Article

Environment patterns and influential factors of biological invasions: a worldwide survey

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Abstract

Invasive species damage ecological balance, reduce species diversity and threat humans. Biological invasions have become a global problem. In order to provide knowledge on prediction, impact assessment, control management and mechanism exploration of biological invasions, the present study analyzed the environment patterns and influential factors of biological invasion worldwide, and developed quantitative relationships of biological invasions based on the data extracted from global invasive species database. The results indicated that human buildings were mostly invaded by invasive species, second by natural forest and agricultural area. Human disturbed environments held the largest numbers of invasive species. The number of invasive species in a country was positively correlated to the level of economic development and trade activity of the country. There were not linear correlations between the number of invasive species and annual precipitation and annual mean air temperature. There was a suitable range for both annual precipitation and annual mean air temperature within which biological invasions occur more frequently. Land area of a country was not responsible for the number of invasive species. Regression models were developed to describe the relationships between the number of invasive species and climate and economically motivated human activity.

It is concluded that economically motivated human activity plays important role in the introduction of invasive species. Geographical adjacency and climate and environment similarity are responsible for the higher similarity of invasive species between countries. In addition, island countries have more invasive species than non-island countries.

Keywords biological invasion; invasive species; environment patterns; influential factors; regression models

1 Introduction

Biological invasion refers to a process in which a non-native species, that is, alien species, introduced species, or invasive species (Vitousek et al., 1996; Falk-Petersen, 2006; IUCN, 2010), facilitated by human activity or natural ways, invade a new habitat and establish its population (Elton 1958; Mack et al. 2000). Biological invasions always alter the structures of local communities and habitats and result in economic loss. They are recognized to be an important factor for biodiversity loss and species extinction (Chiras, 2001; Molles, 2002). Biological invasions are increasingly receiving great attention around the world. Biological invasions have been considered as one of the three most difficult environmental problems in the world.

So far most research of biological invasions covers the distribution prediction of invasions (Beerling et al., 1995; Underwood et al., 2004; Hellgren et al., 2007; Meyer et al., 2008), impact assessment, prevention and control management systems, etc. The present study aims to identify macro-scale environment patterns and influential factors of biological invasions worldwide, and to develop quantitative relationships of biological invasions. The results are expected to be beneficial to prediction, impact assessment, control management and mechanism exploration of biological invasions.

2 Material and Methods

2.1 Data source

All data in present study were extracted from Global Invasive Species Database (GISD) (ISSG, 2010). GISD was developed by Invasive Species Specialist (ISSG) of International Union for Conservation of Nature (IUCN). Species-based queries can be carried out in GISD. Required regions, environments and invasive species were searched in the database, and all data were stored as the text files for further collation and analysis.

2.2 Methods

Between-environment overlap of invasive species was represented by overlap percentage (Zhang, 2007), O, in which the overlap between environments x and y is the percentage of the number of invasive species shared by environments x and y, n_s, divided by the total number of invasive species of environments x and y, n_t:

$$O=n_s/n_t*100\%$$

where $0 \leq O \leq 100\%$. The greater O means the greater overlap between invasive species of two environments.

Regression model was fitted to represent the relationship between invasive species and climates, land area, and economic development.

One-dimensional orderly cluster analysis of environments and countries was conducted using the method of Zhang and Fang (1982).

3 Results

Until March 30, 2010, in total 677 invasive species were recorded in GISD. The number and ranking of invasive species for various groups of organisms is summarized, as indicated in Table 1, in which each of 68 species have been classified into two groups.

Of 677 invasive species, there are 374 plant species and 270 animal species, which account for more than 95% of the total (Table 2). In addition, 23 species of protozoa, 20 species of fungi and 8 species of viruses are also included in GISD. Tree, shrub and herb hold the most portion of plant species. The insect is the greatest group in invasive animal species, which make up 27% of the animal species. In this database there are also certain numbers of fish, mammal, mollusk and bird.

3.1 Environment patterns of biological invasions

Many invasive species may invade different environments like river, wetland, lakes, plantation, natural forest, etc. The number of invasive species in different environments is indicated in Table 3.

As seen in Table 3, human buildings are mostly invaded by invasive species (345 species), second by natural forest and agricultural area. Overall the human disturbed environments hold the largest numbers of invasive species.

One-dimensional orderly cluster analysis demonstrated that there are not dramatic changes in the number of invasive species between number-adjacent environments (Fig. 1). There are not significant and distinctive environments for biological invasion. The distribution of invasive species in different environments is a continuum.

