Species Composition, Floristic Characteristics, and Influencing Factors of Alien Plants in China: Postprint

Authors: Zhang Jinmeng, Zhu Liangliang, Haonan Yin, Wang Li, Liu Yuli

Date: 2025-03-19T00:00:00+00:00

Abstract

China is one of the countries most severely affected and threatened by biological invasions. Understanding the species composition, floristic characteristics, and influencing factors of alien plants at the national scale is crucial for reducing invasion risks and promoting prevention and control management. Based on the "Dataset of Alien Plants in China," this study statistically analyzed characteristics including species composition, life form, and floristic type, and employed correlation analysis and stepwise regression models to deeply explore the underlying mechanisms linking socioeconomic and ecological factors with alien plants. The results showed: (1) Large families (99 families, 13,741 species) and large genera (205 genera, 7,199 species) among existing alien plants in China contributed 93.41% and 48.94% to the total species number, respectively. In terms of life form composition, herbaceous plants constitute the main component of alien plants in China, accounting for 59.82%. (2) At the national scale, tropical component families occupy a clear advantage, accounting for 52.65% of the total number of families; followed by temperate component families (21.56%) and cosmopolitan families (20.49%). (3) The distribution pattern of the total number of alien plants supports the distribution pattern of floristic component families, i.e., the total number of alien plants and various floristic components are most abundant in the eastern coastal regions and southwestern regions, decreasing toward inland areas. However, the proportion of cosmopolitan and temperate component families is higher in northern provinces and municipalities, while the proportion of tropical component families is highest in southern provinces and municipalities. (4) Correlation analysis indicated that there is a significant positive correlation between the number of invasive species in a family and the number of alien species contained in that family. Economic factors and climatic conditions of each province and municipality jointly determine the spatial distribution patterns of the total number of alien plants and the number of floristic component families in China, but the proportion of each floristic component is mainly influenced by thermal conditions (mean annual temperature). In the future, China should vigorously strengthen the introduction assessment and supervision of herbaceous plants from large families and large genera with tropical characteristics and cosmopolitan distribution.

Full Text

Species Composition, Floristic Characteristics and Influencing Factors of Alien Plants in China

ZHANG Jinmeng[1], ZHU Liangliang[1], YIN Haonan[1], WANG Li[1], LIU Yuli[2]*

[1]School of Geographical Sciences, Jiangsu Second Normal University, Nanjing 211200, China

[2]Institute of Sustainable Development, Huzhou University, Huzhou 313000, Zhejiang, China

Abstract

China is one of the countries most severely affected and imperiled by biological invasions. Mastering the species composition, floristic characteristics, and influencing factors of alien plants on a national scale is paramount to mitigating the risk of alien plant invasion and bolstering preventive measures. Based on a comprehensive dataset of alien plants in China, this paper statistically analyzed the species composition, life form, floristic component and other characteristics. Furthermore, it employed correlation analysis and a stepwise regression model to deeply explore the influence mechanism of alien plants from socioeconomic indicators and ecological factors. The results were as follows: (1) The existing alien plants in China belonging to large families (99 families, encompassing 13,741 species) and genera (205 genera, with 7,199 species) significantly contributed 93.41% and 48.94% to the total species number, respectively. Regarding life form composition, herbaceous plants dominated the alien plants in China, comprising 59.82% of the total. (2) Nationally, tropical component families held a significant advantage, accounting for 52.65% of the total families, followed by temperate families (21.56%) and cosmopolitan families (20.49%). (3) The distribution pattern of the total number of alien plants mirrored that of their floristic components, that is, the total number of alien plants and their floristic components were most abundant in the eastern coastal and southwestern regions, gradually decreasing inland in China. Notably, cosmopolitan and temperate families were more prevalent in northern provinces, whereas tropical families dominated southern regions. (4) Correlation analysis underscored a robust linear relationship between the number of invasive alien species and the total alien species within the same family. Socio-economic factors and climate conditions of various provinces and cities jointly determined the spatial distribution pattern of alien plants and floristic component family numbers in China. However, the proportion of each floristic component was mainly influenced by heat conditions (annual average temperature). In the future, China should vigorously strengthen the introduction assessment and supervision of alien plants, particularly the herbaceous plants of large families and genera with tropical characteristics and cosmopolitan distributions.

Keywords: alien plants, floristic component, species composition, diversity, distribution pattern

Introduction

Alien species refer to species, subspecies, or other reproductive units that occur outside their natural range and potential dispersal range, representing a concept relative to native plants within a specific region (Chen et al., 2021; Lin et al., 2022; Liu et al., 2022). When numerous alien species are introduced into new regions through intentional or unintentional human activities, establishing themselves in natural or semi-natural ecosystems and causing economic, ecological, or environmental harm to the recipient region, they are termed invasive alien species (Richardson et al., 2000; Pyšek et al., 2020; Chen et al., 2022). Between 1970 and 2017, the conservative annual economic cost of preventing and controlling alien species invasions worldwide exceeded hundreds of billions of dollars, with an upward trend (Diagne et al., 2021). Among these, alien plant invasions constitute the largest number and variety of global biological invasions, causing direct economic losses of $100.4 billion (Zhao et al., 2024) and posing severe threats to national economies, ecosystems, biodiversity, social environments, and human livelihoods—considered one of the most serious ecological threats of the 21st century (Pyšek et al., 2020; Liu et al., 2022; Chen et al., 2023; Kripal & Chaeho, 2023).

