers three periods: ancient, modern, and future. The findings provide insights into how to adjust *Gastrodia elata*'s wild cultivation areas in response to climate change and further offer evidence for exploring the impact of climate change on the growth of authentic Chinese medicinal herbs.

KEYWORDS

Gastrodia elata, *Gastrodia elata* Blume, local chronicles, MaxEnt model, traditional Chinese medicine

1 Introduction

Gastrodia elata, commonly known as Chijian (赤箭), Shencao (神草), Guiduyou (鬼督邮), and Bailongpi (白龙皮), is the dried tuber of the orchid plant *Gastrodia elata* Blume (Chinese Pharmacopoeia Commission, 2025). It is now widely distributed in Jilin, Jiangxi, Sichuan, Guizhou, Yunnan, and Xizang in China, as well as in Nepal, Bhutan, India, Japan, the

Korean Peninsula, and Siberia. Orchids possess high ornamental, culinary, medicinal, and ecological value. However, all wild orchids worldwide are listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), representing over 90% of protected endangered plants and constituting a flagship group in plant conservation (Luo et al., 2003).

Gastrodia elata has been a valued medicinal herb in traditional Chinese medicine for over two millennia. Ancient Chinese medical texts contain nearly 1,300 practical prescriptions using *Gastrodia elata*, and it also plays an important role in dietary therapy, such as *Gastrodia elata* wine. Owing to its rising medicinal and economic significance, it has become vital for local economic development and rural income generation. Long-term harvesting of wild *Gastrodia elata* has led to a rapid decline in wild resources. Urban development and frequent deforestation also contribute to the destruction of *Gastrodia elata* habitats and the degradation of wild populations (Chen et al., 2014). In 2021, *Gastrodia elata* was designated a second-class nationally protected wild plant (National Forestry and Grassland Administration, Ministry of Agriculture and Rural Affairs, 2021). Presently, the production of *Gastrodia elata* relies predominantly on artificial cultivation. Selecting optimal cultivation areas and producing high-quality *Gastrodia elata* can revitalize mountainous economies while promoting wild resource conservation and sustainable utilization, thereby strengthening the brand advantage of authentic *Gastrodia elata* medicinal materials in China.

Climate change has become the most important factor affecting plant distribution (Zhao et al., 2021). Shifts in production areas of traditional Chinese medicinal materials are increasingly linked to climatic impacts, such as in the cases of *Panax ginseng* (Zhao et al., 2016) and Fuling (Jiang et al., 2024). Professor Zhu Kezhen proposed that there had four cold and four warm periods in ancient Chinese climatic history. The interval from the Eastern Han Dynasty to the Wei, Jin, and Southern and Northern Dynasties (early period to A.D. 600) was a cold period, while the Sui, Tang, and late Northern Song Dynasties (around A.D. 600 to A.D. 1100) were relatively warm. Subsequently, from the late of the Northern Song Dynasty to the early Ming Dynasty (A.D. 1100 to A.D. 1400), two brief cooling phases followed by recovery occurred. The Little Ice Age (LIA, A.D. 1400 to A.D. 1900) brought marked temperature declines during the Ming and Qing Dynasties. As *Gastrodia elata* favors cool, humid climates, its distribution is expected to shift with changing temperature and moisture regimes.

China has a wealth of historical documents documenting the medicinal plant *Gastrodia elata* Bl. Despite some confusion in recorded names, all belong to the genus *Gastrodia elata* Bl. of the Orchidaceae family. Descriptions of its habitat first appear in the Eastern Han text *Shen Nong Ben Cao Jing* (神农本草经) under the name “Chijian.” *The Wu Pu Ben Cao* (吴普本草) (A.D. 239) provides the earliest record of its production areas, using “Guiduyou” as the principal designation. From the Eastern Han Dynasty onward, medical texts meticulously document the growing environment and geographical origins of *Gastrodia elata*. Through these rich historical records, we can trace the distribution of its medicinal materials across different historical periods. From the Eastern Han Dynasty to the Sui and Tang Dynasties, *G. elata* was widely distributed in present-day Shandong, Henan, Shaanxi, and Gansu, with Shandong as the primary production region. In modern times, major production areas have shifted to southwestern China, notably Guizhou and Yunnan. Given its stringent environmental requirements and high climatic sensitivity, historical climate variation likely drove these distributional changes.

Based on the changes in China’s climate from the Eastern Han Dynasty to the present, studying whether the production areas and true origins of *Gastrodia elata* have changed accordingly can enhance us to understand the historical evolution and contemporary status of traditional production regions. Under the current severe global warming trend, species may be forced to migrate toward colder and wetter places (Li and Chen, 2014), suggesting a potential northward shift in cultivation areas for *G. elata*. Researching the impacts of future climate change on *Gastrodia elata* production areas thus provides a critical foundation for the development of China’s *Gastrodia elata* industry.

This study systematically reviewed ancient Chinese texts on *Gastrodia elata* since the Eastern Han Dynasty to reconstruct historical distribution patterns based on documented production areas. The study introduced the MaxEnt model to assist in analyzing the impact of climate on changes in *Gastrodia elata* production areas. Through these research methods, the analysis addresses four core questions: (1) classifying *Gastrodia elata* production areas during the Eastern Han Dynasty and various periods of the Qing Dynasty according to classical Chinese literature; (2) evaluating the main influencing factors of ancient *Gastrodia elata* production area distribution; (3) determining the climatic correlates and primary drivers of contemporary *Gastrodia elata* distribution; (4) exploring potential changes in *Gastrodia elata* production areas under the background of future climate warming.

2 Materials and methods

2.1 Collection and compilation of historical data

2.1.1 Collection of historical data

This study primarily draws on historical documents from four periods: the Eastern Han to Sui–Tang Dynasties (A.D. 25–907), the Song, Jin, and Yuan Dynasties (A.D. 960–1368), the Ming Dynasty (A.D. 1368–1644), and the Qing Dynasty (A.D. 1636–1912).

Sources from the Eastern Han to Sui–Tang periods include *Shen Nong Ben Cao Jing* (神农本草经), *Wu Pu Ben Cao* (吴普本草), *Ben Cao Jing Ji Zhu* (本草经集注), *Xin Xiu Ben Cao* (新修本草), and *Nan Shi* (南史). Texts from the Song, Jin, and Yuan Dynasties comprise *Kai Bao Ben Cao* (开宝本草), *Jia You Ben Cao* (嘉佑本草), *Ben Cao Tu Jing* (本草图经), *Shao Xing Ben Cao* (绍兴本草), *Song Shi Di Li Zhi* (宋史地理志), *Jin Shi* (金史), and *Da Yuan Yi Tong Zhi* (大元一统志), supplemented by poetry and local chronicles.