Table 1 Number of invasive species for various groups of organisms*.

Group	Number of invasive species	Group	Number of invasive species	Group	Number of invasive species
Shrub	95	Crustacean	17	Tunicate	3
Herb	94	Fungus	13	Centipede/millipede	2
Tree	93	Alga	11	Coral	2
Insect	73	Amphibian	10	Palm	2
Fish	46	Reptile	10	Sea star	2
Grass	46	Virus	8	Comb jelly	1
Vine/climber	41	Succulent	7	Flatworm	1
Aquatic plant	40	Fern	6	Jellyfish	1
Mammal	36	Arachnid	5	Nematode	1
Mollusk	29	Bryozoan	5	Rush	1
Bird	24	Annelid	4	Sponge	1
Microorganism	20	Sedge	3	Total	677

*Collected from ISSG (2010)

Table 2 Numbers and proportions of various groups of organisms*.

Group	Number of species	Percent (%)
Plant	374	55.24
Animal	270	39.88
Protist	23	3.40
Fungus	20	2.95
Virus	8	1.18

*Collected from ISSG (2010)

Table 3 Number of invasive species for various environments*.

Sequence number	Environment	Number of invasive species	Sequence number	Environment	Number of invasive species
1	Ruderal/disturbed	345	11	Coastland	145
2	Natural forest	292	12	Lake	123
3	Agricultural area	252	13	Estuarine	107
4	Urban area	212	14	Marine habitat	74
5	Riparian zone	200	15	Host	28
6	Planted forest	197	16	Desert	24
7	Wetland	185	17	Tundra	15
8	Range/grassland	167	18	Vector	10
9	Scrub/shrub land	164	19	Ice	1
10	Water course	158			

*Collected from ISSG (2010)

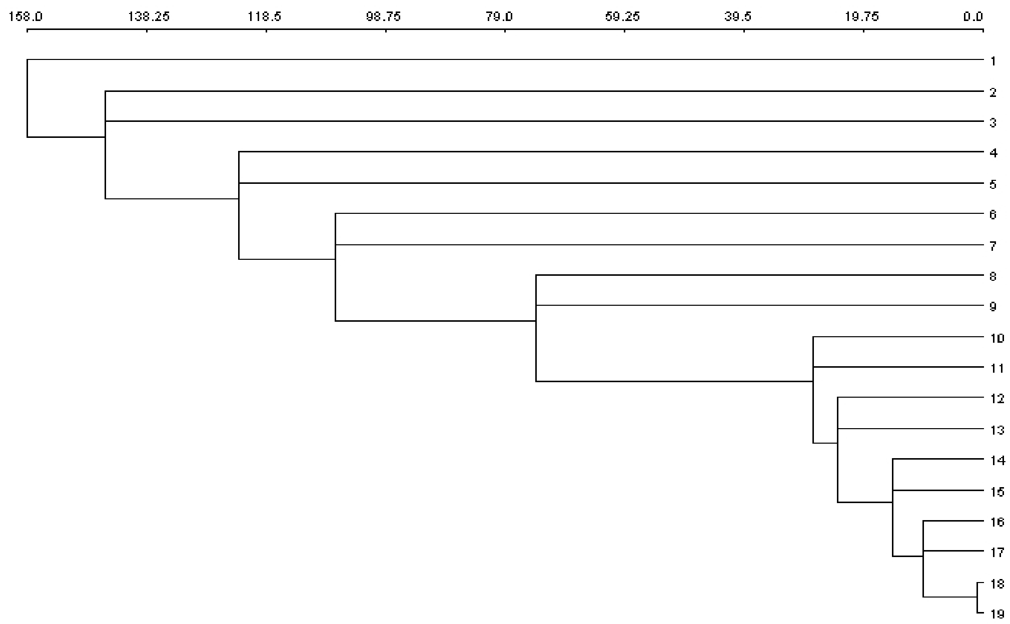

Fig. 1 One-dimensioanl orderly cluster analysis of various environments.
See Table 3 for the content of sequence number.

There are 425 invasive species for aquatic environments (coastal area, estuarine, lake, ocean, riparian area, river, wetland), of which 217 species are plants, 182 species are animals and 26 species are protozoa and fungi. Between-environment overlap percentages of invasive species for aquatic environments are indicated in Table 4. It can be found that lake and river share the most invasive species (*O*=70%). This has resulted from the natural linkage between river and lake. Ocean and lake do not share invasive species. In general wetland shares certain numbers of invasive species with other aquatic environments except for ocean.