China' s unique geographical location, complex topography, diverse climate, and rich biodiversity, combined with rapid economic development and accelerated global economic integration, have made it one of the countries most severely affected and threatened by alien species invasions. Economic globalization and climate change are facilitating and intensifying the spread of invasive alien species (Fonseca et al., 2019; Li & Shen, 2020; Finch et al., 2021), with new alien species introductions continuing to increase, though growth trends vary by taxonomic group and geographic region (Pyšek et al., 2020). Among the more than 660 identified alien invasive species in China, over 90% were intentionally introduced or unintentionally brought in by humans (Chen et al., 2022), with natural dispersal being extremely rare. Habitat fragmentation and destruction of natural ecosystems have intensified alien species invasion pressures, leading to increasingly severe future biological invasion trends in China (Pyšek et al., 2017; Qin et al., 2023). After alien organisms enter new regions, climatic conditions and habitat heterogeneity in the new area are critical factors determining whether the species can adapt, survive, reproduce, disperse, and cause invasive harm (Zhou et al., 2020; Chen et al., 2021; Chen et al., 2022). Research indicates that combining climatic factors (annual mean temperature and precipitation) with socio-economic indicators better explains the distribution patterns of alien invasive plants in China, with warm, humid, and economically developed eastern coastal and southwestern regions harboring more invasive species than western and northern regions (Chen et al., 2021, 2023; Chen et al., 2022; Zhang et al., 2023; Yang et al., 2023). Over the past 80 years, the number of alien species in China' s coastal and southern regions has been steadily accumulating and has not yet reached saturation (Banerjee et al., 2024).

Plant flora represents a natural complex of plant families, genera, and species, reflecting evolutionary processes and responses to geological and climatic change histories (Lu et al., 2018; Liu et al., 2023). The floristic study of alien invasive plants has been a focal point in Chinese academia (Liu et al., 2022), with extensive research results at the provincial level (Hou et al., 2019; Xie et al., 2020; Song et al., 2021; Wan et al., 2022). Tropical components dominate the invasive plant flora in southern Chinese provinces at the family and genus levels, while temperate components increase significantly in northern provinces (Yin et al., 2023). Currently, research on the floristic characteristics and influencing factors of alien invasive plants in China has concentrated on smaller regional scales, primarily in economically developed coastal areas or southwestern regions (Chen et al., 2021, 2023). While analyses of the geographic distribution patterns and determinants of alien invasive plants nationwide have been relatively thorough (Chen et al., 2021; Chen et al., 2022; Zhang et al., 2023), studies on the spatial distribution patterns of floristic characteristics remain scarce. Wang et al. (2016) analyzed the floristic characteristics of alien invasive seed plants nationwide but did not elaborate on their influencing factors.

Currently, few studies focus on alien plants in China, primarily because comprehensive databases reflecting alien plant information are scarce (Lin et al., 2022). According to the broad concept of alien plants, they include cultivated, escaped, naturalized, and invasive plants, among which cultivated plants constitute the main body of alien plants in China (Lin et al., 2022). China' s large latitudinal span creates significant north-south differences, with some plants requiring greenhouse cultivation in the north but capable of open-field cultivation, naturalization, and even invasion in the south, thus cultivated plants still pose potential invasion risks. Many introduced alien plants escape from indoor cultivation into natural environments, with long lag times between initial establishment and full-scale invasion (Xie et al., 2001; Banerjee et al., 2024). Therefore, a clear understanding of alien plant floristic characteristics and their influencing factors is crucial for future alien plant introduction assessment and invasion prevention and control in China, and is significant for analyzing which floristic components of alien plants are more likely to become potential invaders. Based on the China Alien Plant Dataset, combined with data on China' s economic levels and climatic conditions, this study explores the following questions: (1) What are the species composition and floristic component characteristics of alien plants in China? (2) What are the spatial distribution characteristics of various floristic components? (3) What are the main influencing factors? The research results will help understand the species composition and evolution trends of alien invasive plants at regional scales (Wu et al., 2010; Yin et al., 2023) and provide guidance for reducing alien plant invasion risks and management efforts.

1. Data and Methods

1.1 Data Sources

The China Alien Plant Inventory was obtained from the published "Dataset of Alien Plants in China," encompassing 283 families, 3,233 genera, and 14,710 taxa (Lin et al., 2022). The China Alien Invasive Plant Inventory was derived from published data by Ma & Li (2018). Provincial socio-economic indicator averages from 1999 to 2022, including Gross Domestic Product (GDP), import trade value (IMP), number of inbound tourists (visitors), and urban green area (UGA), were obtained from the National Bureau of Statistics China Statistical Yearbook website (http://www.stats.gov.cn/sj/ndsj/). Natural ecological indicators, including annual mean temperature (Ta), annual mean precipitation (Pa), average temperature in January (T1), and average temperature in July (T7), were sourced from the China Meteorological Data Network National Meteorological Science Data Center website (http://data.cma.cn/).

Due to missing data such as urban green area in Hong Kong, Macao, and Taiwan regions, with Hong Kong and Macao having small areas and lacking accurate authoritative records, and limited survey data on alien plants, these regions were excluded from relevant regression analyses.

1.2 Data Processing

Following the distribution area classification principles for world seed plant families by Wu et al. (2003) and Wu et al. (2010), we classified the distribution area types of alien plant families in China. The 283 alien plant families in China can be divided into 47 distribution area types. Fern families were classified according to "Pteridophytes of China" (Wu and Qin, 1991). Since the origins of alien plants in China are global, and many taxa lack accurate authoritative records domestically, for unrecorded alien plant families, we used information from The World Flora Online (WFO, https://www.worldfloraonline.org/) for distribution area classification.

