Global ore trade is an important gateway for non-native species: A case study of alien plants in Chinese ports

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Abstract

Aim: Biological invasion has become one of the most important environmental concerns in many countries, with considerable time, money and effort being spent in the prevention and eradication of invasive species. Since mineral ores tend to harbour seeds from the local plants, our aim was to study the non-native plants collected in Chinese ports to understand the influence of global ore trade on biological invasion.

Location: China.

Methods: We surveyed 75 ore heaps across six types of ore in 22 Chinese port cities from 2010 to 2016 and collected 737 voucher specimens of non-native plants, out of which 709 specimens were traced to the country of origin. Using the software Maxent, we evaluated the risk of invasion from these non-native plants based on the global ore trade flow, traced their route and predicted the regions in China most vulnerable to invasion by these plants.

Results: Of the 407 non-native plant species identified, most were from India, followed by Malaysia, Swaziland, Mexico, and Iran. Taxonomically, there were representations from 49 families, notably Fabaceae, Poaceae, Asteraceae and Solanaceae. The non-native plant species were represented by varying number of species, from a single specimen to 179. Analysis of the invasion risk indicated that the entire coast of China was at high risk. Furthermore, two major potential introduction pathways...
were also identified, namely the Yangtze drainage basin and the land from the Gulf of Tonkin to Sichuan Basin.

**Main conclusion:** An important pathway for the invasion of non-native plants is the inadvertent transportation of seeds through global ore trade networks. Based on this study, we suggest greater monitoring and cooperation in the international ore trade for better management, and creating public awareness of the dangers of non-native species to help minimize the risk of transporting non-native plants by the global ore trade network.

**KEYWORDS**
biological invasion, China, international transport, non-native plants, ore trade, risk prediction

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**1 | INTRODUCTION**

The rapid development of regional and global trade has accelerated the process of global economic integration (McNeely, Mooney, Neville, Schei, & Waage, 2001). However, along with economic integration, there has also been inadvertent biological homogenization as well, in the form of non-native species being transported along with the traded goods and materials between native and non-native regions (Stace & Crawley, 2015; Xie, Li, & Wang, 1996). Biological invasion has become one of the most important environmental and economic issues that many governments, NGOs, scientists, and even common citizens are concerned about, and are working to tackle (Kumschick et al., 2015; Vilà et al., 2011; Vitousek, D’Antonio, Loope, Rejmanek, & Westbrooks, 1997). It has become a significant threat to agriculture and animal husbandry, as well as the health, stability and community structure of local ecosystems (D’Antonio, Jackson, Horvitz, & Hedberg, 2004; Ehrenfeld, 2010; Vilà et al., 2011). The environmental problems caused by invasive species have been regarded as an important factor affecting the economic development and well-being of people in many countries (Lambdon et al., 2008; Pyšek et al., 2012). In addition, non-native species may also carry and transmit pathogens that could infect crops, livestock and humans as well (Hof, Araujo, Jetz, & Rahbek, 2011). Non-native species are spreading rapidly in most countries and regions across the globe, damaging native ecosystems, and are even associated with novel epidemics (Catford, Vesk, Richardson, & Pyšek, 2012).

Studies of non-native species have spanned the entire range of the invasion process. These include understanding the invasion process, behaviour of the non-native species, mechanism of dispersal and spread, and management and disaster control techniques (Blackburn, Delean, Pyšek, & Cassey, 2016; Capellini, Baker, Allen, Street, & Venditti, 2015; Capinha, Essl, Seebens, Moser, & Pereira, 2015; Cassey, Vall-Llosera, Dyer, & Blackburn Tim, 2015; Dyer et al., 2017; Garcia-Diaz, Ross, Ayres, & Cassey, 2015; van Kleunen et al., 2015; Mateo et al., 2015). In turn, governments have developed laws and regulations related to prevention and control, as well as to monitor lists (i.e. white lists) of known invasive alien species (Pyšek & Richardson, 2010).

In recent years, ores have begun to be recognized as a new vector of non-native species, in the context of globalization (Chen, Xia, Zhou, & Yu, 2015; Li et al., 2016; Sun, Shao, Zhang, Liang, & Song, 2012; Yu et al., 2019). Ores can be mixed with soil during mining and are therefore likely to contain plant seeds or other propagules (Chen et al., 2015; Liu et al., 2013; Sun et al., 2012). When the turnover of the ores is high (usually in good economic times), the seeds do not have the opportunity to germinate as they are incinerated during the processing of the ore. If the ores are stored unused for long periods (as during an economic downturn), however, any seeds in the ore heaps tend to germinate, especially in the presence of rain (Chen et al., 2015). It is when these plants grow and reproduce that they can potentially damage the local ecosystem and threaten the ecological security of the importing country (Figure 1).