Table 4 Overlap percentage (%) of invasive species for various aquatic environments*.

	Costal area	Estuary	Lake	Ocean	Riparian area	River	Wetland
Costal area	-	18	7	11	27	10	21
Estuary	18	-	30	35	10	23	21
Lake	7	30	-	8	11	70	32
Ocean	11	35	8	-	3	6	4
Riparian area	27	10	11	3	-	20	38
River	10	23	70	6	20	-	37
Wetland	21	21	32	4	38	37	-

*Collected from ISSG (2010)

There are 445 invasive species in terrestrial environments (ruderal/disturbed, natural forest, planted forest, shrub, and grassland), of which 298 species are plants, 133 species are animals and 14 species are protozoa and so on. Plant is the largest group of invasive species in terrestrial environments. Overlap percentage of invasive species in terrestrial environments demonstrated that natural forest and planted forest, and natural forest and ruderal/disturbed share the most invasive species. Generally between-environment overlap of invasive species in terrestrial environments is higher than aquatic environments.

In addition, urban area and agricultural area share a number of invasive species (138 species), with overlap percentage of 42%. The number of invasive species in agricultural area is 40 more than that in urban area, in which plant species hold the greatest proportion.

Table 5 Overlap percentage (%) of invasive species for various forest environments*.

	Ruderal/ disturbed	Planted forest	Natural forest	Shrub	Grassland
Ruderal/disturbed	-	38	50	37	38
Planted forest	38	-	60	38	27
Natural forest	50	60	-	39	30
Shrub	37	38	39	-	51
Grassland	38	27	30	51	-

*Collected from ISSG (2010)

Table 6 Information of non-island countries chosen*.

Group	Climate	Country	Annual precipitation (mm)	Annual mean air temperature (ºC)	Level of economic development and trade activity	Land area (10,000 km^2)	Number of invasive species
I	Temperate marine climate	Germany	714	9	5	36	139
	Temperate marine climate	France	619	10	5	55	188
	Temperate marine climate	Czech	700	8	3	8	92
II	Mediterranean climate	Portugal	750	16	5	9	122
	Mediterranean climate	Spain	750	16	5	50	166
	Mediterranean climate	Italy	750	15	5	30	170
	Mediterranean climate	Greece	700	18	3	13	101
III	Tropical desert climate	Egypt	125	22	2	100	63
IV	Tropical grassland climate	Nigeria	1968	26	1	92	50
	Tropical grassland climate	Benin	1150	26	1	11	20
V	Temperate continental climate	Mongolia	185	0	1	118	30

*Calculated from ISSG (2010) and internet resources

3.2 Influential factors of biological invasions

Searching GISD by country or location have yielded two sets of species, alien species, i.e., alien invasive species, and native species, that is, the native species with invasion potentiality.

3.2.1 Non-island countries

In total five groups of climates with 11 non-island countries were chosen for analysis, as indicated in Table 6. Five groups of climates are chosen based on the definitions of Wikipedia (2010) and Peel et al. (2007). They are temperate marine climate (Germany, France, Czech), Mediterranean climate (Portugal, Spain, Italy, Greece), tropical desert climate (Egypt), tropical grassland climate (Nigeria, Benin) and temperate continental climate (Mongolia), respectively.

Regression relationships between the number of invasive species (s) and annual precipitation (x_1; mm), annual mean air temperature (x_2; ºC), level of economic development and trade activity (x_3), and land area (x_4; 10,000 km^2) were fitted with the data in Table 6 as follows:

s-x_1:

s=117.7054-0.0183x_1, n=11, r^2=0.023, F=0.215, p=0.654

s=-0.0001x_1^2+0.1766x_1+43.2133, n=11, r^2=0.311, F=1.805, p=0.225

s-x_2:

s=131.4428-1.8366x_2, n=11, r^2=0.063, F=0.605, p=0.457

s=-0.7158x_2^2+18.4206x_2+30.2042, n=11, r^2=0.784, F=14.545, p=0.002

s-x_3:

s=2.4576+30.9435x_3, n=11, r^2=0.904, F=84.76, p=0.001

s-x_4:

s=126.5768-0.4815x_4, n=11, r^2=0.107, F=1.08, p=0.33

It is obvious that the number of invasive species for non-island countries is significantly correlated to the level of economic development and trade activity of the country. The level of economic development and trade activity of a country determines the number of invasive species in this country. However there are not significant linear correlations between the number of invasive species and annual precipitation and annual mean air temperature. The relationships between the number of invasive species and annual precipitation and annual mean air temperature appear to be a bell curve. Presumably there is a fixed range for both annual precipitation and annual mean air temperature within which species invade frequently. Land area of a country is not correlated to the number of invasive species. According to these results, a multivariable regression is developed as the following:

$$s=6.849-0.0365x_1+0.00002x_1^2+3.4683x_2-0.1455x_2^2+28.8981x_3,$$
$$n=11,\ r^2=0.919,\ F=11.497,\ p=0.05$$

The modeled number of invasive species based on the multivariable regression above is shown in Table 7.