For the Ming and Qing Dynasties, materials consist mainly of local gazetteers, accessible via the Erudition-China Fangzhi Library¹ and the National Library of China–National Digital Library of China.² This study selected 261 local gazetteers from the aforementioned three historical periods, extracting important information related to the origin of *Gastrodia elata*. Relevant records were classified into three categories: “Wu Chan” (物产), “Tu Chan” (土产), and “Tu Gong” (土贡). For completely duplicated entries across local chronicles, only the earliest occurrence was retained.

1 <http://dh.ersjk.com/spring/user/mlogin>

2 <http://www.nlc.cn/>

2.1.2 The distribution map of *Gastrodia elata*

This study visually presents the geographical areas where *Gastrodia elata* was distributed in different historical periods. We converted the geographical locations mentioned in ancient texts into modern coordinates and drew distribution maps of *Gastrodia elata* for five historical periods based on modern maps of China. Data processing was conducted using ArcGIS 10.8 with the GCS_WGS_1984 geographic coordinate system. Base map data were obtained from 1:1,100,000 scale maps and administrative boundary shapefiles provided by the Ministry of Natural Resources of the People's Republic of China.³ Historical place names and administrative boundaries were standardized and mapped with reference to authoritative sources, including the *China Historical Place Names Dictionary* and the *China Historical Atlas*.

The territorial extent of ancient China varied considerably over time. Initially confined primarily to the Central Plains, the territory expanded under successive dynasties, with gradual incorporation of ethnic minority regions. Consequently, early historical records for peripheral areas may be incomplete. Nevertheless, existing ancient documents and objective historical facts permit reconstruction of the long-term migratory dynamics of *Gastrodia elata* across ancient China. According to records in ancient local gazetteers, we inferred that the frequency of *Gastrodia elata*'s appearance in these documents was closely related to local production activities. Therefore, we counted the occurrences of *Gastrodia elata* in local gazetteers from each period to estimate its yield.

2.2 MaxEnt model

2.2.1 Species occurrence data

This study collected distribution data of *Gastrodia elata* in 18 provinces of China, including Guangxi, Yunnan, Hubei, Hunan, Chongqing, Guizhou, Anhui, Henan, Shaanxi, and Gansu, by reviewing databases such as the Global Biodiversity Information Facility⁴ and the China Digital Plant Herbarium,⁵ as well as related literature.

Occurrence records lacking precise coordinates were georeferenced using Baidu Satellite Maps.⁶ Records with ambiguous locality descriptions, unverifiable coordinates, or substantial discrepancies between reported and mapped locations were excluded. To prevent overfitting caused by excessive sampling point spacing, we utilized ENMTools software to eliminate duplicate and low-precision data within 1 km × 1 km grid cells (Warren et al., 2009). Following this filtering, 135 current occurrence points were retained. For compatibility with MaxEnt, all coordinates were formatted as CSV files ordered by species name, longitude, and latitude.

2.2.2 Screening of environmental variables

This study utilized 19 bioclimatic factors from current (1970–2000) and future (2081–2100) climate data, all sourced from the

World Climate Database (WorldClim, <http://www.worldclim.org>) with a spatial resolution of 30 arcseconds. Future-period data were obtained from the sixth phase of the International Coupled Model Intercomparison Program (CMIP6), employing the second-generation medium-resolution climate system model (BCC-CSM2-MR) released by the National Center for Climate Change (Beijing). Four shared socioeconomic pathways (SSPs) from the IPCC Sixth Assessment Report were selected: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Occurrence records of *Gastrodia elata* and the 19 bioclimatic variables were input into MaxEnt. Key environmental predictors were identified using percent contribution, permutation importance, jackknife analysis, and correlation tests. Variables with Pearson correlation coefficients exceeding 0.85 were excluded if they exhibited low contribution based on jackknife evaluation (Zhang et al., 2020). Ultimately, nine critical environmental factors were retained for modeling the suitable distribution areas of *Gastrodia elata* (Table 1).

2.2.3 Establishing the MaxEnt model and parameter settings

The distribution point data of *Gastrodia elata* (csv.) and the screened environmental factor data (asc.) were imported into MaxEnt. A random 75% of occurrence points was designated as the training dataset, with the remaining 25% reserved for model validation (Phillips et al., 2017). The output is generated as Logistic-format and ASCII-type files. The analysis was executed with 10 replicates, and options for creating prediction maps, response curves, and variable importance assessments via jackknife analysis were enabled. The maximum number of background points was set to 10,000, all other parameters remained at default values (Li et al., 2024). For variable weight determination, Variable contributions were further evaluated using jackknife-derived response curves. The model was run 10 times, and the average of the 10 outputs was computed. Model predictive performance was evaluated using the area under the receiver operating characteristic (ROC) curve (AUC), with values approaching 1 indicating higher predictive accuracy.

2.2.4 Plotting the forecast distribution

Simulation outputs were mapped using ArcMap to delineate suitable habitat zones for *Gastrodia elata*. The natural breaks (Jenks) approach was applied to categorize the suitability zones (Zhang et al.,

TABLE 1 Leading environmental variables selected in the model.

Code	Environmental variables	Units
bio12	Annual precipitation	mm
bio10	Mean temperature of warmest quarter	°C
bio6	Min temperature of coldest month	°C
bio7	Temperature annual range	°C
bio2	Mean diurnal range	°C
bio15	Precipitation seasonality	/
bio3	Isothermality	/
bio17	Precipitation of driest quarter	mm
bio18	Precipitation of warmest quarter	mm

³ <http://bzdt.ch.mnr.gov.cn/>

⁴ <http://www.gbif.org>

⁵ <http://www.cvh.ac.cn/>

⁶ <https://www.earthol.com/>

2025), resulting in four types: unsuitable zones ($p < 0.25$), low suitability zones ($0.25 \leq p < 0.5$), medium suitability zones ($0.5 \leq p < 0.7$), and high suitability zones ($p \geq 0.7$). Spatial analysis tools in ArcGIS were subsequently applied to reclassify the raster layers and calculate the area and proportional extent of each suitability class.