Knowledge of non-native species introduction pathways is an essential foundation for the early detection and rapid response necessary for the prevention of the establishment of populations of non-native species (Capinha et al., 2015; Waage & Reaser, 2001; Wan, Peng, & Wang, 2010). Introduction pathways of non-native species are typically closely related to human activities, such as tourism, trade and construction projects, especially in infrastructure (Hulme, 2015). Species introductions increased during the 20th century, especially after the economic globalization following World War II, leading to a sharp increase in biological invasions (Hulme,

**FIGURE 1** Representative non-native plants and ore heaps at Chinese ports. (a) Cenchrus longispinus (Hack. ex Kneuck.) Fernald (spiny burr grass or gentle Annie) on coal heaps in Yingkou, imported from North Korea; (b) Anoda cristata (L.) Schltdl. (spurred anoda or crested anoda) on nickel ore heaps in Lianyungang, imported from South Africa; (c) Lactuca serriola L. (prickly lettuce or compass plant) on nickel ore heaps in Lianyungang, imported from South Africa; (d) Ambrosia psilostachya DC. (Cuman ragweed or perennial ragweed) on iron ore heaps in Rizhao, imported from Romania; (e) Xanthium italicum Moretti (cocklebur) on iron ore heaps in Rizhao, imported from Romania; (f) Digeria muralata Mart. (false amaranth) on iron ore heaps in Rizhao; (g) Corchorus asplenifolius Burch. (Jute mallow) on nickel ore heaps in Lianyungang, imported from South Africa; (h) Iron ore heaps in Caofeidian, imported from Swaziland; (i) Iron ore heaps in Rizhao, imported from India; (j) Iron ore heaps in Caofeidian, imported from Swaziland
2. The important role of vectors began to be recognized in the introduction of non-native species, such as ballast materials, animal and plant products, wood packaging materials, and even the vehicles themselves used in international transport, such as ships, airplanes and trucks (Haack & Cavey, 1997; Keller, Geist, Jeschke, & Kühn, 2011; Wonham, Walton, Ruiz, Frese, & Galil, 2001). As a result, various regulations and international initiatives have been put in place, such as the Convention on Biological Diversity (CBD), the Global Invasive Species Program (GISP) and the GloBallast Programme to prevent and mitigate the harmful effects of biological invasions.

In order to prevent the introduction of non-native species into China, the Chinese Academy of Inspection and Quarantine (CIQ, www.caq.org.cn) has carried out a monitoring programme for early detection of non-native species at the ports of entry. In 2010, the monitoring system detected a large number of non-native plants growing on ore heaps. Since then, CIQ has listed imported ores as a key vector of non-native species that need to be monitored. Based on the data gathered, CIQ has developed a list of non-native plants associated with ore transport. In the past seven years, it has continuously tracked imported ores in China and collected invasive plants growing on ore heaps, prepared specimens and gathered information about the plants, their relatedness and the country of origin of the minerals. We show here that the ore trade network is a new pathway of biological invasion, while identifying the flow, composition and country of origin of non-native plants, as well as the distribution of the ports of entry in the context of a global ore trade network. We hope these results will be useful for developing an early warning system for potential invasive species, and will aid decision-making in industrial management, and developing control measures against non-native species.

2 | METHODS

2.1 | Study area and data collection

39 major seaports and river ports along the east coast of China were visited from July to October during the period 2010–2016, and monitored twice each year (summer and autumn). The local departments of customs (former Entry-Exit Inspection and Quarantine Bureau) also carried out regular inspection on ore heaps, with attention to non-native plants, in order to adjust the times of the monitoring work to coincide with the invasion of non-native plants. We examined 75 ore heaps at ports in 22 port cities (Figure S1) and explored 65 heaps for information about the country of origin of the ore. We collected specimens and took photographs of the non-native plants, and determined the country of origin of the ores by inquiry, in order to construct a comprehensive database of the non-native plants growing on ore heaps in China. Sampling was done prior to the instructions of the local quarantine departments of CIQ to the port authority or the cargo owners, directing them to destroy all non-native plants and initiate measures to prevent the subsequent growth of these plants. All specimens and images were identified by referring to Flora of China (www.iplant.cn/foc), eflora (www.eflor

as.org) and the Tropicos nomenclature database (www.tropicos.org).