Table 7 Modeled number of invasive species of non-island countries based on multivariable regression.

	Germany	France	Czech	Portugal	Spain	Italy
Observed	139	188	92	122	166	170
Modeled	157	158	98	156	156	157
Observed	Greece	Egypt	Nigeria	Benin	Mongolia	
Modeled	101	63	50	20	30	

Table 8 Overlap percentage (%) of invasive species for various groups of climates*.

	I	II	III	IV	V
I	-	71	18	9	9
II	71	-	21	10	9
III	18	21	-	27	11
IV	9	10	27	-	9
V	9	9	11	9	-

*Collected from ISSG (2010)

As indicated in Table 8, climate groups I and II share the greatest number of invasive species. Despite the climates of temperate marine climate and Mediterranean climate are different, however frequent species exchanges owing to geographical adjacency of the two groups of countries have resulted in a greater Overlap of their invasive species.

Temperate marine climate has a uniform precipitation in a year and temperature varies slightly over a year. The summer of Mediterranean climate is dry and warm, and the winter is wet and cold. The climate conditions together with advanced economic development and active trade activity for the countries with temperate marine climate and Mediterranean climate, have resulted in more invasive species in these countries. Tropical desert climate countries, such as Egypt, have less precipitation and higher temperature over a year and thus native species are scarce. However there are also certain numbers of invasive species for its economic level and trade activity. For instance, in Egypt there are 63 invasive species including 36 animal species and 22 plant species. Of 63 invasive species, 46 species are from the aquatic environment, which demonstrates that Egypt mainly faces the threat from invasive species of coastal land but not invasion to inland.

Countries with a tropical grassland climate like Nigeria and Benin have relatively fewer invasive species (53 species) due to their relative low economic level and trade activity. Temperate continental climate has less precipitation and the difference of winter-summer temperature is relatively greater. Fewer invasive species in countries with a temperate continental climate, such as Mongolia (30 invasive species), were resulted from this climate and the low economic level and trade activity.

Overall the difference of the number of invasive species among various countries is mainly due to the difference of economic development and trade activity. As a bridge of Europe and Africa countries, Egypt has a greater similarity with both climate groups I-II and IV. In a similar way, groups III and IV have a certain Overlap in invasive species.

It is found that five species invade all groups of climates. They are all animals, including a fish, Cyprinus carpio, and a rinderpest virus (RPV).

3.2.2 Island countries

Four typical island countries, Japan, Philippines, Indonesia and New Zealand were chosen for analysis of biological invasion. They belong to different climate patterns, as indicated in Table 9.

Regression relationships between the number of invasive species (s) and annual precipitation (x_1; mm), annual mean air temperature (x_2; ºC), level of economic development and trade activity (x_3), and land area (x_4; 10,000 km^2) were fitted with the data in Table 9 as follows:

s-x_1:

s=365.5-0.093x_1, n=4, r^2=0.441, F=1.576, p=0.336

s=-0.0001x_1^2+0.3550x_1-68.5, n=4, r^2=0.521, F=0.543, p=0.692

s-x_2:
s=336.4614-7.7512x_2, n=4, r^2=0.972, F=69.323, p=0.014
s=0.1702x_2^2-14.6158x_2+398.9038, n=4, r^2=0.973, F=18.087, p=0.164
s-x_3:
s=97.0909+23.5455x_3, n=4, r^2=0.621, F=3.283, p=0.212
s-x_4:
s=200.0724-0.2887x_4, n=4, r^2=0.160, F=0.382, p=0.599

Table 9 Information of island countries chosen*.