In the quantitative composition analysis of plant families and genera, family classification standards were: monotypic family (1 species), oligotypic family (2–5 species), medium family (6–10 species), larger family (11-20 species), and large family (21 species) (Yin et al., 2023). Among China' s 283 plant families, there are 53 monotypic families, 65 oligotypic families, 38 medium families, 28 larger families, and 99 large families. Genus classification standards were: monotypic genus (1 species), oligotypic genus (2–4 species), medium genus (5–8 species), larger genus (9–12 species), and large genus (>13 species) (Hou et al., 2019). The R/T ratio (tropical component families to temperate families) serves as an indicator for measuring floristic properties (Xin et al., 2017). Stepwise regression modeling was used to establish optimal regression models for economic levels and natural indicators (Chen et al., 2022; Chen et al., 2023; Zhang et al., 2023), with standardized regression coefficients used to quantify the explanatory power and direction of each factor on dependent variables. Excel 2010 software was used for data processing and analysis, ArcGIS 18.8.2 software for mapping distribution patterns, and Origin Pro for generating correlation heatmaps.

2. Results

2.1 Species Composition

2.1.1 Family Quantitative Composition As shown in Table 1 , although monotypic, oligotypic, medium, and larger families collectively accounted for 65.02% of total families, they contained only 5.59% of total species. In contrast, the 99 large families contributed 93.41% of total species. Large families such as Orchidaceae (263 genera, 1,174 species), Cactaceae (142 genera, 1,173 species), Fabaceae (200 genera, 662 species), Asteraceae (214 genera, 597 species), Bromeliaceae (63 genera, 588 species), Arecaceae (153 genera, 500 species), Crassulaceae (29 genera, 494 species), Euphorbiaceae (26 genera, 489 species), Asphodelaceae (25 genera, 480 species), Aizoaceae (94 genera, 432 species), Apocynaceae (86 genera, 422 species), Myrtaceae (42 genera, 410 species), Asparagaceae (58 genera, 404 species), Poaceae (110 genera, 343 species), Rosaceae (44 genera, 274 species), Lamiaceae (56 genera, 241 species), and Araceae (47 genera, 238 species) each contained more than 200 species. These 17 families collectively comprised 1,652 genera and 8,921 alien species, representing 51.10% of total genera and 60.65% of total species, with Orchidaceae and Cactaceae alone containing 1,174 and 1,173 alien species, respectively.

2.1.2 Genus Quantitative Composition As shown in Table 2 , China' s alien plant flora includes 1,579 monotypic genera, accounting for 48.84% of total genera but contributing only 10.73% of total species. Oligotypic genera totaled 998, representing 30.87% of total genera and containing 2,606 alien species (17.72% of total species). Medium genera comprised 321 taxa (9.93% of total genera) with 1,965 species (13.36% of total species). Larger genera were the least numerous with only 130 genera (4.02% of total) containing 1,361 species. Large genera totaled 205, representing just 6.34% of total genera but containing 7,199 species–48.94% of total species, representing the highest contribution rate. Among large genera, Euphorbia (436 species), Eucalyptus (262 species), Aloe (214 species), Mammillaria (142 species), Hoya (141 species), Haworthia (140 species), Dendrobium (133 species), Agave (126 species), Conophytum (120 species), Tillandsia (119 species), Aechmea (119 species), Begonia (117 species), Nepenthes (100 species), Crassula (99 species), Oxalis (85 species), Echeveria (75 species), and Echinopsis (70 species) collectively contained 2,498 alien species, accounting for 16.98% of total species.

2.1.3 Functional Type Composition As shown in Figure 1 [Figure 1: see original paper], when classified by life cycle, annual to biennial plants (ABP) comprised 61 families, 366 genera, and 819 species, representing 21.55%, 11.32%, and 5.57% of totals, respectively. Annual/biennial to perennial plants (APP) included 49 families, 168 genera, and 266 species (17.31%, 5.20%, and 1.81%, respectively). Perennial plants (PP) were the most numerous, with 277 families, 2,965 genera, and 13,625 species (97.87%, 91.71%, and 92.62%, respectively). When classified by life form, China' s alien herbaceous plants comprised 147 families, 1,745 genera, and 8,800 species, representing 51.94%, 53.97%, and 59.82% of totals, respectively, making them the dominant component of alien plants. Trees totaled 109 families, 255 genera, and 633 species (4.30% of total species), including 34 families, 119 genera, and 336 species of herbaceous vines, and 53 families, 145 genera, and 297 species of woody vines. Alien aquatic plants (AP) comprised 51 families, 115 genera, and 272 species (1.85% of total species).

2.2 Floristic Components of Alien Plant Families in China

As shown in Table 3 , tropical floristic component families held absolute dominance nationwide, encompassing 27 types with 149 families (52.65% of total families). Among these, pantropic distribution type comprised 62 families (21.91% of total), representing the highest proportion. Type 3 included 16 families (5.65%), while type 2S contained 14 families (4.95%), with other tropical component types containing 7-1 families each. Temperate component floristic types totaled 17 categories with 61 families (21.56%). Type 8-4 comprised 19 families (6.71% of total), while types 9 and 8 included 11 and 10 families (3.89% and 3.53%, respectively), with other temperate component types containing 8-1 families each. Cosmopolitan distribution ranked third with 58 families (20.49% of total). Types (16) and (17) collectively comprised 15 families (5.30% of total). The R/T ratio of 2.44 indicates that China' s alien plant families are predominantly tropical in nature.

2.3 Spatial Distribution Patterns of Alien Plant Floristic Components

The spatial distribution characteristics of total alien plant numbers (NAP) and family floristic components are illustrated in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper]. Nationally, cosmopolitan, tropical, temperate, and other component families exhibited similar distribution patterns, being most abundant in eastern coastal and southwestern regions and decreasing inland. Jiangsu, Zhejiang, Fujian, and Taiwan provinces along the eastern coast, and Yunnan and Sichuan provinces in the southwest contained the highest numbers of families across all floristic components. Yunnan Province had 51 cosmopolitan, 113 tropical, and 41 temperate families, while Taiwan Province had 50, 118, and 49 families respectively, making these the most floristically rich regions nationally (Figure 2: a–c). In contrast, Inner Mongolia, Ningxia, and Qinghai had the lowest floristic richness across all components. Notably, Hebei Province and Beijing also exhibited rich alien plant floristic components, particularly Beijing with 48 cosmopolitan, 94 tropical, 44 temperate, and 9 other component families (Figure 2).