Before this study was carried out, all collections were compared and checked against lists of China IAPs to confirm that all species presented in this study are transferred by ore trade. All specimens have been preserved in the reference herbarium of non-native weeds in CIQ and the herbarium of the Institute of Botany, Chinese Academy of Sciences (PE).

2.2 | Spatial distribution and ore trade network flows of non-native plants

We mapped the spatial distribution of the non-native plants using ARCGIS 10.0 (ESRI), based on the country of origin and dispersal of the ores in Chinese ports, and determined the relative contribution of each country. We also analysed the ore trade network flows using the R package, “circize” (R x64 3.6.0) (Gu, Gu, Eils, Schlesner, & Brors, 2014).

2.3 | Prediction of areas vulnerable to the establishment of non-native plants

We used the maximum entropy-based distribution model (MaxEnt, Version 3.4.1) for comparison with other species models. Information on climatic variables is also required to determine the regions most vulnerable for the establishment of non-native species. For this purpose, we downloaded the set of 19 available bioclimatic variables at a resolution of 2.5 arc-min (~5 km) under “current” climate conditions (1960–1990) from www.worldclim.org (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). The ports of entry in the aforementioned 22 cities (Figure S1) were georeferenced using known latitude and longitude values to represent the presence of the non-native plant species (Table S1); 70% was used as the training set, and 30% as test data. Cross-validation was maintained in the replicate runs, and iterations were fixed at 500. We used 0.1 as the regularization number in case of over fitting of the test data (Phillips, Anderson, & Schapire, 2004; Remya, Ramachandran, & Jayakumar, 2015). Model evaluation was based on the area under the receiver operating characteristic curve, with 0.5 representing a random, uninformative discrimination and 1.0 reflecting a perfect discrimination. A Jackknife approach was employed to assess the importance of variables in the final model (Phillips, Anderson, & Schapire, 2006). Finally, we used ARCGIS V. 10.0 (ESRI, Redlands, CA, USA) to generate the output for further analysis.

3 | RESULTS

3.1 | Types of ore, and countries of origin

In the process of monitoring and surveillance over the past seven years, we collected 737 plant specimens growing on ores imported...
from overseas and dumped in heaps in ports. Of these, we identified accurately the country of origin for 709 specimens, made up of six kinds of ore. Among the ores of unknown origin, there were 12 collections of iron, for which we were unable to distinguish between Peru and Brazil as the source nation.

Among the various types of ore, the most common among our collections were iron ore (615), followed by aluminium ore (35), bauxite aluminium ore (25) and nickel ore (17; Table S2). Of the 615 collections of iron ore, most were imported from India (299), followed by Malaysia (69), Swaziland (44), Mexico (38) and Iran (35). We traced the ores to 14 exporting countries in this study, including India (339 collections), Iran (70), Malaysia (69) and Swaziland (44; Figures 2–4 and Table S2). Most of the non-native plant species (65.9%) were found on iron ore heaps. Further details regarding the ores, plants and countries of origin, are available in Table S2.

3.2 Non-native species composition

All specimens from our 2010–2016 collections from ore heaps were identified except for a small number with incomplete characters. In total, 407 non-native plant species were recorded from 49 families, and 212 genera. Some of the most commonly represented families were Fabaceae (57 species), Poaceae (55), Asteraceae (42), Solanaceae (26) and Chenopodiaceae (19) (Figure 5), which also accounted for about 50% of non-native species recorded in this study.

At the generic level, Solanum (12 species), Polygonum (12), Eragrostis (10), Cyperus (8), Amaranthus (8) and Physalis (8) were the most common. Of the 407 non-native plants, 108 species belonging to 28 families and 76 genera were recorded in China for the first time. Further details are available in Table S1.

3.3 Distribution of non-native plants in China’s ports

Interestingly, non-native plants were not found to grow on the ores imported from neighbouring countries through land ports in Xinjiang and Inner Mongolia. However, non-native plants were found to grow on all ores imported through the seaports along the coast (Figure 3). Furthermore, greater numbers of non-native plants were detected on ores at ports in Shandong and Jiangsu provinces than in other provinces. Some of the port cities with large numbers of alien plants were Rizhao (179 collections), Qingdao (87), Changzhou (67), Jiayin (53) and Zhenjiang (53). In these port cities, ores imported from India, Thailand, Romania, Malaysia, Swaziland and Iran were found to contain larger numbers of non-native plants, when compared to ores from other countries. Ores from India appear to be particularly prone to carry invasive plant seeds. For example, 85 out of 179 collections at Rizhao were from India. Even higher proportions of specimens were from India in ore heaps found in Changzhou (85/67), Xiamen (48/49) and Qingdao (48/87).