3 Results

3.1 Distribution of *Gastrodia elata* during the Eastern Han to Southern-Northern Dynasties periods

The historical distribution of *Gastrodia elata* during the Eastern Han to Southern and Northern Dynasties periods is illustrated in Figure 1. In classical Chinese texts of this era, the species was predominantly recorded under the official name “Chijian” (赤箭). The earliest record origins in the *Wu Pu Ben Cao* (吴普本草), which cites Taishan (泰山) in present-day Shandong Province and Shaoshi (少室) in the Songshan area of Henan Province. Subsequently, Tao Hongjing’s *Ben Cao Jing Ji Zhu* (本草经集注) expanded the known production areas to include Chencang (陈仓) and Yongzhou Prefecture (雍州), corresponding to modern-day Shaanxi Province and portions of Nei Mongol Autonomous Region and Gansu Province.

3.2 Distribution area of *Gastrodia elata* during the Sui and Tang Dynasties

The distribution of *Gastrodia elata* during the Sui and Tang Dynasties, as derived from Tang Dynasty literature, is illustrated in Figure 2. There is no relevant record of *Gastrodia elata* production

areas exist in the literature of the Sui Dynasty. During the Tang Dynasty, the *Xin Xiu Ben Cao* (新修本草) documented no additional localities beyond those previously recorded, with distribution still concentrated in the Taishan (泰山), Shaoshi (少室), Chencang (陈仓), and Yongzhou Prefecture (雍州) regions. The *Nan Shi* (南史) mentions that “*Gastrodia elata* grows on the mountains of Taishan (泰山) and Laoshan (崂山)”, a description consistent with the *Shen Nong Ben Cao Jing* (神农本草经), which states it “grows in valleys”. These indicate that *Gastrodia elata* production was predominantly concentrated along the Yellow River basin during this period.

3.3 Distribution of *Gastrodia elata* during the Song, Jin, and Yuan Dynasties

During the Song, Jin, and Yuan Dynasties, the distribution of *Gastrodia elata* was reconstructed from 22 records in ancient herbals and local gazetteers (Figure 3). Notably, the names “Chijian” (赤箭) and *Gastrodia elata* frequently co-occur in texts of this period. Records under “Chijian” largely reiterate earlier production areas, while additional localities are documented under the *Gastrodia elata* entry. Both the *Kai Bao Ben Cao* (开宝本草) and *Jia You Ben Cao* (嘉佑本草) identify Yunzhou Prefecture (郛州) in Shandong Province, Lizhou Prefecture (利州) in Sichuan Province, and the Tai and Laoshan mountain ranges as sources, with Yunzhou Prefecture regarded as producing the premium variety. According to the *Gao Li Shi* (高丽史), during the reign of Emperor Wenzong (A.D. 1046–1083), Song emperors dispatched medical officials to Goryeo bearing gifts of 100 medicinal herbs, including *Gastrodia elata* from Yunzhou Prefecture (郛州). The presentation of this superior variety as imperial tribute corroborates the claim that “*Gastrodia elata* from Yunzhou Prefecture (郛州) is superior” and confirms Shandong’s continued status as a high-quality production area during this era.

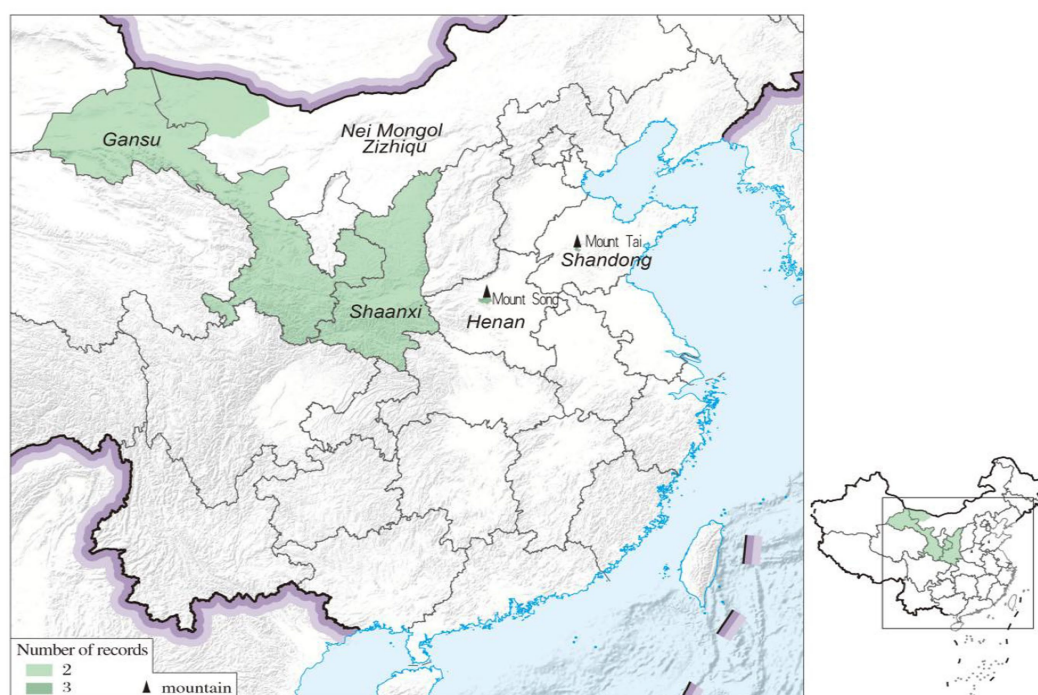


FIGURE 1
Distribution of *Gastrodia elata* production areas during the Eastern Han to Southern-Northern Dynasties periods.



FIGURE 2
Distribution of *Gastrodia elata* production areas during the Sui and Tang Dynasty.



FIGURE 3
Distribution of *Gastrodia elata* production areas during the Song, Jin, and Yuan Dynasties.

The *Ben Cao Tu Jing* (本草图经) further expanded the documented range, citing additional production areas in Jingdong (京东), Jingxi (京西), Hunan Prefecture (湖南), and Huainan Prefecture (淮南), primarily along the Huai River. The illustrations of *Gastrodia elata* in *Shao Xing Ben Cao* (绍兴本草) and other

classical texts bear the inscription “*Gastrodia elata* from Shaozhou Prefecture (邵州)”, indicating Shaozhou’s prominence as a high-quality production region. Additionally, a poem by Song Dynasty poet Rao Jie requesting *Gastrodia elata* from the elders of Xiangyang Prefecture (襄阳), suggests that Xiangyang Prefecture (襄阳) may

have also been a producing area. Historical records such as *Da Yuan Yi Tong Zhi* (大元一统志) further show that *Gastrodia elata* was also produced in Dongping Prefecture (东平府) and Songzhou Prefecture (嵩州府).

