Geographical distribution and determining factors of different invasive ranks of alien species across China

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Authors' contributions

LW, SD, and QZ conceived the ideas and designed the methodology; SD and LW contributed to the ideas on the writing and edited the manuscripts; XL and XC collected the data; YW and ZL analyzed the data; and QZ led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication. The authors declare no conflicts of interest.

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

The species density of alien species increased from the northwest to the southeast regions of China.

Climatic and social factors affecting species density distribution were determined

Life-form spectra traits of various invasive alien species were found

Geographical distribution and determining factors of different invasive ranks of alien species across China

Abstract

Determination of the geographical distribution and life-form spectra of alien species with different invasive abilities are essential to understand the process of invasion and to develop measures to manage alien species. Based on six classifications of Chinese alien species, environmental and social data, species density, life-form spectrum of alien species, and the relationship between species density of alien species and climatic or social factors were determined. The species density of alien species increased from the northwest to the southeast regions of China for all the six ranks. The boundary line between low and high species density of alien species was consistent with the dividing line of population density (the "Hu Line"). Mean annual precipitation was the most important factor for species density in malignant invaders, serious invaders, local invaders, and species requiring further observation (Ranks I, II, III, and V, respectively). Gross domestic product per square kilometer and annual minimum temperature were the most important factors in mild invaders and cultivated aliens (Ranks IV and VI, respectively). Annual and biennial herbs made up 52.9% to 71.2% of total species in Ranks I to IV; shrubs and trees 3.7% to 14.7%. The annual and biennial herbs were 35.5% and 32.6%, and the shrubs and trees were 25.3% and 31.6% in Ranks IV and VI. Results implied that precipitation was the most important factor on species density for the invasive alien species. However, social factors and temperature were the most important factors for the non-invasive alien species. The invasive alien species had a high proportion of annual and biennial herbs and non-invasive alien had a high proportion of shrubs and trees. It is important to understand the geographical distribution and life-form spectra of various invasive alien species for alien species controls.

Key-words: classification; climatic factors; “Hu Line”; invasive ranks; life-form spectra; social factors

1. Introduction

Noxious alien invasive plants have attracted extensive attention owing to their significant threats to biodiversity, environment, and economies at local, regional, and global scales (Çelik and Gulersoy, 2014; Feng and Zhu, 2010; Liu et al., 2006; Liu et al., 2005; Majewska et al., 2018; Smith, 2016; Thapa et al., 2018; Thuiller et al., 2005; Xie et al., 2001). Alien species in China are those with origins outside China and that have been introduced into China either intentionally or accidentally (Jiang et al., 2011). China has a long history of accidental or deliberate introduction of exotic plant species via international trade (Liu et al., 2005). The country has a huge territory area (more than 9.6 million km^2), spanning 52° in longitude and 50° in latitude, which supplies favorable habitats for alien species (Feng and Zhu, 2010). Alien species have more opportunities to naturalize, establish stable populations, expand their living space, and to compete for resources with native species (Jiang et al., 2011; Milbau and Stout, 2008). Therefore, studying the regional distribution and life-form spectra of alien species is essential to understand the process of invasion and to develop management measures.

Some alien invasive species have caused huge ecological and economic losses worldwide; however, not all alien species are noxious (Xie et al., 2001). According to *The Checklist of the Chinese Invasive Plants* (Ma and Li, 2018), 562 alien species have been recorded in China. Ma et al. (2018) classified Chinese alien species into the following six invasive ranks: malignant invaders, serious invaders, local invaders, mild invaders, species requiring further observation, and cultivated aliens based on their harm to the ecological environment and economic development, biological characteristics, and geographical distribution range (Ma and Li, 2018). Although previous studies have been conducted on the geographical distribution of several reported invasive species (Chen et al., 2017; Feng et al., 2011; Feng and Zhu, 2010; Liu et al., 2005; Pan et al., 2015) or a single species (Liu et al., 2016; Wang et al., 2016b), these studies have failed to show the complete characteristics of alien species distribution by considering a difference in their invasive ranks. In addition, even though relationships between natural and social factors and distribution patterns have been reported (Chen et al., 2017; Liu et al., 2005; Pan et al., 2015), factors that are the most important in influencing the distribution of different ranks of invasive alien species have not been fully examined.