Climate	Country	Annual precipitation (mm)	Annual mean air temperature (ºC)	Level of economic development and trade activity	Land area (10,000 km^2)	Number of invasive species
Temperate and subtropical monsoon climate	Japan	1500	15	5	38	212
Tropical monsoon and tropical rain forest climate	Philippines	2500	27	3	30	119
Tropical rain forest climate	Indonesia	2000	26	1	190	145
Temperate marine climate	New Zealand	2000	13	5	27	242

*Calculated from ISSG (2010) and internet resources

From the results above, the number of invasive species for island countries is largely correlated to the level of economic development and trade activity of the country. There are not significant linear correlations between the number of invasive species and annual precipitation and annual mean air temperature. On the other hand, the relationships between the number of invasive species and annual precipitation and annual mean air temperature may be described with a bell curve. It is speculated that there is a reasonable range for both annual precipitation and annual mean air temperature, within which biological invasion occurred more frequently. Land area of an island country is not correlated to the number of invasive species.

As the developed countries, Japan and New Zealand have active trade activities with other countries and thus possess the most invasive species. Of 212 invasive species in Japan, there are 111 animal species and 86 plant species. Due to the less trade activities and relative backward economic development, the number of invasive species of Philippines and Indonesia is less than New Zealand and Japan. It is interesting that Indonesia' invasive species are less than Philippines in terms of their land area and the area of tropical rain forests. As indicated in Table 10, Philippines and Indonesia share the most invasive species (92 invasive species), attributing to their geographical adjacency and the similarity in climate patterns.

In total 28 species invade all of the four island countries, of which 8 invasive species are recorded in the list of 100 of the world's most worst invasive species (ISSG, 2010). The eight species are Achatina fulica (mollusk), Anoplolepis gracilipes (insect), Cyprinus carpio (fish), Eichhornia crassipes (aquatic plant), Gambusia affinis (fish), Pueraria montana var. lobata (vine, climber), rinderpest virus (microorganism), and Trachemys scripta elegans (reptile).

Table 10 Overlap percentage (%) of invasive species for island countries chosen*.

	Japan	Philippines	Indonesia	New Zealand
Japan	-	30	29	25
Philippines	30	-	53	15
Indonesia	29	53	-	18
New Zealand	25	15	18	-

*Collected from ISSG (2010)

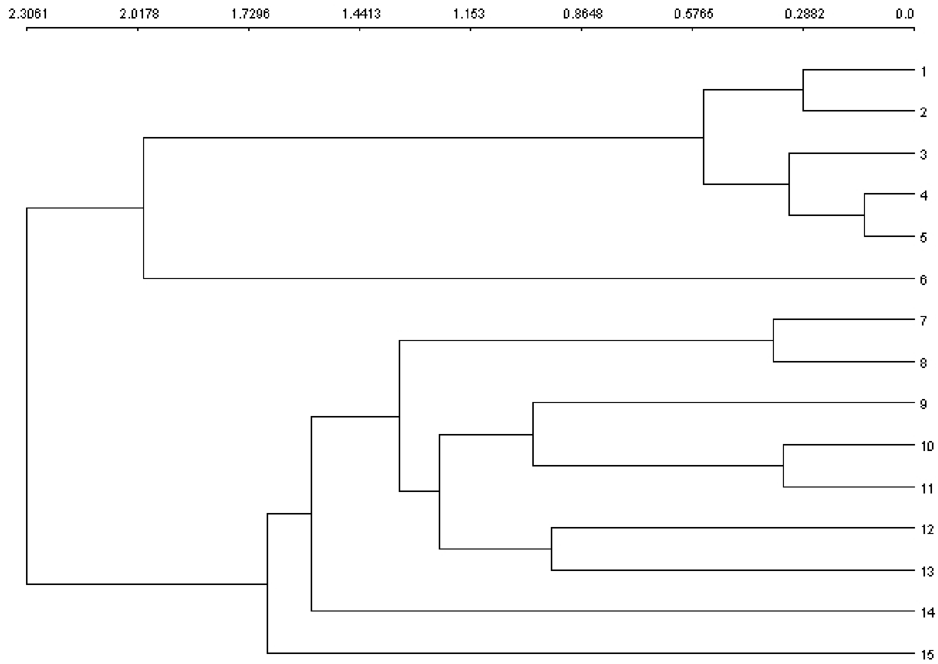

Fig. 2 One-dimensional orderly cluster analysis of various countries in regard to four indices. Countries 1-15 represent New Zealand, Japan, France, Italy, Spain, Indonesia, Germany, Portugal, Greece, Czech, Egypt, Nigeria, Mongolia, and Benin.