3.4 Distribution area of *Gastrodia elata* during the Ming and Qing Dynasties

The Ming Dynasty (A.D. 1368–1644) and the Qing Dynasty (A.D. 1636–1912) coincided with a global cold interval, which was first proposed by Matthes in 1939 as the “Little Ice Age”. This climatic episode is generally considered to have commenced in the 13th–14th centuries and culminated between the mid-16th and mid-19th centuries (Xu, 2009). Among the four cold periods in China, the Ming and Qing Dynasties were also the most prolonged and severe (Zhang, 2007).

3.4.1 Distribution area of *Gastrodia elata* in the Ming Dynasty

A total of 82 origin records for *Gastrodia elata* were compiled in the local chronicles of the Ming Dynasty (Figure 4). The species was extensively distributed, covering 14 provinces including Shaanxi, Shanxi, Shandong, Anhui, Henan, Hubei, and Jiangsu. In Ming Dynasty literature, it provides the most detailed accounts for Shandong, Shaanxi, and Shanxi provinces, with 10, 6, and 4 records, respectively. Notably, Hanzhong Prefecture (汉中府) in Shaanxi Province and Pingyang Prefecture (平阳府) in Shanxi Province each accounted for seven entries, indicating that wild *Gastrodia elata* was widely distributed with relatively abundant yields in these three provinces.

The high-quality production areas are extensively documented in Ming Dynasty ancient texts, and exhibit a multi-point distribution pattern. Both *The Cheng Hua Shan Xi Xian Zhi* (成化山西县志) (A.D. 1475) and *The Wan Li Ping Yang Fu Zhi* (万历平阳府志) (A.D. 1615) mentioned that Zhaocheng County (赵城), Yueyang County (岳阳), and Puzhou County (蒲州) in Shanxi Province, once presented *Gastrodia elata* as tribute to the imperial court. In addition, *The Jia Jing An Qing Fu Zhi* (嘉靖安庆府志) (A.D. 1554) recorded that *Gastrodia elata* from Anqing Prefecture (安庆府) in Anhui Province, was procured and used by the Nanjing Imperial Hospital. Similarly, *The Long Qing Bao Qing Fu Zhi* (隆庆宝庆府志) (A.D. 1567) attests that *Gastrodia elata* from Shaozhou Prefecture (邵州府) was renowned for its superior quality.

Ming texts further document the occurrence of *Gastrodia elata* on several prominent mountains, including Mount Tai in Shandong Province, Mount Song in Henan Province, Mount Heng in Hunan Province, and Mount Wudang in Hubei Province. Relative to the preceding two periods, the distributional range of *Gastrodia elata* further expanded during the Ming Dynasty, with production areas extending along the middle and lower reaches of the Yangtze River, showing a trend toward multi-point development. Nevertheless, the main production areas remained concentrated in northern regions.

3.4.2 Distribution area of *Gastrodia elata* in the Qing Dynasty

As the imperial dynasty closest to the modern era, the Qing Dynasty benefits from relatively well-preserved local gazetteers. This study systematically compiled 207 origin records for *Gastrodia elata* from historical materials during the Qing Dynasty, producing a distribution map of production areas during this period (Figure 5).



FIGURE 4
Distribution of *Gastrodia elata* production areas during the Ming Dynasty.



FIGURE 5
Distribution of *Gastrodia elata* production areas during the Qing Dynasty.

During this period, *Gastrodia elata* was primarily cultivated across 22 provinces, including Shaanxi, Guizhou, Shandong, Hubei, Hunan, Jiangsu, Anhui, Gansu, and Sichuan. Local gazetteers indicate that Hubei, Hunan, and Shandong were the principal production centers, with widespread cultivation documented in each. In Shandong Province, *Gastrodia elata* was still produced in six prefectures and 14 counties, though yields declined relative to earlier periods. In Hubei Province, cultivation occurred in six of the 10 prefectures, while in Hunan Province production was recorded in 15 prefectures and counties. According to the local chronicles, the high-quality production areas shifted southward from Shandong. Anqing and Lu'an in Anhui Province emerged as primary production hubs. *The Guang Xu Huo Shan Xian Zhi* (光绪霍山县志) (A.D. 1905) highlighted *Gastrodia elata* from Huoshan County (霍山) for its abundant yield and superior quality. Furthermore, *The Yong Zheng Yang Zhou Fu Zhi* (雍正扬州府志) (A.D. 1733) also noted the premium quality of *Gastrodia elata* from Gaoyou County (高邮).

Relative to the Ming Dynasty, the distributional range of *Gastrodia elata* expanded further during the Qing Dynasty. Primary production areas exhibited a north-to-south migratory trend, with origins extending east to west and encompassing virtually the entire Yangtze River basin. This transformation resulted in a shift of *Gastrodia elata* production areas from Shandong and Shanxi provinces to Guizhou, Sichuan, Yunnan, and adjacent regions.

3.5 Current distribution of *Gastrodia elata* suitable habitats and its major climatic factors

Model accuracy was validated using the mean AUC value from 10 MaxEnt replicates. The mean AUC for the contemporary *Gastrodia elata* distribution model was 0.945, exceeding the 0.9 threshold for

high predictive performance, and indicating reliable habitat suitability simulations. Contemporary distribution pattern of *Gastrodia elata* are strongly governed by climatic factors, ranked by contribution rate as follows: bio12, bio10, bio6, bio7, bio2, bio15, bio3, bio17, and bio18. Notably, the combined contribution rate of the top four climatic factors reaches 93%. The species response curves derived from MaxEnt indicate that *G. elata* exhibits optimal suitability ($p > 0.5$) under the following climatic ranges: bio12 is 727.31 to 1762.74 mm, bio10 is 13.89 to 25.83 °C, the optimal range of bio6 is −8.1 to 3.83 °C, and the optimal range of bio7 is 22.57 to 30.95 °C.