A plant life-form is characterized by the adaptation of plants to their environmental conditions (Batalha and Martins, 2002; Weber et al., 2008). Whether a naturalized alien plant can adapt to a new environment largely depends on its life-form type (Weber et al., 2008). A life-form spectrum is the simplest and most conclusive classification scheme for characterizing adaptations of a group of plants in favorable seasons (Batalha and Martins, 2004; Weber et al., 2008). Therefore, the life-form spectra of alien species in different invasive ranks may reflect the characteristics of their adaptation to a new environment (Chen et al., 2017; Weber et al., 2008). However, whether different ranks of invasive plants have various life-form spectra and the characteristics of the spectra remain unclear.

In the present study, we used checklist data of Chinese alien species and invasive ranks of alien species to determine the distribution of alien species, the relationship between the distribution density and social or natural factors, and the life-form spectra of different invasive ranks. Our objectives were to determine: 1) How the distribution characteristics of alien species differed among different invasive ranks, and 2) How social or natural factors affect the distribution of alien species.

2. Materials and methods

2.1 Data collection of alien species

We collected data of alien species and their distribution from *The Checklist of the Chinese Invasive Plants* (Ma and Li, 2018). The alien species included 562 species, belonging to 80 families and 325 genera that were distributed in 23 provinces, 5 autonomous regions, 4 municipalities, and 2 special administrative regions in China. According to the *Flora of China*, these species were classified into five life-forms, i.e., annual herb, biennial herb, perennial herb, shrubs, and trees (Huang et al., 2009; Jiang et al., 2011; Weber and Li, 2008).

2.2 Definition of invasive ranks of alien species

Table 1 here

Based on the academic literature (up to December 2012), field investigation, specimen records, and taxonomic research, *The Checklist of the Chinese Invasive Plants* was published in cooperation with experts from all over China (Ma and Li, 2018). In this book, the alien species in China have been defined into six ranks (Table 1) based on their biological and ecological characteristics, invading distribution, and influence on ecological environments and the national economy (Ding et al., 2008; Ma and Li, 2018). Rank I, malignant invaders (37 species), have not only caused enormous economical and ecological loss but have invaded more than one physical geographical region at the national scale. Rank II, serious invaders (50 species), have caused huge economical and ecological loss and a worse influence on society, and have invaded at least one physical geographical region at national level. Rank III, local invaders (73 species), have caused huge economical and ecological loss at the local scale and are distributed in at least one physical geographical region. Rank IV, mild invaders (79 species), have caused low economical and ecological loss at the local or national levels; however, they cannot invade into new geographical regions owing to their biological characteristics. Rank V, species requiring further observation (225 species), refers to those species that have been in a naturalized state but have not invaded into other regions, or their invasion features have not been determined. Rank VI, cultivated aliens (98 species), have been reported as an invasive species, but have been in a state of cultivation for a long period or are unable to establish a stable population even if they occasionally escape into the natural environment (Ma and Li, 2018; Yan et al., 2014).

2.3 Definition of alien species density in different invasive ranks

We used alien species density, i.e., the ratio of invasive alien species richness to the area of an administrative region, to reduce bias resulting from different areas of administrative regions (Wang et al., 2017). For some municipalities and special administrative regions, the number of alien species is often higher than that of small cities or villages. Considering the small territories of those special administrative regions, we incorporated Beijing and Tianjin into Hebei province, Hong Kong and Macao into Guangdong province, and Chongqing into Sichuan province (Feng and Zhu, 2010; Wang et al., 2017) to reduce the bias of alien species density owing to small area.

2.4 Selection of factors and data collection

As the world's third largest country, China covers five climatic zones (cold-temperate, temperate, warm-temperate, subtropical, and tropical) (Wang et al., 2016a; Xie et al., 2001, Yin et al., 2016). Influenced by the continental monsoon, the country spans four precipitation areas (humid, semi humid, semiarid, and arid). Therefore, temperature and precipitation may be closely linked to alien species density. Four climatic factors, annual maximum temperature (AMAT), annual minimum temperature (AMIT), mean annual precipitation (MAP), and mean annual temperature (MAT), were selected to examine the relationship between climatic factors and alien species density (statistically significant at the 95% level). These monthly data were obtained from a dataset of 825 ground weather stations in China from 1981 to 2010 (http://data.cma.cn/).