NCF: Number of cosmopolitan families; NTrop.F: Number of tropical families; NTemp.F: Number of temperate families; NOF: Number of other families. The same below.

The distribution pattern of alien plants in China supported that of family floristic components (Figure 3: a), being most abundant in eastern coastal and southwestern regions and decreasing inland. The richest regions for alien plants were Taiwan (6,211 species), Beijing (5,244 species), Fujian (3,667 species), Guangdong (3,544 species), and Yunnan (3,404 species), while the poorest regions were Inner Mongolia (2 species), Qinghai (70 species), Tibet (84 species), and Ningxia (95 species). As shown in Figure 3: b, Hainan and Guangxi had the highest R/T values at 8.63 and 4.73, respectively, with Chongqing (3.9), Gansu (3.5), Hunan (3.5), Guangdong (3.3), and Fujian (3.0) also exceeding 3. The lowest R/T values occurred in Shandong (1.07), Hubei (1.17), Qinghai (1.25), Xinjiang (1.3), and the three northeastern provinces. Regarding the proportion of alien plant family floristic components, cosmopolitan families had the highest proportions in northern and central-western provinces, such as Inner Mongolia (100%), Tibet (63.33%), Shanxi (58.06%), Qinghai (57.14%), and Henan (51.35%). In contrast, proportions were lower in Fujian (21.79%), Taiwan (22.03%), Yunnan (23.94%), Beijing (24.62%), and Shanghai (24.85%) (Figure 3: c). Tropical component families had the highest proportions in southeastern coastal and southwestern regions, including Hainan (62.73%), Guangxi (56.35%), Fujian (55.31%), Guangdong (52.94%), Taiwan (51.98%), Chongqing (53.42%), and Yunnan (53.05%), while proportions were lowest in Inner Mongolia (0%), Qinghai (23.81%), Tibet (26.67%), and Shanxi (29.03%) (Figure 3: d). Temperate component families had the highest proportions in Jilin (29.63%), Hubei (29.51%), Liaoning (28.99%), Shandong (28.3%), and Xinjiang (27.03%) (Figure 3: e). Other types had the highest proportions in Guangdong (5.88%), Guangxi (5.56%), Beijing (4.62%), Hainan (4.55%), and Fujian (4.47%) (Figure 3: f).

NAP: Number of alien plants; PCF: Proportion of cosmopolitan families; PTrop.F: Proportion of tropical families; PTemp.F: Proportion of temperate families; others: Proportion of other components. The same below.

2.4 Correlation Analysis Between Alien and Invasive Plants in China

As shown in Figure 4 [Figure 4: see original paper], a significant positive correlation exists between the number of alien species and the number of invasive species within the same family (R^{2} = 0.4, P < 0.001), indicating that families with higher alien species diversity contain more invasive species. Species-rich families such as Asteraceae, Fabaceae, Poaceae, and Euphorbiaceae—super-large families—contained the most invasive plant species, with 85, 60, 54, and 22 species respectively (Ma & Li, 2018).

Data in brackets indicate alien species number and invasive species number, respectively.

2.5 Analysis of Influencing Factors on Alien Plant Floras

As shown in Figure 5 [Figure 5: see original paper], total alien plant numbers, introduced plants, naturalized plants, invasive plants, and floristic component family numbers across provinces and municipalities all showed significant positive correlations with economic indicators such as import trade and inbound tourist numbers. Annual mean import trade value exhibited the highest explanatory power for total alien plant numbers and introduced plant numbers, with correlation coefficients of 0.673 ($P < 0.001$) and 0.683 ($P < 0.001$), respectively, indicating that higher economic levels, more frequent foreign trade, and greater numbers of inbound tourists result in more alien species introduced through trade and unintentional human transport, and more complex floristic components. Urban green area showed significant positive correlations with total alien plant numbers, naturalized plants, and invasive plants, suggesting that urban green spaces provide habitats for alien plant establishment, escape, and invasion. Among natural factors, January mean temperature, annual mean temperature, and annual mean precipitation all showed significant positive correlations with naturalized plants, invasive plants, cosmopolitan families, and tropical families, indicating that better water and heat conditions, particularly winter temperatures, support more alien plants across all floristic components, with larger proportions of tropical floristic plants and richer other components. However, the proportion of cosmopolitan families showed significant negative correlations with total alien plant numbers and water-heat conditions across provinces.

As shown in Table 4 , stepwise regression analysis identified three significant influencing factors—import trade value, urban green area, and annual mean precipitation—to establish optimal models, with high explanatory power for total alien plant numbers and introduced alien plant numbers (R^{2} = 0.656 and 0.666, respectively). Annual mean precipitation and import trade value were the main influencing factors for naturalized and invasive plants, with optimal model R^{2} values of 0.550 and 0.525, respectively. Import trade value also significantly influenced the numbers of cosmopolitan families (0.397, $P < 0.05$), tropical families (0.571, $P < 0.001$), and temperate families (0.577, $P < 0.001$). Among natural factors, annual mean precipitation (0.435, $P < 0.01$) affected cosmopolitan family numbers, while annual mean temperature (0.777, $P < 0.001$) and July mean temperature (-0.474, $P < 0.05$) influenced tropical family numbers. Annual mean temperature was a key influencing factor for the proportions of cosmopolitan and tropical families, with standardized coefficients of -0.592 ($P < 0.001$) and 0.708 ($P < 0.001$), respectively.