According to the simulation results, suitable habitat ($p > 0.2$) closely matches the documented contemporary distribution of *Gastrodia elata*. The high-suitability zones predominantly encircle the Yunnan–Guizhou–Sichuan region surrounding the Sichuan Basin, with the additional scattered areas along the Yangtze River corridor, including Chongqing, Hubei, Hunan, Xizang, Anhui, Jiangxi, and other provinces, as well as portions of coastal provinces such as Zhejiang and Fujian (Figure 6). The medium and low suitability zones mainly extend outward from these core areas, encompassing larger expanses across the Yunnan–Guizhou–Sichuan region, Central China, Liaoning, Jilin, Tibet Autonomous Region, Taiwan Province, Guangdong Province, and other provinces and cities. Notably, major *Gastrodia elata* cultivation bases persist to the present day in Anhui, Shaanxi, Gansu, Sichuan, and Yunnan provinces.

3.6 Future distribution of suitable habitats for *Gastrodia elata* and major climatic factors from 2081 to 2100

Future climate projections for the 2090s were evaluated under four Shared Socioeconomic Pathways: SSP126, SSP245, SSP370, and SSP585. Mean AUC values for the *Gastrodia elata* distribution models

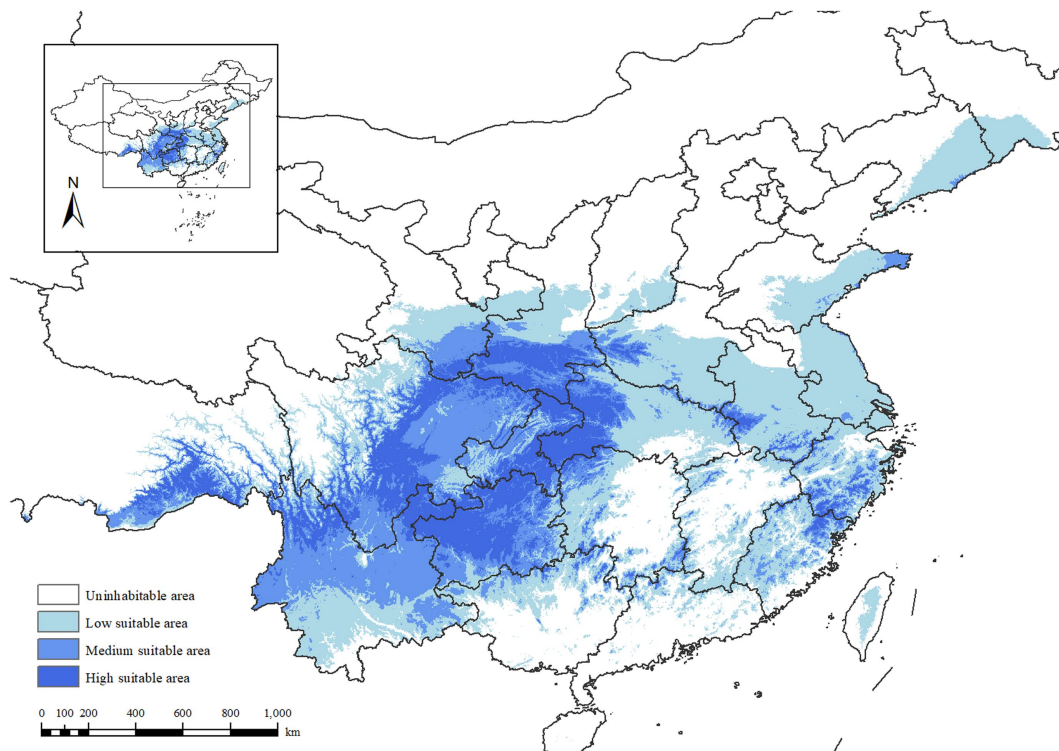


FIGURE 6
Gastrodia elata distribution suitable area in modern times.

were 0.972, 0.972, 0.973, and 0.972, respectively all exceeding the 0.9 threshold for robust predictive performance. Across all scenarios, the dominant climatic predictors were bio12, bio10, and bio6. In SSP126 and SSP370, bio10 contributed marginally more than bio6, whereas in SSP245 and SSP585, bio6 contributed slightly more than bio10. Both variables, however, remained markedly less influential than bio12. The cumulative percent contributions of these three factors across the four scenarios were 89.8, 86.8, 90.1, and 90.0%, respectively. Specifically ($p > 0.2$): Under SSP126 scenario, the optimal range for bio12 is 945.44 to 4252.97 mm, bio10 is 11.62 to 29.37 °C, and bio6 is −10.05 to 10.25 °C; under SSP245 scenario, the optimal range for bio12 is 859.93 to 5287.77 mm, bio6 is −7.8 to 11.84 °C, and bio10 is 12.75 to 30.09 °C; under SSP370 scenario, the optimal range for bio12 is 948.48 to 3688.07 mm, 14.44 °C < bio10 < 31.27 °C, and −7.21 °C < bio6 < 10.53 °C; while under SSP585 scenario, the optimal range for bio12 is 965.57 to 4364.54 mm, −6.95 °C < bio6 < 11.25 °C, and 14.14 °C < bio10 < 31.56 °C.

Under the four scenarios, projected suitable habitat distributions for *Gastrodia elata* exhibit notable divergence. In SSP126 scenario, the suitable area expands to 2.456×10^6 km², representing moderate growth while maintaining overall stability. The high-suitability zones predominantly encircle the Sichuan Basin, encompassing key areas in Sichuan, Chongqing, Guizhou, and Yunnan, with scattered occurrences persisting in warm, humid regions of southwestern and south-central China. The medium-suitability zones cover Yunnan, Guizhou, Shaanxi, Gansu, Anhui, Hubei, and Zhejiang, whereas low-suitability areas extend across Yunnan, Guizhou, Guangxi, Guangdong, Jiangxi, Fujian, Anhui, Henan, Hubei, Jiangsu, Shandong, Jilin, and Liaoning. Under SSP245, the suitable area

contracts slightly 2.407×10^6 km². Portions of the Guangxi–Chongqing border transition from medium to low suitability, and low-suitability zones in coastal Fujian, Guangdong, and Zhejiang diminish, while coastal Jiangsu shifts from low to medium suitability. SSP370 projects a suitable area of 2.243×10^6 km², characterized by substantial contraction of low-suitability zones and minor expansion of high-suitability areas. Localized low-suitability zones in southern regions turned into unsuitable, and all suitability classes in Tibet are reduced. Notably, the high-suitability areas in the border area of Hubei and Hunan expanded. The area of suitable zone in SSP585 is 2.416×10^6 km². Some low-suitability zones in southern Jilin and Liaoning Province is transition to medium suitability, and certain medium-suitability areas in Shaanxi become highly suitable. Southern suitable areas continue to contract, whereas central regions exhibit gradual expansion.