Two social variables, gross domestic product (GDP) and population density (PD), were collected from the *Statistical database of China's economic and social development* in a big data platform for economic and social research of China (http://data.cnki.net/) from 2010 to 2019. According to GDP, PD, and area of the administrative region, we defined GDP per capita (GPC) as the ratio of GDP to population, and ground GDP (GDP per square kilometer) as the ratio of GDP to area of administrative region (Zeng and Chen, 2018). In the past, many alien species had been introduced either accidentally or deliberately into China by international sea trade. Therefore, distance from port (DFP) might be an important factor influencing alien species density. DFP is defined as a straight-line distance from an administrative capital city to the nearest harbor.

2.5 Data analysis

Redundancy analysis was conducted using Canoco 5.0 (ver. 5.0, Microcomputer Power) (Šmilauer and Lepš, 2003) to analyze the relationship between natural or social factors and alien species density to compute the total effect of all factors on alien species density variation and to plot the ordination graph of the relationships.

The forward method was used to analyze the explanatory power of individual factors to alien species density variation (statistical significance at $p < 0.05$). A histogram of the life-form spectra was drawn using SigmaPlot version 10.0 (Systat Software, Inc.). A distribution map of alien species density was drawn using ArcGIS Desktop 8.3 (Esri Inc.).

3. Results

3.1 Geographical distribution of species density of alien species

Fig. 1. here

Species density of alien species in total and in the six ranks increased from the northwest inland to the southeast coastal areas of China (Fig. 1). The boundary line between the low and high density of alien species was consistent with the “Hu Line” (Qi et al., 2016). The “Hu Line” was discovered as a dividing line for the Chinese population density, revealing a spatial relationship between human activity and the natural environment (Chen et al., 2016; Hu et al., 2016). For total species density, the species density of alien species was more than 2 species/km^2 in the regions east of the line, whereas it was less than 1 species/km^2 in those west of the line. From Ranks I to VI, the species density of alien species was greater than 1 species/km^2 in most of the regions east of the line, whereas it was less than 1 species/km^2 in those west of the line (Fig. 1).

3.2 Relationship between species density of alien species and social or climate factors

Fig. 2. here

The AMAT, AMIT, MAT, GDP, GPC, Ground GDP, MAP, and PD had positive relationships with species density in the total and six ranks of alien species; however, the DFP had a negative relationship (Fig. 2). All social and climatic factors explained from 78.5% to 89.5% (p = 0.02) of the variation in species density of the different invasive ranks (Table 2). The MAP was the most important factor on species density in the total and in Ranks I, II, III, and V of alien species, and explained from 45.9% to 48.1% of the variation. The ground GDP and AMIT were the most important factors for Ranks IV and VI, explaining 54.3% and 48.6% of the variation, respectively. The ground GDP explained 10.2% of the variation in species density in Ranks II and IV and the AMIT from 3.9% to 12.8% of the variation in the total and in Ranks I, II, IV, and V. The GPC, PD, and GDP were important significant social factors in the total and in Ranks I to VI ($p < 0.05$), explaining 7.0% to 20.4% of the variation in species density.

Table 2 here

3.3 Life-form spectra of alien species in China

Fig. 3. here

In total alien species, annual and biennial herbs (260 species) accounted for 46.1%, perennial herbs (196 species) for 34.7%, shrubs (73 species) for 12.9%, and trees (35 species) for 6.2% (Fig. 3). In Ranks I to IV, the annual and biennial herbs changed from 52.9% to 71.2%, perennial herbs from 25% to 35.1%, shrubs and trees from 3.7% to 14.7%. However, in Ranks V to Rank VI, the annual and biennial herbs changed from 32.6% to 35.6%, perennial herbs from 35.7% to 39.1%, shrubs and trees from 25.3% to 31.6% (Fig. 3).

4. Discussion

4.1 Distribution characteristics of alien species in various invasive ranks

Alien species density in various ranks increased from the northwest to the southeast regions of China. The results were consistent with previous studies on the geographical distribution of invasive species (Chen et al., 2017; Qi et al., 2004; Weber et al., 2008). Furthermore, we found that a boundary line between low and high alien species density was the “Hu Line.” The line is regarded as a boundary of geographical structure, climate, and economic and social development (Chen et al., 2016; Hu et al., 2016; Liu et al., 2017; Qi et al., 2016). Therefore, our results showed that the distribution of alien species was correlated with social and climatic factors that influence the distribution and invasion of alien species.