3.2.3 Joint relationship of island and non-island countries

Four indices, annual precipitation, annual mean air temperature, level of economic development and trade activity, and land area were used to conduct one-dimensional orderly cluster analysis (Fig. 2). Countries were ranked according to the number of invasive species as New Zealand, Japan, France, Italy, Spain, Indonesia, Germany, Portugal, Greece, Czech, Egypt, Nigeria, Mongolia, and Benin. The results indicated that New Zealand, Japan, France, Italy, Spain, and Indonesia are similar to each other, and there are similarities within the remaining countries, in terms of these indices.

Using the joint data of Tables 6 and 10, the regression relationship between the number of invasive species (s) and annual precipitation (x_1; mm), annual mean air temperature (x_2; ºC), level of economic development and trade activity (x_3), and land area (x_4; 10,000 km^2) are fitted as follows:

s-x_1:
$s=0.0251+96.4484x_1$, $n=15$, $r^2=0.076$, $F=1.075$, $p=0.319$
$s=-0.0001x_1^2+0.3550x_1-68.5$, $n=15$, $r^2=0.521$, $F=0.543$, $p=0.692$
s-x_2:
$s=147.5578-1.4347x_2$, $n=15$, $r^2=0.029$, $F=0.397$, $p=0.539$
$s=0.1702x_2^2-14.6158x_2+398.9038$, $n=15$, $r^2=0.973$, $F=18.087$, $p=0.164$
s-x_3:
$s=23.5231+30.1231x_3$, $n=15$, $r^2=0.647$, $F=23.864$, $p=0.0003$
s-x_4:
$s=135.4242-0.2136x_4$, $n=15$, $r^2=0.027$, $F=0.364$, $p=0.557$

It is concluded that the number of invasive species in a country is positively correlated to level of economic development and trade activity of the country. The level of economic development and trade activity of a country determines the number of invasive species of the country. There are not significant linear correlations between the number of invasive species and annual precipitation and annual mean air temperature. Relationships between the number of invasive species and annual precipitation and annual mean air temperature appear to be a bell curve. It seems that there is a limited range for both annual precipitation and annual mean air temperature within which species invade more frequently. Land area of a country is not correlated to the number of invasive species. A multivariable regression is thus developed as the following:

$$s=5.9724+0.0129x_1+0.0000175x_1^2+12.2522x_2-0.5144x_2^2+12.6117x_3,$$
$$n=15,\ r^2=0.839,\ F=9.456,\ p=0.001.$$

The modeled number of invasive species based on the multivariable regression above is shown in Table 11.

Table 11 Modeled number of invasive species based on multivariable regression.

Country	Germany	France	Czech	Portugal	Spain	Italy	Greece	Egypt
Observed	139	188	92	122	166	170	101	63
Modeled	156	155	127	153	153	157	115	54
Country	Nigeria	Benin	Mongolia	Japan	Philippines	Indonesia	New Zealand	
Observed	50	20	30	212	119	145	242	
Modeled	82	27	22	196	141	85	237	

It is concluded that economically motivated human activity plays important role in the introduction of invasive species. Geographical adjacency and climate similarity are responsible for the higher similarity of invasive species between different countries. Overall island countries have more invasive species than non-island countries.

3.2.4 Analysis of 100 most worst invasive species

In 100 most worst invasive species, there are 56 species of animals, 36 species of plants, 2 species of protozoa, 5 species of fungi and 1 species of virus. Compared to the complete list of all invasive species, animals and fungi are economically and ecologically important than plants (Table 12).

Table 12 Number and proportion of various groups of organisms*.

Group	Total number of invasive species	Number of species in 100 most worst invasive species	Percent (%)
Plant	374	36	9.63
Animal	270	56	20.74
Protist	23	2	8.70
Fungus	20	5	25.00
Virus	8	1	12.5

*Collected from ISSG (2010)

Table 13 Information of invasive species for various groups of climates*.

Group	Country	Total number of invasive species	Number of species in 100 most worst invasive species	Percent (%)
I	Germany	139	26	18.71
	France	188	36	19.15
	Czech	92	16	17.39
	Total	212	42	19.81
II	Portugal	122	25	20.49
	Spain	166	37	22.29
	Italy	170	35	20.59
	Greece	101	19	18.81
	Total	211	48	22.75
III	Egypt	63	16	25.40
IV	Nigeria	50	10	20.00
	Benin	20	7	35.00
	Total	53	12	22.64
V	Mongolia	30	5	16.67

*Calculated from ISSG (2010)

Table 14 Information of invasive species for island countries chosen*.