By the 2090s, optimal growth regions for *Gastrodia elata* will be concentrated in the transitional regions of Sichuan, Chongqing, Guizhou, and Shaanxi. Moderately suitable areas will be distributed across Yunnan, Sichuan, Guizhou, Anhui, Hunan, and Jilin, while the low-suitability zones will span Yunnan, Sichuan, Chongqing, Guizhou, Hubei, Hunan, Henan, Anhui, Gansu, Shanxi, Jiangsu, Shandong, Jilin, and Liaoning. The current suitable area encompasses 2.361×10^6 km², with potential expansion anticipated under various future climate scenarios. Suitability is projected to decline in Guangdong, Guangxi and Fujian, but increase in Shaanxi, Hubei and Henan. From the perspective of the centroid of suitable area, climate warming trend will drive a shift from western to central and from southern to northern regions, resulting in an overall northward expansion of the distributional range (Figure 7).

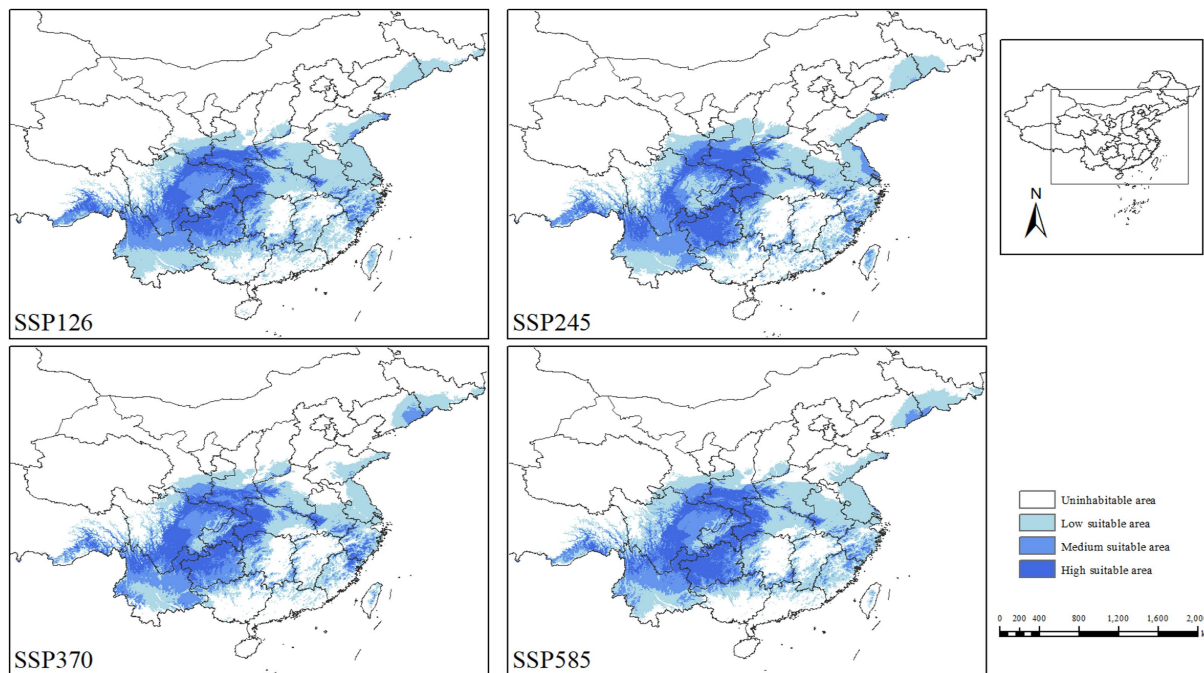


FIGURE 7

Prediction results for *Gastrodia elata* distribution area under different climate scenarios in the 2090s.

4 Discussion

4.1 Precipitation and temperature are the main factors affecting *Tianma* cultivation

The growth of *Gastrodia elata* depends nutritionally on its symbiotic fungus, *Trichoderma*. Therefore, cultivating *Gastrodia elata* requires creating suitable environmental conditions for both partners. The optimal growth temperatures for *Gastrodia elata* and *Trichoderma* range from 20 to 25 °C, however, sustained summer soil temperatures exceeding 30 °C or winter temperatures below −5 °C can impair plant development (Xu, 2000). Soil moisture between 40 and 60% during the growth period promotes fungal and plant growth, whereas levels exceeding 70% are detrimental (Yang, 1993).

Simulation results identify precipitation as a key determinant of *Gastrodia elata*'s growth, with bio12 and bio15 ranking first and fifth, respectively, in percent contribution. The contribution of bio12 exceeds 50%, consistent with the species' sensitivity to humidity and explaining its scarcity in arid regions such as Northwest China and northern North China. Additionally, bio15 values above 61.69% inhibit growth, indicating that *Gastrodia elata* requires a relatively stable moisture regime, and cultivation should be avoided in areas with pronounced seasonal precipitation or prolonged dry seasons.

Temperature also strongly influences *Gastrodia elata*'s distribution. Results show that bio10 and bio6 rank second and third in contribution, with optimal ranges of 13.89–25.83 °C and −8.1–3.83 °C, respectively. This interval indicates that both excessively high summer temperatures or low winter temperatures can retard growth and reduce yield, corroborating previous research findings. Field surveys of wild *Gastrodia elata* in the Wumeng Mountain of Guizhou documented a mean temperature of 3.8 °C for the coldest month and 24 °C for the warmest month, both within the optimal thermal range (Yang et al., 2022).

According to the MaxEnt model, the suitable distribution areas of *Gastrodia elata* in modern times are mainly concentrated in south-western, central, and southern China, specifically Yunnan, Sichuan, Guizhou, Chongqing, Anhui, Hubei, Hunan, and Xizang, which align closely with current production areas. Simulations indicate that warm and humid forested landscapes characterized by basin and hilly terrain are optimal. The Qinba Mountain region, Dabie Mountain region, Yiliang area in Yunnan, Bijie area in Guizhou Province, and Linzhi area in Tibet are highly suitable for *Gastrodia elata* cultivation, consistent with existing production patterns. The Qinba Mountain span the junction of Sichuan, Chongqing, Shaanxi, and Hubei, while the Dabie Mountains lie at the intersection of Anhui, Hubei, and Henan, these constitute two major production zones, encompassing counties such as Ningqiang County (宁强) and Chenggu County (城固) in Shaanxi, Tongjiang County (通江) and Qingchuan County (青川) in Sichuan, Jinzhai County (金寨) and Huoshan County (霍山) in Anhui, Yingshan County (英山) and Xuan'en County (宣恩) in Hubei, and Shangcheng County (商城) in Henan. The high concordance between modeled and empirical distributions suggests that expanding wild-like cultivation in these regions is feasible, though soil and altitudinal requirements must also be considered (Peng and Wang, 2007).