4.2 Characteristics of life-form spectra in various ranks of alien species

The life-form of alien species may be a good indicator for predicting invasions in the regional distribution (Chen et al., 2017; Pheloung et al., 1999). Annual, biennial, and perennial herbs, shrubs, and trees are the most frequently analyzed traits of life-form spectra (Chen et al., 2017; Lloret et al., 2004). In the present study, the spectra of Ranks I, II, III, and IV were annuals and biennial herbs, followed by perennial herbs, shrubs, and trees from high to low, which was a similar spectrum to that of the total alien species (Fig. 2). This is the general life-form spectra of the naturalized taxa in China (Jiang et al., 2011; Lambdon et al., 2008; Ma and Li, 2018; Weber et al., 2008). The high proportion of annual and biennial herbs in the life-form spectra might be due to their short juvenile period, rapid population growth, and small seed mass facilitating the invasion of disturbed land (Rejmanek and Richardson, 1996; Weber et al., 2008). One possible reason for a high proportion of perennial herbs was that their perennial life cycles, clonal growth ability, and vegetative propagation play an important role during the invasion process (Huang et al., 2009; Liu et al., 2006; Milbau and Stout, 2008). There were two possible reasons for relatively low rates of shrubs and trees: first, the introduction history of trees in China is relatively short

(Zheng and Zhang, 2006), and, second, the time-lags of trees between introduction and naturalization are always much longer than those of grasses or herbs (Jiang et al., 2011).

However, Ranks V and VI had lower annual and biennial herbs and higher shrubs and trees than that of Ranks I to IV. One possible reason for this is that most shrubs and trees have low reproduction capacity and a long development time; therefore, they are classified as non-invasive aliens because their populations are easier to control (Zheng and Zhang, 2006).

4.3 Relationship between climatic factors and alien species density

Our findings showed that the MAP was the most important factor on species density in the total and Ranks I, II, III, and V of alien species. There are two possible reasons for these findings. The first one is that the natural habitat of most alien species is in pan tropic or temperate ecosystems (Wang et al., 2016a), and the species tend to live in the same or similar climates that have a high rate of precipitation in China. The second reason is that the invasive species in the total and Ranks I, II, III, and V had a relatively high proportion of annual and biennial herbs as their life-forms. These species, with their high fecundity and multiple reproduction, can quickly occupy open disturbed habitats under adequate precipitation (Fumanal et al., 2007).

Our results found that AMIT was the most important factor on the distribution density of alien species in Rank VI (cultivated aliens). The species in Rank VI might have a longer history of being introduced into China and most of the species were cultivated from agriculture and horticulture (Chen et al., 2017). During long-term agricultural and horticultural production, the distribution of species is relatively stable and strictly restricted by temperature, especially the AMIT (Kriticos et al., 2003). For these invasive species, their distribution area was ever-expanding; therefore, the temperature had a low relationship with their distribution (Table 2).

4.4 Relationship between social factors and alien species density

Our results showed that social factors (GPC, ground GDP, PD, and GDP) had a significant effect on alien species density (explained from 25.9% to 74.7%). Anthropogenic activities play an important role in the introduction of alien species, either intentionally or unintentionally (Chen et al., 2015; Ding et al., 2008; Guo et al., 2016; Jiang et al., 2011; Wang et al., 2016a). The higher density of human population with frequent resource exchanges has made it easy to introduce alien species (Feng and Zhu, 2010; Jiang et al., 2011). It has been well documented that China's booming economy has greatly increased international trade and changed patterns of plant naturalization/invasion (Lin et al., 2007; Thuiller et al., 2005; Weber and Li, 2008). Therefore, GPC, ground GDP, PD, and GDP are indispensable factors that influence the distribution density of alien species.

In Ranks I, II, III, V, and VI, the effect of social factors was lower than that of climatic factors because these species might depend on their natural invasive capacity to change their distribution density. In Rank IV, the species have a low capacity to invade new geographical regions owing to the inability to adapt to new environment, e.g. cold and arid conditions; thus, their distribution might largely depend on social factors. The ground GDP, an indicator reflecting a degree of economic development and concentration, becomes the most important factor on their species density (Zeng and Chen, 2018). DFP was not a significant factor on the distribution density of alien species because geographical isolation was greatly decreased as there has been rapid growth of infrastructure, such as airports, seaports, and railway and motorway stations, and transportation networks in China (Ding et al., 2008).