![Figure 2](image-url)  
**Figure 2** Map showing countries of origin of imported ores, and the proportions of non-native plants on ore heaps attributed to each country. Each inserted pie chart shows the proportions of non-native plants originating from the associated country of origin that were recorded as new during our study (red), non-native plants originating from the associated country of origin that were already present before our study began (blue), and those originating from all other countries (white). The distribution of newly recorded non-native species across the 13 countries of origin identified is shown in the lower left.
The ores in the coastal ports north of Liaoning are mainly imported from North Korea. Although some weeds appeared on these ore heaps, they were not alien plants, but native species such as Polygonum orientale L., Kummerowia striata (Thunb.) Schindl., and Mollugo stricta L. In contrast, all the ore heaps from the ports in Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong and Guangxi had non-native plants growing on them. More information about the ports, types of ore and their countries of origin is given in Table S3.

3.4 | Prediction of the potential geographical distribution of non-native plants

We used maxent (Version 3.4.1; Phillips, Dudík, & Schapire, 2019) to detect regions conducive to the establishment of non-native plants, based on the values of AUC (area under the curve). AUC values greater than 0.95 indicated that the model accurately predicted the potential geographical distribution of the non-native plants found on imported ore heaps (Figure S2). The jackknife evaluation result indicated that the climatic variable (mean of diurnal temperature range, Bio 2) was the most important single predictor for predicting the geographical distribution (Figure S3). Vulnerable areas were predicted to be mainly located along the coast of China, including Shandong peninsula, Liaoning peninsula, Yangtze River estuary, the coastal area of Zhejiang province, and the land area in the Gulf of Tonkin. Two potential introduction pathways, along the river from the Yangtze River estuary to Sichuan Basin, and from the land area off the Gulf of Tonkin northward to Sichuan Basin, were found to be at high risk of invasion (Figure 6). However, these two are not the only potential introduction pathways, as the coastlines of North Korea and South Korea were all found to be at high risk of invasion by non-native plants in the wake of global ore trade.
4.1 | Global ore trade network represents a vital introduction pathway of alien plants

We undertook this study to understand and map the distribution of non-native and invasive plants coming into China by means of imported ores and establishing on the ores stored in heaps at various ports. China has been the largest importer of iron ore in the world since 2002, accounting for more than 60% of the iron ore traded annually. In 2012, Chinese import of iron ore reached a record high of 744 million tons (http://www.chinairn.com/news/20130614/084150408.html). Interestingly, although 70% of China’s imported iron ore comes from Brazil and Australia, few weeds were found in these
ores. This may be due to the preponderance of underground mines, iron ore treatments and careful inspection associated with these countries (Chen et al., 2015; Li, 2013; Sun et al., 2012). A considerable number of small and medium-sized steel companies in China mainly obtain their iron ore from other countries, such as India, South Africa and Iran. Despite being relatively minor exporters of iron ore to China, some of these countries (in particular, India) have contributed the majority of non-native plants to China (Figure 4), perhaps because of open-pit mining and the mixing with surface soil during mining and dumping (Chen et al., 2015; Li, 2013; Liu et al., 2013; Sun et al., 2012).

Based on their flow in the global trade network, it is clear that ores have played an important role in the introduction and establishment of non-native plants in China (Figure 4). Unfortunately, even though the ore trade is an important pathway for the introduction of non-native species, this seed bank has long been overlooked, and until now, few countries have conducted a risk assessment or quarantined ores. Furthermore, along with non-native plant seeds, ores
are also likely to carry microorganisms, fungi, worms and insects, and the associated risk to the ecological health of the importing country. Therefore, appropriate attention needs to be paid to the ore trade network.

4.2 Risk of invasion of non-native plants from ores

A wide variety of non-native plants were found on ore heaps, including herbaceous plants, shrubs and tree seedlings, of which 108 new recorded species of non-native plants were identified. Non-native species often become invasive in foreign habitats, perhaps because of the absence of any co-evolved species or other factors that keep them in check in their native habitats. For example, *Anoda cristata* (L.) Schltdl. (common name: spurred anoda or crested anoda), a species in apparent ecological balance in its native Central America and South America, has become one of the most harmful invasive alien weeds upon being introduced to South Africa and Australia (Fan et al., 2012). Similarly, *Croton bonplandianus* Baill. (Common name: three-leaved caper), native to South America, has become an invasive weed in India and Africa (Xia et al., 2019). Other well-known invasive species are *Ipomoea hederifolia* L. (Common name: scarlet morning glory or scarlet creeper or star ipomoea) and *Heliotropium europaeum* L. (Common name: European heliotrope or European turn-sole), which are quarantined in many countries (Huang, 2014; Xu & Qiang, 2018). With these and many other examples known to wreak havoc as invasive species, and the knowledge that ships carrying ore can become vectors for seeds with the potential of becoming invasive in the importing countries, it stands to reason that countries involved in ore trade need to pay more attention to the seeds carried across the seas due to the ore trade networks (Liu et al., 2013).