In summary, the distribution of *Gastrodia elata* is governed by both temperature and precipitation. This study underscores the importance of mitigating drought and temperature extremes during the growth period. When cultivating *Gastrodia elata*, it is recommended to monitor temperature conditions in winter and summer, particularly minimum monthly temperatures in winter, and implement timely insulation measures. Concurrently, precipitation should be followed to prevent water deficit or waterlogging, maintaining soil moisture conducive to *Trichoderma* proliferation without disrupting the symbiotic nutrient balance, thereby ensuring high yields.

4.2 Distribution of *Gastrodia elata* in ancient periods under the dual influence of climate and human activities

4.2.1 The Eastern Han to Sui and Tang Dynasties

In recent years, historical climate reconstructions indicate a transition from cold to warm conditions in China between the Eastern Han and Sui–Tang periods, with mean winter temperatures during the early cold phase approximately 0.3 °C lower than present, and Tang Dynasty temperatures exceeding contemporary values (Ge et al., 2012). The primary distribution of *Gastrodia elata* has shifted substantially from this period to the present. Historically, the range was confined largely to Shandong, Henan, and Shaanxi provinces along the Yellow River basin, whereas contemporary production is concentrated in southern China, principally Guizhou, Sichuan, Anhui, and Hubei. It is evident that primary production areas of *Gastrodia elata* in history were more northerly than current locations.

There have two factors likely account for this pattern. First, climatic conditions during the Eastern Han to Sui–Tang interval were comparable to or warmer than present, and the Yellow River basin maintained sufficient soil moisture to support *Gastrodia elata* growth in northern regions. Second, early agricultural development and political centers were concentrated in the Yellow River basin. According to *The China Historical Atlas*, from the Han to Tang Dynasties, the population reached approximately 60 million, with roughly 55% residing in the Yellow River Basin, and the Guanzhong (关中) region constituted a densely populated core area. Political centers were also predominantly situated in Guanzhong (关中), contributing to more extensive development and documentation in northern China.

4.2.2 The Song, Jin, and Yuan Dynasties

The climate during the Song, Jin, and Yuan Dynasties was relatively warm, particularly between A.D. 931 and A.D. 1320, when mean winter temperatures in eastern and central China exceeded present values by 0.18 °C (Ge et al., 2012), followed by gradual cooling. Song Dynasty literature document high-quality *Gastrodia elata* production in Shandong Province in northern China, while Sichuan, Hunan, and Huainan also supported cultivation, reflecting the warm, humid conditions favorable for *Gastrodia elata* growth. From the Song Dynasty onward, numerous medical texts including the *Tai Ping Sheng Hui Fang* (太平圣惠方) and *Sheng Ji Zong Lu* (圣济总录), recorded prescriptions containing *Gastrodia elata*, such as *Tian Ma Wan* (天麻丸) and *Tian Ma San* (天麻散). This suggests steadily rising demand and intensified harvesting relative to earlier periods.

Furthermore, the Song Dynasty achieved a southward shift of the political center, accelerating economic development in southern China. Populations migration toward the Jiangnan region established the Yangtze River Basin as the demographic core, leading to expanded cultivation in both lowland plains and montane forests. Consequently, the expansion of *Gastrodia elata* production into the Huang-Huai region during this period reflects adaptation to both contemporary climatic conditions and evolving societal demands.

4.2.3 The Ming and Qing Dynasties

Both the Ming and Qing Dynasties coincided with LIA, characterized by a general cooling trend punctuated by episodic cold and warm fluctuations. Cold intervals prevailed during the 15th, 17th, and 19th centuries, while warm phases were relatively concentrated in the 16th and 18th centuries (Xu, 2009). Compared to modern conditions, the Ming–Qing climate was colder and drier, with abrupt temperature declines shortening sowing windows or prolonging crop maturation (Liu, 2011). These conditions favored the distribution of *Gastrodia elata* in warm, humid regions of the southeastern coast and southwestern China, including Hubei, Anhui, Yunnan, Zhejiang, Hunan, and Guizhou. Historical records indicate that during the Ming Dynasty, *Gastrodia elata* was primarily produced in Shandong, Shaanxi, and Shanxi. By the Qing Dynasty, its distribution had expanded into the Yangtze River Basin, with high-quality areas shifting to Hubei, Hunan, and Jiangsu, which a pattern largely consistent with the contemporary distribution.

During the Ming Dynasty, *Gastrodia elata* was mainly distributed in Shandong, Shaanxi, and Shanxi, despite a predominantly cold national climate with mean winter temperatures in eastern and central China 0.39 °C lower than present. However, *Gastrodia elata* has a certain degree of cold tolerance, and northern forests, particularly in the Qinba Mountains, retained relatively high canopy cover, sustaining suitable montane habitats. Warmer southern regions such as Hubei, Hunan, Zhejiang, and Jiangsu also provided favorable environments, and the expansion of *G. elata* production into these areas supports this interpretation. Under the intensifying cold and arid conditions of the Qing Dynasty, southern production areas expanded further, with *Gastrodia elata* also distributed in southeastern and southwestern China. Furthermore, during the Ming and Qing Dynasties, the population continued to rise, reaching approximately 400 million by the Qing period. Agricultural population density exceeded 100 persons per square kilometer, intensifying demand for arable land. As the Yellow and Yangtze River Basins could no longer sustain the growing population, extensive land reclamation expanded into southwestern and southern China. Correspondingly, records documenting *Gastrodia elata* production areas in these regions gradually increased.