5. Conclusions

The geographical distribution of six ranks of alien species increased from the northwest to the southeast regions of China, reflecting a significant relationship with climatic and social factors. Climatic factors, MAP and AMIT, were crucial factors in the distribution of various ranks of invasive alien species. Social factors, GPC, ground GDP, PD, and GDP, were important for the distribution, especially the ground GDP, which was crucial for the distribution of species and requires further research. Invasive alien species had a high proportion of annual and biennial herbs and a low proportion of shrubs and trees. Non-invasive alien species had a low proportion of annual and biennial herbs and a high proportion of shrubs and trees. Understanding the geographical distribution and life-form spectra of various invasive alien species is essential for Chinese policy maker to: 1) enact strict quarantine laws preventing intentional and accidental introduction of alien species in economically developed areas; 2) pay close attention to invasion of alien species in mild environment (e.g. southeastern coastal areas in China); 3) focus on controlling introduction and invasion of annual and biennial herbs.

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Figure legends:

Fig. 1. Geographical distribution of species density of different ranks of alien species in China. (T) Total; (I) Rank I, malignant invaders; (II) Rank II, serious invaders; (III) Rank III, local invaders; (IV) Rank IV, mild invaders; (V) Rank V, species requiring further observation; (VI) Rank VI, cultivated aliens.

Fig. 2. Relationship between species density of different invasive ranks of alien species and environmental factors. Climate and social factors: (AMAT) Annual maximum temperature; (AMIT) Annual minimum temperature; (MAP) Mean annual precipitation; (MAT) Mean annual temperature; (PD) Population density; (GPC) GDP per capita; (ground GDP) GDP per square kilometer; (DFP) Distance from port. Species density: (T) Total species; (I) Rank I, malignant invaders; (II) Rank II, serious invaders; (III) Rank III, local invaders; (IV) Rank IV, mild invaders; (V) Rank V, species requiring further observation; (VI) Rank VI, cultivated aliens. Red hollow arrows represent environmental factors; blue solid arrows represent species density of alien species.

Fig. 3. Life-form spectra of alien species in different invasive ranks. Life forms: (A+B) annual and biennial herbs, (P) perennial herbs, (S) shrubs, (T) trees. Species density: (T) Total species; (I) Rank I, malignant invaders; (II) Rank II, serious invaders; (III) Rank III, local invaders; (IV) Rank IV, mild invaders; (V) Rank V, species requiring

further observation; (VI) Rank VI, cultivated aliens.

Table 1

Characteristics of different invasive ranks of alien species in China.

Rank	Number of family	Ratio to total (%)	Number of genus	Ratio to total (%)	Number of species	Ratio to total (%)
Rank I*	12	15.0	29	8.9	37	6.4
Rank II	18	22.5	38	11.7	50	9.0
Rank III	28	35.0	56	17.2	73	13.3
Rank IV	30	37.5	61	18.8	79	14.2
Rank V	49	61.2	149	45.8	225	39.8
Rank VI	42	52.5	87	26.8	98	17.3
Total	80	100	325	100	562	100

*Rank I, malignant invaders; Rank II, serious invaders; Rank III, local invaders; Rank IV, mild invaders; Rank V, species requiring further observation; Rank VI, cultivated aliens.

Table 2

Variation of geographical distribution of species density explained by social and climate factors in China.

Invasive rank	Total explain (%)	Significant factors	Explains	Pseudo-F	*p*
Total	85.6	MAP	47.4	23.4	0.002
		GPC	12.5	7.8	0.014
		PD	11.7	12.7	0.006
		GDP	7.0	5.1	0.046
		AMIT	3.9	5.0	0.048
Rank I	83.8	MAP	46.8	22.8	0.002
		PD	12.3	12.4	0.006
		GPC	9.7	5.6	0.034
		GDP	8.4	5.7	0.04
		AMIT	4.2	5.0	0.05
Rank II	86.7	MAP	45.9	22.1	0.002
		GPC	12.9	7.8	0.002
		Ground GDP	10.2	10.6	0.01
		GDP	8.8	6.5	0.03
		AMIT	6.4	9.0	0.004
		MAT	5.8	7.8	0.018