Country	Number of invasive species	Number per 100 invasive species	Percent (%)
Japan	212	44	20.75
Philippines	119	24	20.17
Indonesia	145	36	24.83
New Zealand	242	50	20.66

*Calculated from ISSG (2010)

Based on the records, of 100 most worst invasive species, there are 73 species for aquatic environment and 67 species for terrestrial environment. Biological invasion to both aquatic environment and terrestrial environment are nearly equally important.

In total 53 species are from agricultural area and 54 for urban area. There is not distinctive difference in invasive species of the two environments.

Except for Benin, for most island and non-island countries the ratio of invasive species in 100 most worst invasive species to the total number of invasive species is generally around 20% (Tables 13 and 14).

4 Discussion and Conclusions

Based on the results above, some conclusions may be drawn as follows:

(1) The number of invasive species in a country is positively correlated to the level of economic development and trade activity of the country. Relationships between the number of invasive species and annual precipitation and annual mean air temperature appear to be a bell curve. There is likely a limited range for both annual precipitation and annual mean air temperature within which species invade more frequently. Regression models were developed to describe the relationships between the number of invasive species and climate and economically motivated human activity.

(2) Geographical adjacency, climate and environment similarity are responsible for higher similarity of invasive species between different countries.

(3) The environments for biological invasion are diverse. Even in harsh environment of desert areas twenty-four invasive species were recorded. In general, invasive species in temperate humid areas is most diverse, followed by tropical humid areas, tropical arid areas, temperate arid areas, and boreal areas.

(4) The diversity of invasive plant species and animal species are different. Invasive plant species are more diverse than animal species. This is due to the higher trophic level of animal species than plant species. Animal species (predation, competition, etc.) will influence more trophic levels than plant species (mainly competition). Furthermore, a higher ratio of invasive animal species in the list of 100 most worst invasive species is attributed to the same reason.

(5) Island countries generally hold more invasive species than non-island countries.

Successful establishment of a given invasive species depends on both biotic and abiotic factors in the new environment, including climate and environmental conditions in the area of invasion (Worner and Gevery, 2006). Climate is considered to be one of the most important factors influencing the establishment of invasive species in new locations (Peacock et al., 2006; Zhang, 2010). It is necessary to develop quantitative methods that can detect the climatic factors influencing the establishment for invasive species from existing climatic and species distribution data (Anderson, 2005; Sutherst and Maywald, 2005; Worner, 1994). Up till now various climate-based models have been developed and applied to predict the establishment of invasive species in new regions (Carpenter et al., 1993; Robertson et al., 2001; Farber and Kadmon, 2003; Beaumonta et al., 2005; Stockwell, 1997; Stockwell et al., 2006; Elith et al., 2006; Phillips et al., 2006; Skov et al., 2008). Similarly, models and quantitative methods are also needed in the analysis of the number of invasive species with country as the basic unit, as done in present study. The present study proved that climate especially annual precipitation and annual mean air temperature is not linearly correlated to the number of invasive species in a country. Given a suitable range of climate, the number of invasive species is determined by human activity and other factors, a conclusion somewhat different from that for single species.

As mentioned above, successful biological invasions depend on not only characteristics of species and environment conditions, but also between-species interactions. Species composition of native communities will greatly determine the establishment of invasive species. Further surveys on species composition of invaded regions are thus needed. Food webs are suggested to be studied in order to predict the successful establishment of invasive species.

It is thus suggested that information as climate (Hijmans et al., 2005), bio-resource, and biological invasion related economic data for every country should be recorded in the global invasive species database, in order to provide basic data for developing more effective models on biological invasions and finding more valuable influential factors (Hirzel et al., 2002). More countries and more influential factors should be used to make more reasonable analysis in the future.

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References

Andersen MC. 2005. Potential applications of population viability analysis to risk assessment for invasive species. Human and Ecological Risk Assessment, 11: 1083-1095

Beaumonta LJ, Hughes L, Poulsen M. 2005. Predicting species distributions: use of climatic parameters in BIOCLIM and its impact on predictions of species' current and future distributions. Ecological Modelling, 186: 250-269

Beerling DJ, Huntley B, Bailey JP. 1995. Climate and the distribution of Fallopia japonica-use of an introduced species to test the predictive capacity of response surfaces. Journal of Vegetation science, 6:269-282

Carpenter G, Gillison AN, Winter J. 1993. DOMAIN:a flexible modeling procedure for mapping potential distributions of plants and animals. Biodiversity and Conservation, 2:667-680