3. Discussion

3.1 Species Composition Characteristics of Alien Plants in China

China has introduced a rich diversity of alien plants, with large families showing significant dominance at both family and species levels, contributing 34.98% of total families and 93.41% of total species. Notably, Orchidaceae and Cactaceae each exceed 1,000 species, likely related to extensive introduction of indoor ornamental plants (horticultural and floral species). Oligotypic families also represent a relatively high proportion (22.97%) but contribute only 0.38% of total species. Monotypic and oligotypic genera dominate at the genus level, collectively accounting for 79.67% of total genera, while large genera show clear dominance in total species, contributing 48.94% of total species, indicating pronounced differences in dominance among families and genera within China’ s alien plant flora.

Herbaceous plants constitute the main body of alien plants in China, with annual and biennial herbs being predominant, consistent with existing research (Li & Shen, 2020). Life form represents the result of long-term plant adaptation to environmental conditions during evolution and reflects comprehensive regional physical geography (Li et al., 1981; Zhang, 2003). Herbaceous plants possess stronger environmental adaptability than woody plants (Li et al., 1981). Annual or biennial ephemeral plants exhibit clear advantages in r-life history strategies, typically featuring strong reproductive capacity and seed dispersal ability (Zhang and Xiao, 2013; Hou et al., 2019), as exemplified by invasive plants such as Alternanthera philoxeroides, Solidago canadensis, and Erigeron annuus. This study demonstrates that alien plant families with higher species diversity contain more invasive species, with super-large families such as Asteraceae, Fabaceae, Poaceae, and Euphorbiaceae harboring the most invasive plant species. Previous provincial-scale studies have shown that Asteraceae, Fabaceae, and Poaceae constitute the main body of invasive plants (Hou et al., 2019; Song et al., 2021; Wan et al., 2022; Yin et al., 2023), with these families being predominantly herbaceous, consistent with our findings. Herbaceous plants account for 59.82% of alien plants in China and have been extensively introduced intentionally as forage, ornamentals, fiber plants, vegetables, and turfgrass, further increasing the potential risk of alien plant invasion and becoming a significant environmental issue.

3.2 Floristic Characteristics of Alien Plant Families in China

In terms of family floristic components, China’ s alien plant flora comprises 13 types and 34 variants, representing a relatively complex distribution pattern. Tropical component families hold clear dominance with 149 families (52.61% of total), among which pantropic distribution type (62 families, 21.91%) shows the highest proportion. Temperate component families rank second with 62 families (21.91%), followed by cosmopolitan distribution type (58 families, 20.49%). These results align with findings on tropical floristic components of invasive plants in China (Ma & Li, 2018), which identified 70 invasive plant families divided into 9 distribution area types, with tropical component families comprising 35 families (50% of total), including 20 pantropic families (28.57%). However, cosmopolitan invasive plant families totaled 29 (41.43% of total), higher than the proportion for alien plants overall. Temperate component families successfully invading China represented the smallest proportion at 8.57%, showing substantial differences from the proportion of temperate components among alien plants. Large families such as Asteraceae, Fabaceae, Poaceae, Amaranthaceae, and Solanaceae are all cosmopolitan families with broad adaptability. Invasive plants possess strong invasion capabilities, including traits such as large leaf area, high photosynthetic rates, nitrogen utilization efficiency, water use efficiency, growth rate, small seed mass, strong adaptability, and allelopathic effects (van Kleunen et al., 2010; Mathakutha et al., 2019; Zhang et al., 2021). Asteraceae species are predominantly herbaceous with small, numerous seeds (achenes) featuring pappus or spine structures that significantly enhance dispersal (Quan et al., 2018). Some Asteraceae species exhibit high stress tolerance and phenotypic plasticity (Davidson et al., 2011; Wang et al., 2022); for example, Chromolaena odorata shows strong drought resistance (Li et al., 2022), while Bidens frondosa, Bidens pilosa, and Parthenium hysterophorus demonstrate high phenotypic plasticity in response to light, water, and nutrients (Pu et al., 2010; Wei et al., 2017; Pan et al., 2017). Fabaceae species possess extensive root systems and nitrogen-fixing capabilities (Lu et al., 2023), providing strong adaptability. Poaceae species enhance invasiveness by increasing specific leaf area and light utilization efficiency (Xu et al., 2022a,b). Among pantropic families, Euphorbiaceae, Malvaceae, Acanthaceae, Balsaminaceae, and Araceae contain numerous alien plants and varying numbers of invasive plants, with Euphorbiaceae having the most alien invasive species (22 species). Euphorbiaceae is primarily distributed in tropical and subtropical regions, possesses significant economic and ornamental value, and has been introduced to China in large numbers and over a long history, including invasive herbaceous species such as Euphorbia cyathophora, E. hirta, E. hypericifolia, and Ricinus communis (Ma & Li, 2018).

Regarding the proportions of alien plant floristic components, clear spatial differences exist across regions. Northern and central-western provinces show higher proportions of cosmopolitan families, while southeastern coastal and southwestern regions have higher proportions of tropical families, and northern coastal provinces have the highest proportions of temperate families. Previous studies have demonstrated that heat levels are important factors affecting the invasion success of tropical component plants (Chen et al., 2021, 2023; Qin et al., 2023; Yang et al., 2023). Provinces with larger tropical and subtropical climate proportions have higher proportions of invasive plant tropical component families, such as Jiangsu (84.62%), Chongqing (47.36%), and Yunnan (50.85%). Conversely, Shandong, Henan, and Heilongjiang have higher proportions of temperate plant genera at 36.60%, 34.13%, and 68.00%, respectively (Yin et al., 2023).