Rank III	82.2	MAP	47.6	23.6	0.002
		PD	9.4	8.8	0.014
		GPC	9.4	5.5	0.03
		GDP	9.1	6.4	0.034
Rank IV	86.4	Ground GDP	54.3	20.2	0.002
		GDP	20.4	20.2	0.004
		AMIT	12.8	24.9	0.002
Rank V	89.5	MAP	48.1	24.1	0.002
		GPC	14.8	10.0	0.002
		Ground GDP	10.2	12.0	0.004
		GDP	7.2	5.8	0.036
		AMIT	4.7	7.0	0.014
Rank VI	78.5	AMIT	48.4	24.4	0.002
		GPC	9.8	12.5	0.03
		PD	8.3	7.4	0.018
		GDP	7.8	5.5	0.044

Figure 1
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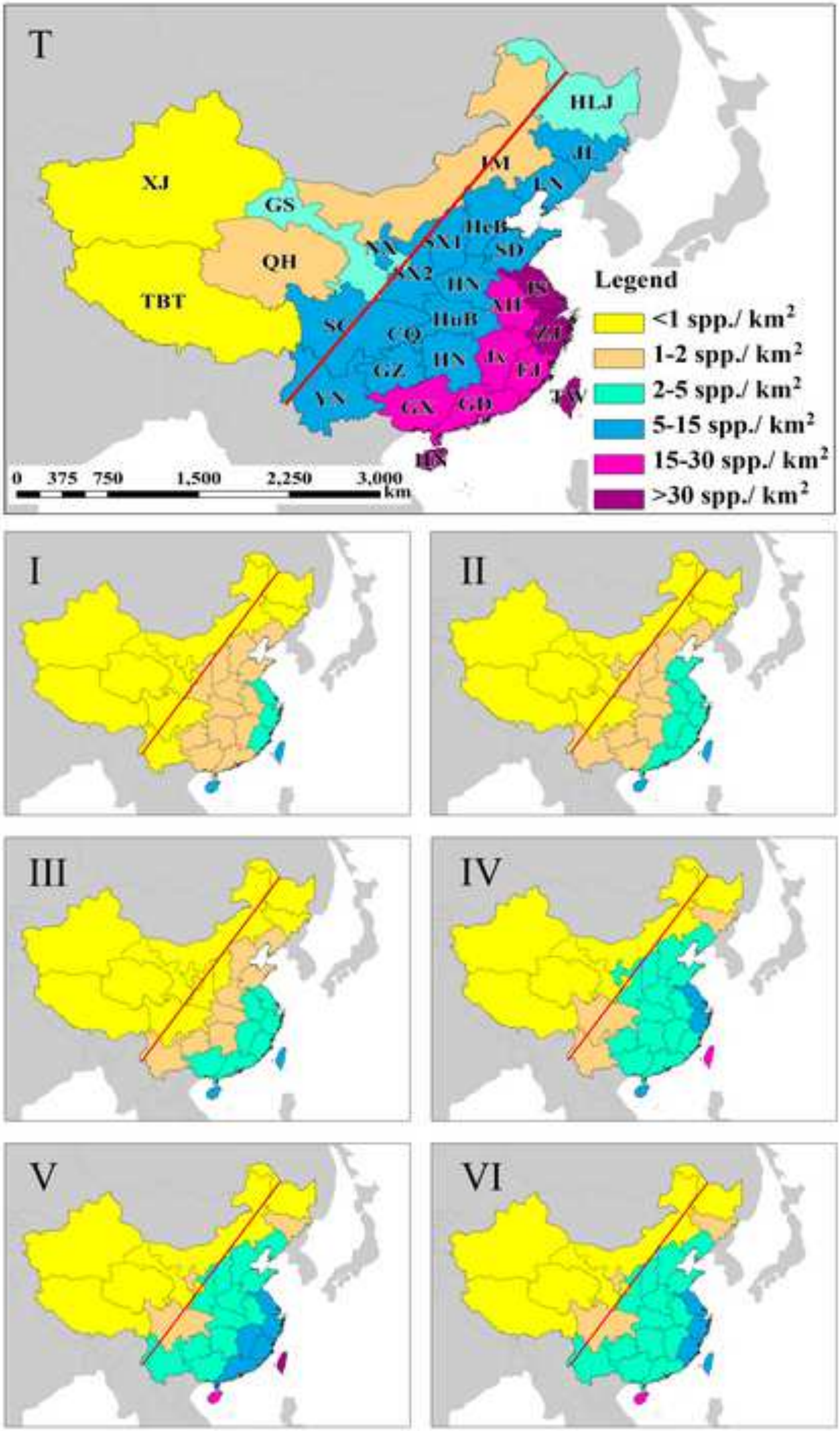