Shandong Province, historically a premium production area, continued to yield *Gastrodia elata* during the Ming and Qing Dynasties, though both output and quality declined. According to *The Ming Da Zheng Zuan Yao* (明大政纂要) (A.D. 1895), land in Tai'an Prefecture (泰安府), Shandong Province, became barren and agricultural yields diminished. The imperial court dispatched eunuchs to harvest wild *Gastrodia elata*, depriving farmers of marketable goods and plunging the populace into severe hardship. Local chronicles of the Qing Dynasty similarly recorded a decline in *Gastrodia elata* production in Shandong Province compared to earlier periods. The prevailing cold, arid climate likely suppressed fungal symbiont activity, impairing nutrient acquisition by *Gastrodia elata*. By the 20th century, Shandong had virtually disappeared from historical records as a *Gastrodia elata* provenance.

From the Eastern Han to the Ming–Qing period, the primary production areas of *Gastrodia elata* shifted progressively southward and expanded westward. Beginning in the Song Dynasty, intensive agricultural development, deforestation, and degradation of wild habitats in the Yellow River Basin diminished the region's status as

a high-quality production area. During the Ming and Qing Dynasties, in addition to Shaanxi, Shanxi, Hunan, Hubei, and Anhui, abundant *Gastrodia elata* populations were documented in Yunnan, Guizhou, and Sichuan. These regions, characterized by vast, sparsely populated landscapes with minimal anthropogenic disturbance and extensive old-growth forests, provided critical habitat for *Gastrodia elata* and its symbiotic fungus, offering abundant host resources and a stable microclimate, and thus emerged as new genuine production zones.

By the 20th century, local gazetteers frequently documented the Qinba Mountains and the Wumeng Mountains in southwestern China as the principal high-quality production areas. For instance, *The Kang Xian Xian Zhi* (康县县志) recorded that *Gastrodia elata* from Kang County (康县) was of superior quality and potent efficacy, while *The Kai Yang Xian Zhi* (开阳县志) noted substantial local production routinely exported to other regions. This geographical reconfiguration was driven not only by LIA climatic shifts during the Ming and Qing Dynasties, but also by political and economic transformations. The measures of reform of native chieftain system by the Ming and Qing governments strengthened administrative ties between the southwestern frontier and the central government (Zuo, 2024). Concurrently, migration from Hubei-Guangzhou to Sichuan promoted cultural integration and economic exchange, on the medicinal material of *Gastrodia elata* would also affect the recognition and use of local medicinal products. The expanding influence of Han Medicine and Han People likely affected local perceptions and utilization of *Gastrodia elata* as a medicinal products.

In conclusion, the historical redistribution of *Gastrodia elata* reflects the interplay of multiple factors. Available evidence indicates that these distributional shifts represent both ecological adaptation to prevailing climatic conditions across historical periods and the interaction between human activities and the natural environment, including population migration and evolving demand for medicinal herbs. In northern China, climatic cooling and high population density contributed to deforestation and ecological degradation, progressively constricting *Gastrodia elata* habitat. Conversely, southern regions, particularly the southwest, emerged as primary production zones owing to superior ecological conditions and relatively limited anthropogenic disturbance, thereby establishing the foundation for the contemporary distribution pattern of *Gastrodia elata*.

4.3 Future climate warming may influence the northward migration of *Gastrodia elata* cultivation areas

Since the 1970s, China has experienced pronounced global climate change, with mean annual temperatures increasing by 1.5–1.6 °C over the past five decades (China Meteorological Administration Climate Change Center, 2024). A comparison of *Gastrodia elata* distribution during the Qing Dynasty and the contemporary period reveals that while the overall range, concentrated along the Yangtze River Basin, has remained relatively stable, primary production areas have shifted substantially. For example, coastal provinces such as Guangdong, Zhejiang, Shandong, Jiangsu, and Fujian have largely lost cultivation areas for *Gastrodia elata*. MaxEnt projections for 2081–2100 indicate that southern coastal regions will become unsuitable for *Gastrodia elata*, whereas suitable habitat will

expand in northern provinces including Henan, Hubei, and Hunan, and suitability will increase in Liaoning and Jilin. Consequently, the suitable range of *Gastrodia elata* is projected to continue shifting northward over the next seven decades. Notably, altitude, soil composition, and land use strongly modulate the distribution of optimal *Gastrodia elata* habitat, a phenomenon requiring further investigation. Studies indicate that altitude induces regional differences in temperature and precipitation, enabling *Gastrodia elata* to develop numerous variants across different altitude gradients (Luo, 2023). Land-use analyses further suggest that optimal habitats will expand under future scenarios, with mid- to high-altitude zones progressively extending into northern forested areas and reaching maximal extent by 2100 (Gong et al., 2025).

The findings reveal a northward migration trend in *Gastrodia elata* production areas under global warming. Historically, Shaanxi, Shanxi, and Shandong Province in northern China were the genuine production regions. Although cultivation persisted in Shaanxi and Shanxi during the Ming–Qing and modern periods, the cultivated area has progressively contracted. Shandong Province, once a principal production area over an extended historical interval, experienced a gradual decline in documented distribution after the Ming–Qing transition. Although model simulations indicate that portions of Shandong retain potential suitability, actual cultivation is now exceedingly rare. Over time, climatic shifts have diminished formerly prominent high-quality production zones, while Yunnan, Guizhou, and Sichuan, previously lacking documented *Gastrodia elata* distribution, have emerged as primary production centers. In addition to climatic drivers, anthropogenic activities and political–economic factors have facilitated the long-distance displacement of core medicinal herb production areas. The evolving geography of *Gastrodia elata* production, from antiquity to the present, underscores the multifaceted influence of climatic and societal dynamics on medicinal plant distribution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SL: Investigation, Software, Writing – original draft, Writing – review & editing. ZW: Formal analysis, Supervision, Writing – review & editing. XL: Project administration, Supervision, Writing – review & editing.

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Generative AI statement

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fclim.2026.1784735/full#supplementary-material>

SUPPLEMENTARY SHEET 1

Ancient documentary records concerning the habitats of *Gastrodia elata*.

SUPPLEMENTARY SHEET 2

Contemporary distribution coordinates of *Gastrodia elata*.

SUPPLEMENTARY DATA SHEET 1

The species distribution data used in the Maxent model.

SUPPLEMENTARY DATA SHEET 2

Model results under historical scenarios.

SUPPLEMENTARY DATA SHEET 3

Model results under SSP126 scenarios.

SUPPLEMENTARY DATA SHEET 4

Model results under SSP245 scenarios.

SUPPLEMENTARY DATA SHEET 5

Model results under SSP370 scenarios.

SUPPLEMENTARY DATA SHEET 6

Model results under SSP585 scenarios.

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