3.3 Influencing Factors on Total Alien Plant Numbers, Floristic Characteristics, and Spatial Patterns

This study reveals that total alien plant numbers, total family numbers, and family numbers of all floristic components in China exhibit similar distribution patterns—most abundant in eastern coastal, southern, and southwestern regions and decreasing inland—mirroring the distribution patterns of alien invasive organisms (Chen et al., 2022, 2023; Yang et al., 2023). Regions with higher socio-economic levels and better climatic conditions have the highest alien plant richness. Climate (annual mean temperature and precipitation) combined with socio-economic indicators better explains these distribution patterns (Zhang et al., 2023; Chen et al., 2023; Yang et al., 2023). Large-scale studies have shown that alien species richness is closely related to socio-economic factors and human activities such as GDP, population density, and international trade (Fonseca et al., 2019; Zhang et al., 2023; Yang et al., 2023). China' s eastern coastal, southern, and southwestern provinces have higher GDP, urbanization levels, and population size and density than northwestern and northern inland regions (Luo et al., 2018). For example, Guangdong Province has been a key region for international trade since the 19th century (Croddy, 2022) and is China' s richest region in alien plants. This study' s finding of extremely significant positive correlations between total alien plant numbers—especially introduced plants—and socio-economic indicators such as import trade value and inbound tourist numbers supports these conclusions. Research also indicates that alien plants in China' s coastal and southern regions have been steadily accumulating over the past 80 years and have not yet reached saturation (Banerjee et al., 2024). Economically developed regions with large international trade volumes and high disturbance levels facilitate alien plant dispersal to new areas, where climatic conditions determine whether species can adapt, survive, reproduce, disperse, and cause invasive harm (Chen et al., 2021; Chen et al., 2022).

China' s eastern coastal, southern, and southwestern regions have tropical or subtropical climates similar to those of tropical America—the primary origin of China' s alien plants (Lin et al., 2022). Climate similarity between origin and introduction regions facilitates alien plant reproduction, dispersal, naturalization, and invasion, making these regions hotspots for alien plant invasion.

Notably, some economically developed but cold northern regions, such as Beijing (5,244 species), also have rich alien plant diversity. In these areas, diverse alien plants can be cultivated using various greenhouse facilities, making alien plant numbers more closely related to local economic, social, and horticultural development levels (Lin et al., 2022). Studies have shown that reports of alien invasive plants in northern China and some inland major cities have been increasing over the past 50 years, gradually becoming hotspots for alien plant invasion (Qin et al., 2023; Banerjee et al., 2024), a trend possibly related to high ecosystem sensitivity to climate change (Hu et al., 2023) and rapid land-use changes in these regions (Zhu et al., 2022).

In summary, China has a rich diversity of alien plants, with herbaceous plants being particularly prominent and constituting the main body of alien plants. Tropical component families dominate the flora with 149 families (52.65% of total), among which pantropic distribution type (21.91%) shows the highest proportion. China' s eastern coastal, southern, and southwestern regions with higher socio-economic levels and better climatic conditions have the richest alien plant diversity, and provinces with higher heat levels have larger proportions of tropical components. Therefore, management and control efforts should be continuously strengthened in the most alien plant-rich regions, particularly eastern coastal and southwestern provinces. Introduction assessment and escape monitoring should be vigorously enhanced for herbaceous plants from large families and genera with tropical characteristics and cosmopolitan distributions, with controlled introduction quantities. In northern economically developed regions, invasion risk assessment and potential invasion range studies should be further strengthened to develop lists of potential invasive plants, while controlling introductions of cosmopolitan and temperate component plants to reduce the probability of successful invasion following escape.

References

BANERJEE AK, FENG H, BHOWMICK AR, et al., 2024. Alien flora are accumulating steadily in China over the last 80 years [J]. iScience, 27(4): 109952.

CHEN J, MA FZ, ZHANG YJ, et al., 2021. Spatial distribution patterns of invasive alien species in China [J]. Global Ecology and Conservation, 26: e01432.

CHEN J, ZHANG YJ, LIU W, et al., 2023. Distribution patterns and determinants of invasive alien plants in China [J]. Plants, 12: 2341.

CHEN XL, NING DD, XIAO Q, et al., 2022. Factors affecting the geographical distribution of invasive species in China [J]. Journal of Integrative Agriculture, 21(4): 1116-1125.

CRODDY E, 2022. Guangdong Province [M]// CRODDY E. China' s provinces and populations: a chronological and geographical survey. Berlin: Springer International Publishing: 165-198.

DAVIDSON AM, JENNIONS M, NICOTRA AB, 2011. Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis [J]. Ecology Letters, 14(4): 419-431.

DIAGNE C, LEROY B, VAISSIERE A, et al., 2021. High and rising economic costs of biological invasions worldwide [J]. Nature, 608(7924): 571-576.

FINCH DM, BUTLER JL, RUNYON JB, et al. 2021. Effects of climate change on invasive species [M]// POLAND TM, PATEL-WEYNAND T, FINCH DM, et al. Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector. Berlin: Springer International Publishing: 57-83.

FONSECA R, BOTH C, CECHIN SZ, 2019. Introduction pathways and socio-economic variables drive the distribution of alien amphibians and reptiles in a megadiverse country [J]. Diversity and Distributions, 25(7): 1130-1141.

HOU XX, XIN JP, LU MT, et al., 2019. Analysis of flora, life form and reproductive characteristics of alien species in Jiangsu Province [J]. Chinese Journal of Ecology, 38(9): 1982-1990. [Hou Xinxing, Xin Jianpan, Lu Mengting, et al., 2019. Flora, life form and reproductive characteristics of alien invasive plants in Jiangsu Province [J]. Chinese Journal of Ecology, 38(9): 1982-1990.]

HU Y, WEI F, FU B, et al., 2023. Ecosystems in China have become more sensitive to changes in water demand since 2001 [J]. Communications Earth & Environment, 4: 444.

KRIPAL S, CHAEHO B, 2023. Ecological restoration after management of invasive alien plants [J]. Ecological Engineering, 197: 107122.