Figure 2
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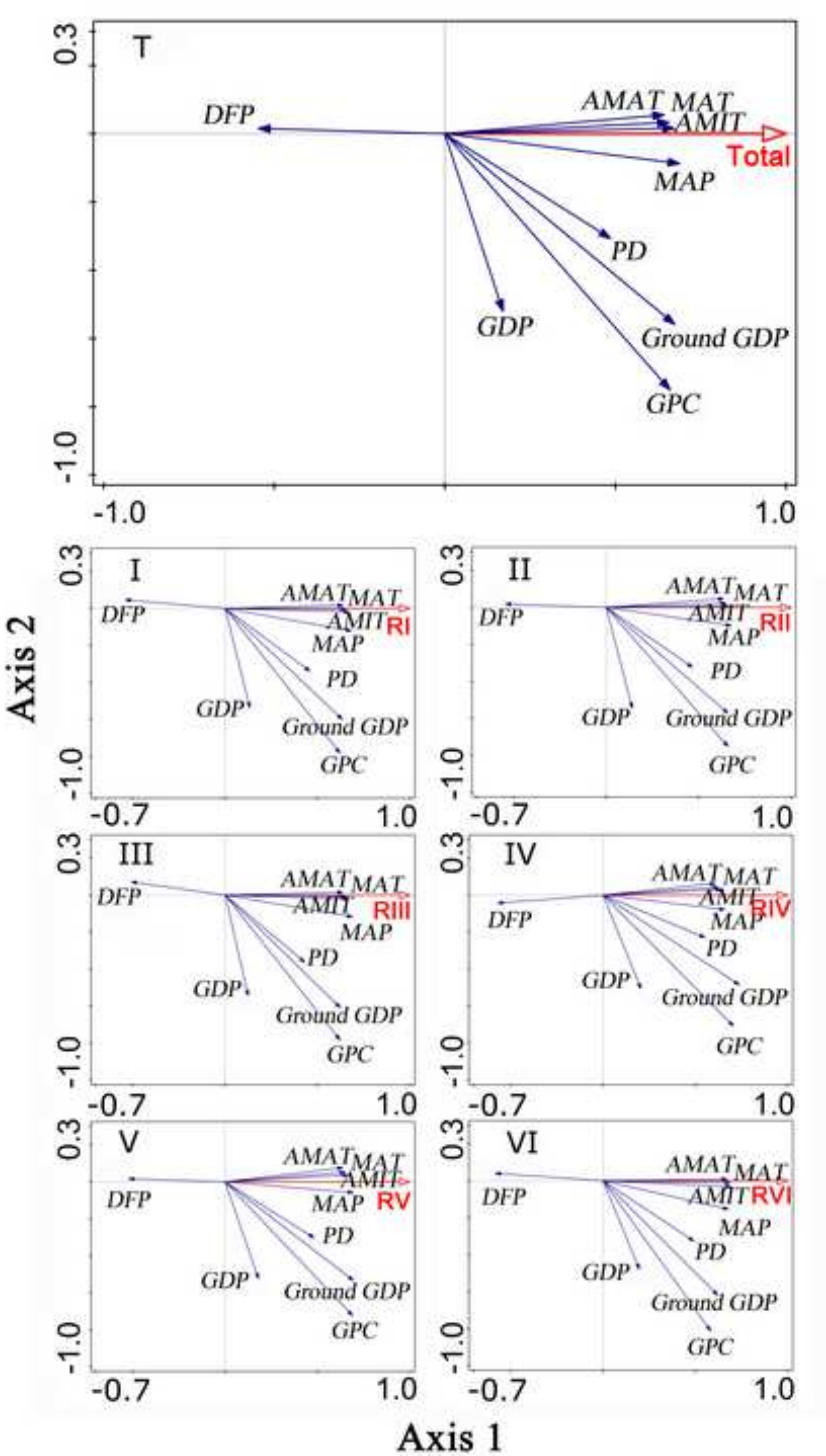

Figure 3
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