This study found that a total of 300,000 km$^2$, mainly along the coastal China, are predicted to be suitable for the establishment of non-native invasive plants transported along with imported ores (presence probability between 0.5 and 1.0). Two introduction pathways are recognized, namely the Yangtze drainage basin from East Sea (Shanghai) across Central China (Wuhan) to Sichuan Basin, and the area from South China (Guangxi) to Sichuan Basin. Since such a large area is vulnerable to invasion, the establishment and spread of these non-native plants are likely to be a substantial threat to biosecurity in China and also in Korea.
4.3 | “Seed bank” of non-native plants transported by imported ores

Unfortunately, the international ore trade has brought non-native plant seeds into Chinese ports for so long that what is essentially a robust seed bank of these plants has inadvertently been established, particularly near the ports. Two factors have contributed to the establishment of this seed bank. First, some of the imported ore comes from countries that practice open-pit mining (Chen et al., 2015; Liu et al., 2013). The problem with open-pit mining, as compared with underground mines, is that it is inevitably mixed with soil (containing seeds) from the interlayer that forms on account of rain and landslides (Chen et al., 2015; Li, 2013; Liu et al., 2013; Sun et al., 2012). For example, 70% of Indian iron ore mines are open-pit, and according to the statistics of the China Inspection and Quarantine Bureau, up to 80% of ore imported from India was considered laden with alien plant seeds. The second factor that has contributed to the establishment of this “seed bank” is that the imported ores tend to sit in heaps near ports, sometimes for long periods of time, especially if conditions are not ready for smelting (such as an economic downturn). This allows for the germination, and even flourishing, of the non-native plants on the heaps, leading to flowering and eventual dispersal of seeds by wind, rain, insects, birds or bats.

4.4 | Suggestions for control measures and international management

First, it is important to increase the frequency and intensity of ore weed monitoring and permanent inspection, and to take appropriate control measures in order to control and manage non-native plants transported along with the imported ore. An obvious, but often neglected measure would be to focus on ores that carry a heavy load of non-native plants, especially when obtained from surface mining and slated for storage in unprotected heaps for long periods of time. It is also a good practice to categorize the management of ore heaps according to the type, country of origin and quality of ore. Next, it is important that the local inspection and quarantine authorities supervise port management departments and ore owners in their management of ore heaps. Some useful measures include black, opaque and waterproof material to cover ore heaps during storage periods to avoid sunlight that helps seed germination, concrete slabs below heaps to prevent insects from carrying seeds, regularly removing and incinerating any plants growing on ore heaps and in the surrounding area, promptly reporting the occurrence of unfamiliar weeds in port areas to the local quarantine departments for identification and further action, creating public awareness about the dangers of non-native species and training employers responsible for the ore heaps.

The establishment of a mechanism of international cooperation would go a long way in controlling the entry of invasive species into naïve areas (Fonseca et al., 2013; Packer et al., 2016). The trade in animal and plant products has been recognized by many countries as a major pathway for biological invasions (Levine & D’Antonio, 2003; Perrings, Burgiel, Lonsdale, Mooney, & Williamson, 2010; WTO, 1994). Powerful international accords and organizations such as CBD, International Plant Protection Convention (IPPC) and World Trade Organization (WTO) need to formulate the relevant legal framework and standards to regulate the ore trade among countries. Questions such as the relative share of the responsibility between the importing and exporting countries in preventing the spread of non-native species involved in ore trade, need to be addressed. The ore trade network as an important pathway for biological invasions has become an urgent issue that needs the attention of all countries and relevant international organizations, such as the Convention on Biological Diversity (CBD)—Aichi Biodiversity Target 9 (https://www.cbd.int/sp/targets/). Therefore, further research and risk assessment need to be done to formulate a set of effective mechanisms for international cooperation and management in this important area.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supplementary material of this article.

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**BIOSKETCH**

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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