LI WT, ZHENG YL, WANG RF. 2022. Extension of the EICA hypothesis for invasive Chromolaena odorata [J]. Acta Oecologica, 114: 103803.

LI XX, ZHOU ZY, GUO SX, 1981. The development and evolution of the plants [M]. Beijing: Science Press: 40-50. [Li Xingxue, Zhou Zhiyan, Guo Shuangxing, 1981. The development and evolution of plants [M]. Beijing: Science Press: 40-50.]

LI YY, SHEN ZH. 2020. Roles of dispersal limit and environmental filtering in shaping the spatiotemporal patterns of invasive alien plant diversity in China [J]. Frontiers in Ecology and Evolution, 8: 544670.

LIU Y, XU X, DIMITROV DP, et al., 2023. An updated floristic map of the world [J]. Nature Communications, 14: 2990.

LIN QW, XIAO C, MA JS, 2022. A dataset on catalogue of alien plants in China [J]. Biodiversity Science, 30(5): 22127. [Lin Qinwen, Xiao Cui, Ma Jinshuang, 2022. A dataset on catalogue of alien plants in China [J]. Biodiversity Science, 30(5): 22127.]

LIU YJ, HUANG W, YANG Q, et al., 2022. Research advances of plant invasion ecology over the past 10 years [J]. Biodiversity Science, 30(10): 22438. [Liu Yanjie, Huang Wei, Yang Qiang, et al., 2022. Research advances of plant invasion ecology over the past 10 years [J]. Biodiversity Science, 30(10): 22438.]

LUO T, XU M, HUANG TT, et al., 2018. Rethinking the intensified disparity in urbanization trajectory of a Chinese coastal province and its implications [J]. Journal of Cleaner Production, 195: 1523-1532.

LU LM, MAO LF, YANG T, et al., 2018. Evolutionary history of the angiosperm flora of China [J]. Nature, 554: 234-238.

LU BF, KANG WJ, SHI SL, et al., 2023. Nitrogen fixation system of Legume-Rhizobia and its Carbon-Nitrogen interaction [J]. Chinese Journal of Grassland, 45(11): 119-135. [Lu Baofu, Kang Wenjuan, Shi Shangli, et al., 2023. Nitrogen fixation system of Legume-Rhizobia and its Carbon-Nitrogen interaction [J]. Chinese Journal of Grassland, 45(11): 119-135.]

MA JS, LI HR, 2018. The checklist of the alien invasive plants in China [M]. Beijing: Higher Education Press: 2-176. [Ma Jinshuang, Li Huiru, 2018. The checklist of the alien invasive plants in China [M]. Beijing: Higher Education Press: 2-176.]

MATHAKUTHA R, STEYN C, ROUX PCL, et al., 2019. Invasive species differ in key functional traits from native and non-invasive alien plant species [J]. Journal of Vegetation Science, 30(5):

PAN YM, TANG SC, WEI CQ, et al., 2017. Comparison of growth, photosynthesis and phenotypic plasticity between invasive and native Bidens species under different light and water conditions [J]. Biodiversity Science, 25(12): 1257-1266. [Pan Yumei, Tang Saichun, Wei Chunqiang, et al., 2017. Comparison of growth, photosynthesis and phenotypic plasticity between invasive and native Bidens species under different light and water conditions [J]. Biodiversity Science, 25(12): 1257-1266.]

PU TZ, TANG SC, PAN YM, et al., 2010. Phenotypic plasticity and modular biomass of invasive Parthenium hysterophorus in different habitats in south China [J]. Guihaia, 30(5): 641-646. [Pu Gaozhong, Tang Saichun, Pan Yumei, et al., 2010. Phenotypic plasticity and modular biomass of invasive Parthenium hysterophorus in different habitats in south China [J]. Guihaia, 30(5): 641-646.]

PYŠEK P, PERGL J, ESSL F, et al., 2017. Naturalized alien flora of the world: species diversity, taxonomic and phylogenetic patterns, geographic distribution and global hotspots of plant invasion [J]. Preslia, 89(3): 203-274.

PYŠEK P, HULME PE, SIMBERLOFF D, et al., 2020. Scientists' warning on invasive alien species [J]. Biological Reviews, 95: 1511-1534.

QIN F, HAN BC, BUSSMANN RW, et al., 2023. Present status, future trends, and control strategies of invasive alien plants in China affected by human activities and climate change [J]. e06919.

QUAN W, WANG M, SANG WG, 2018. Selection of simulation models for seed dispersal of invasive plants by wind [J]. Chinese Journal of Ecology, 37(9): 2840-2848. [Quan Wei, Wang Ming, Sang Weiguo, 2018. Selection of simulation models for seed dispersal of invasive plants by wind [J]. Chinese Journal of Ecology, 37(9): 2840-2848.]

RICHARDSON DM, PYSEK P, REJMANEK M, et al., 2000. Naturalization and invasion of alien plants: concepts and definitions [J]. Diversity and Distributions, 6(2): 93-107.

SONG XJ, ZHANG WG, CHEN XY, et al., 2021. The composition and distribution status of alien plant species in Shaanxi Province, China [J]. Chinese Journal of Ecology, 40(12): 3800-3809. [Song Xingjiang, Zhang Wengang, Chen Xiaoyan, et al., 2021. The composition and distribution status of alien plant species in Shaanxi Province, China [J]. Chinese Journal of Ecology, 40(12): 3800-3809.]

VAN KLEUNEN M, WEBER E, FISCHER M, 2010. A meta-analysis of trait differences between invasive and non-invasive plant species [J]. Ecology Letters, 13(2): 235-245.