Chiras DD. 2001. Environmental Science: Creating A Sustainable Future (Sixth Edition). Jones and Bartlett, USA

Elith J, Graham H C, Anderson P R, et al. 2006. Novel methods improve prediction of species distributions from occurrence data. Ecography, 29: 129-151

Elton CS. 1958. The Ecology of Invasion by Animals and Plants. Methuen, USA

Falk-Petersen J, Bøhn T, Sandlund OT. 2006. On the numerous concepts in invasion biology. Biological Invasions, 8: 1409-1424

Farber O, Kadmon R. 2003. Assessment of alternative approaches for bioclimatic modeling with special emphasis on the Mahalanobis distance. Ecological Modelling, 160: 115-130

Hellgren EC, Bales SL, Gregory MS, et al. 2007. Testing a Mahalanobis distance model of black bear habitat use in the Ouachita Mountains of Oklahoma. Journal of Wildlife Management, 71(3): 924-928

Hijmans RJ, Cameron SE, Parra JL, et al. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology, 25: 1965-1978

Hirzel AH, Hausser J, Chessel D, et al. 2002. Ecological-niche factor analysis: how to compute habitat-suitability maps without absence data. Ecology, 83(7): 2027-2036

ISSG.. 2010. Global Invasive Species Database. http://www.issg.org/database/welcome/

IUCN. 2010. Invasive species. http://www.iucn.org/

Mack RN, Simberloff D, Lonsdale WM, et al. 2000. Biotic invasions: cause, epidemiology, global consequences, and control. Ecological Applications, 10: 689-710

Meyer MD, Robertson MP, Peterson AT, et al. 2008. Ecological niches and potential geographical distributions of Mediterranean fruit fly (Ceratitis: capitata) and Natal fruit fly (Ceratitis: rosa). Journal of Biogeography, 35: 270-281

Mulles Jr MC. 2002. Ecology: Concepts and Applications (2rd Edition). McGraw-Hill, Boston, USA

Peacock L, Worner SP, Sedcole R. 2006. Climate variables and their role in site discrimination of invasive insect species distributions. Environmental Entomology, 35(4): 958-963

Peel MC, Finlayson BL, McMahon TA. 2007. Updated world map of the Köppen–Geiger climate classification. Hydrology and Earth System Sciences, 11: 1633–1644

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling, 190(3-4): 231-259

Robertson MP, Caithness N, Villet MH. 2001. A PCA-based modelling technique for predicting environmental suitability for organisms from presence records. Diversity and Distributions, 7:15-27

Skov H, Humphreys E, Garthe S, et al. 2008. Application of habitat suitability modelling to tracking data of marine animals as a means of analyzing their feeding habitats. Ecological Modelling, 212(3-4): 504-512

Stockwell DRB. 1997. Generic predictive systems: an empirical evaluation using the Learning Base System(LBS). Expert Systems With Applications, 12(3): 301-310

Stockwell DRB, Beach, et al. 2006. The use of the GARP genetic algorithm and Internet grid computing in the Lifemapper world atlas of species biodiversity. Ecological Modelling, 195(1-2): 139-145

Sutherst RW, Maywald GA. 2005. Climate model of the red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae): Implications for invasion of new regions, particularly Oceania. Environmental Entomology, 34(2): 317–335

Underwood EC, Klinger R, Moore PE. 2004. Predicting patterns of non-native plant invasions in Yosemite National Park, California, USA. Diversity Distribution, 10: 447-459

Vitousek PM ,Antonio CM, Loope LL. 1996. Biological invasions as global environmental change. American Scientist, 84: 468-478

Wikipedia. 2010. Köppen climate classification. http://en.wikipedia.org/wiki/K%C3%B6ppen_climate_classification#cite_note-1

Worner SP, Gevrey M. 2006. Modelling global insect pest species assemblages to determine risk of invasion. Journal of Applied Ecology, 43(5): 858–867

Worner SP. 1994. Predicting the establishment of exotic pests in relation to climate. In: Quarantine Treatments for Pests of Food Plants (Sharp JL and Hallman GJ eds.).Westview Press, Boulder, USA

Zhang WJ. 2007. Methodology on Ecology Research. Sun Yat-sen University Press, Guangzhou, China

Zhang WJ. 2010. Computational Ecology: Artificial Neural Networks and Their Applications. World Scientific, Singapore

Zhang YT, Fang KT. 1982. Introduction to Multivariable Statistical Analysis. Science Press, Beijing, China