WAN ZX, LIU C, ZHANG ZY, et al., 2022. Current situation and control of alien plant invasion in the Hunan region of the Yangtze River Economic Belt [J]. Journal of Biosafety, 31(3): 235-244. [Wan Zixue, Liu Chuan, Zhang Zhengyun, et al., 2022. Current situation and control of alien plant invasion in the Hunan region of the Yangtze River Economic Belt [J]. Journal of Biosafety, 31(3): 235-244.]

WANG CT, LIU J, XIAO HG, et al., 2016. Floristic characteristics of alien invasive seed plant species in China [J]. Anais da Academia Brasileira de Ciências, 88(3 Suppl.): 1791-1797.

WEI C, TANG S, PAN Y, et al., 2017. Plastic responses of invasive Bidens frondosa to water and nitrogen addition [J]. Nordic Journal of Botany, 35(2): 232-239.

WU ZH, QIN RC, 1991. Pteridophytes of China [M]. Beijing: Science Press: 147, 410. [Wu Zhaohong, Qin Renchang, 1991. Pteridophytes of China [M]. Beijing: Science Press: 147, 410.]

WU ZY, SUN H, ZHOU ZK, et al., 2010. Floristics of Seed Plants from China [M]. Beijing: Science Press: 52-55. [Wu Zhengyi, Sun Hang, Zhou Zhekun, et al., 2010. Floristics of Seed Plants from China [M]. Beijing: Science Press: 52-55.]

WU ZY, ZHOU ZK, LI DZ, et al., 2003. The Areal-types of the World Families of Seed Plants [J]. Acta Botanica Yunnanica, 25(3): 245-257. [Wu Zhengyi, Zhou Zhekun, Li Dezhu, et al., 2003. The Areal-types of the World Families of Seed Plants [J]. Acta Botanica Yunnanica, 25(3): 245-257.]

XIE Y, LI ZY, GREGG WP, et al., 2001. Invasive species in China - an overview [J]. Biodiversity and Conservation, 10(8): 1317-1341.

XIE Y, XU YF, YOU JR, et al., 2020. Species composition, flora and invasion hazard of alien plants in Huangjinhe National Wetland Park [J]. Chinese Journal of Ecology, 39(11): 3613-3622. [Xie Yong, Xu Yongfu, You Jianrong, et al., 2020. Species composition, flora and invasion hazard of alien plants in Huangjinhe National Wetland Park [J]. Chinese Journal of Ecology, 39(11): 3613-3622.]

XIN JP, SUN XX, TIAN RN. 2017. Floristic diversity and fundamental characteristics of seed plants on Mount Jiangjun, Nanjing [J]. Journal of Zhejiang A&F University, 34(4): 629-636. [Xin Jianpan, Sun Xinxin, Tian Runan. 2017. Floristic diversity and fundamental characteristics of seed plants on Mount Jiangjun, Nanjing [J]. Journal of Zhejiang A&F University, 34(4): 629-636.]

XU X, ZHANG Y, LI S, et al., 2022a. Native herbivores indirectly facilitate the growth of invasive Spartina in a eutrophic saltmarsh [J]. Ecology, 103: 3610.

XU X, ZHOU C, HE Q, et al., 2022b. Phenotypic plasticity of light use favors a plant invader in nitrogen-enriched ecosystems [J]. Ecology, 103: 3665.

YANG YB, BIAN ZH, REN WJ, et al., 2023. Spatial patterns and hotspots of plant invasion in China [J]. Global Ecology and Conservation, 43: e2424.

YIN GS, ZHANG SS, CHEN WL, et al., 2023. Analysis on the floristics and diversity of invasive alien plants in Yunnan Province [J]. Journal of Biosafety, 32(1): 16-24. [Yin Genshen, Zhang Shuangshuang, Cheng Wenlei, et al., 2023. Analysis on the floristics and diversity of invasive alien plants in Yunnan Province [J]. Journal of Biosafety, 32(1): 16-24.]

ZHANG D. 2003. Plant life history evolution and reproductive ecology [M]. Beijing: Science Press: 3-7. [Zhang Dayong. 2003. Plant life history evolution and reproductive ecology [M]. Beijing: Science Press: 3-7.]

ZHANG JP, MIAO L, WU PL, et al., 2023. Effects of anthropogenic activities and climate factors on the distribution of invasive alien species in China [J]. Scientia Sinica Vitae, 53(4): 543-550. [Zhang Jiping, Miao Lu, Wu Panlong, et al., 2023. Effects of anthropogenic activities and climate factors on the distribution of invasive alien species in China [J]. Scientia Sinica Vitae, 53(4): 543-550.]

ZHANG SS, XIAO YA. 2013. Life-form and diversity of sexual system of invasive alien plants in China [J]. Bulletin of Botanical Research, 33(3): 351-359. [Zhang Sisi, Xiao Yi' an. 2013. Life-form and diversity of sexual system of invasive alien plants in China [J]. Bulletin of Botanical Research, 33(3): 351-359.]

ZHANG Z, LIU Y, YUAN L, et al., 2021. Effect of allelopathy on plant performance: a meta-analysis [J]. Ecology Letters, 24(2): 348-362.

ZHAO GH, GAO ML, WANG D, et al., 2024. Economic cost assessment of global invasive plants [J]. Acta Prataculturae Sinica, 33(5): 16-24. [Zhao Guanghua, Gao Minglong, Wang Duo, et al., 2024. Economic cost assessment of global invasive plants [J]. Acta Prataculturae Sinica, 33(5): 16-24.]

ZHOU QL, WANG L, JIANG Z, et al., 2020. Effects of climatic and socialactors on dispersal strategies of alien species across China [J]. Science of the Total Environment, 749: 141443.

ZHU Z, ZHANG Z, ZHAO X, et al., 2022. Characteristics of land use change in China before and after 2000 [J]. Sustainability, 14: 14623.

Note: Figure translations are in progress. See original paper for figures.