Department of Economics "S. Cognetti de Martiis"

Via Po, 53 – 10124 Torino (Italy)
Tel. (+39) 011 6704043 - Fax (+39) 011 6703895
URL: http//www.de.unito.it

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Socio-economic drivers of biological invasions. A worldwide, bio-geographical analysis of trade flows and local environmental quality

Sergio Giaccaria e Silvana Dalmazzone

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Sergio Giaccaria and Silvana Dalmazzone

Department of Economics, University of Torino and IRIS- International Research Institute on Sustainability, Via Po, 53, 10122 Torino, Italy.

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[Preliminary version]

Abstract

The introduction of harmful non-indigenous species has long been acknowledged to depend both on the propagule pressure imposed by the openness to international trade, and on the health of the receiving ecosystem, largely determined by the level of anthropogenic disturbance due to local economic activities. We estimate the relative weight of the socio-economic drivers of biological invasions, for 115 countries in all continents and for invasive species of all taxa. Our results confirm the theoretical prior of trade, agricultural imports *in primis*, as an important driver of biological invasions, but also shed more light on the factors of disturbance to local ecosystems that emerge as playing an even more important role. We then develop an analytical model linking introductions of invasive species to import volumes disaggregated by country of origin, and weighted by bioclimatic similarity between source and destination country of the trade flow. The results allow us to identify the relative risk of biological invasions entailed by different directions of trade among 134 countries aggregated in geographic regions.

Keywords: Invasive species, alien species, non-indigenous species, trade, driving forces, propagule pressure, disturbance, bioclimatic similarity.

JEL Classification: Q01, Q27, Q56, Q57

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1. Introduction

Due to their increasing severity, unintended introductions of non-indigenous species (NIS) and the resulting ecological and economic damage have received growing attention in recent years. If there is a long history of studies on biological invasions in the natural sciences, with classical works dating back to the 1950s (e.g. Elton 1958), economics has begun devoting attention to the issue in the last decade, after international scientific and policy-oriented initiatives (such as the Global Invasive Species Programme, sponsored by the United Nations and major international environmental organizations) called for the inclusion of an economic perspective on the driving forces and on the policy options. The corpus of economic analyses is now relatively rich, comprising studies on the valuation of economic costs (e.g. Turpie and Heydenrych 2000, Born *et al.* 2005, McIntosh *et al.* 2007, Adams and Lee 2007, Horsch and Lewis 2009), on the economic determinants (Costello *et al.* 2007, Westphal *et al.* 2007, Hlasny and Livingston 2008, Rodríguez-Labajos *et al.* 2009), on policy strategies (Shogren 2000, Eiswerth and Johnson 2002, Perrings 2005, Leung *et al.* 2005, Finnoff *et al.* 2005, Horan and Lupi 2005, Margolis *et al.* 2005, Costello *et al.* 2006, Batabyal 2006, Mehta *et al.* 2007, Mérel and Carter 2008), on bioeconomic models that examine the influence of specific traits of invading species on their chances of establishing and on the optimal prevention and management options (Finnoff and Tschirhart 2005, Gutierrez and Regev 2005, among others).

A complete survey of the economic literature on biological invasions – a hint on its dimensions being offered by the about 140 Econlit results between 1997 and 2009 – is beyond the scope of this paper. This work places itself among the studies that seek to deepen our understanding of the economic determinants of the phenomenon. Vastly improved availability of data now enables to do much better than the early studies investigating the relative weight of different socio-economic drivers.

Among the initial economic analyses on the issue, Dalmazzone (2000) investigated the degree to which vulnerability to biological invasions depended on the disruption caused by economic activity to ecosystems or rather on the economy's openness to the movement of goods and people (the classical 'disturbance' vs. 'propagule pressure' hypotheses of biological invasions theory). Ecological data referred to established alien plant species in 26 countries, over the 1960s - early 1990s period, but were severely limited in terms of homogeneity in quality and definition of the variables. It is now possible to return on the subject by looking at 115 countries worldwide, with a uniform ecological dataset – the IUCN Global Invasive Species Database – comprising invasive species across all taxa recorded until August 2009.[1] The analysis of the role played by an economy's openness can be refined by disaggregating agricultural and manufactured imports. It is now also possible to employ more detailed proxies of local disturbance than the overall level of production (per capita GDP) or population density: we use the Domestic extraction of biomass, the National Biodiversity Index, the Ecological Footprint of building constructions and of agricultural crops, the Ecological Deficit, the extension of protected areas, and a selection of Environmental Sustainability Indicators (ESI) such as System's Health and overfishing.

This first analysis allows us to offer a much more detailed and reliable view on the relative weight of the different socioeconomic factors affecting vulnerability to biological invasions. We then deepen the investigation with a closer look at the reconfirmed central role played by imports. Several studies have recently dealt with the issue: for example, Hlasny and Livingston (2008) examine the relation between imports, immigration and international travel and introduction of non-indigenous insects in the United States. Westphal *et al.* (2008) conduct the first worldwide study of the impact of international trade (merchandise imports) on biological invasions, refereed to all species, using a regression tree analysis. Costello *et al.* (2007) push the matter further with the first investigation of how the risk of invasions carried by imports varies by trading partner: they use data on shipping, disaggregated by country of origin, and marine species discoveries in the San Francisco Bay until 1994. They distinguish imports arriving from Atlantic/Mediterranean region, West Pacific, Indian Ocean.

Our work aims at following the route indicated by Costello *et al.* (2007): we look at how the composition of trade flows, i.e. disaggregating each economy's imports among source countries, adds to our understanding of biological invasions. Rather than concentrating on one receptor and considering imports by macro-areas of provenience, we analyze invasion risk by trading partner using the same scale for destination and source of invasives, including 134 countries and their bilateral trade flows. As in Westphal *et al.* (2007), our ecological data refer to invasive species across all taxa.

Finally, we considered the limitation imposed by aggregating source and host loci of invasions by country (the scale of economic data) rather than by bio-geographic regions, the ideal empirical approach pointed to by Levine and D'Antonio (2003)

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[1] The GISD database (www.issg.org) compiled by the Invasive Species Specialist Group of the IUCN, is the most comprehensive database on invasive species worldwide currently available. It includes 227 countries and 357 alien invasive species across all taxa. The number of observations in our analysis is the result of the availability of data for all regressors (see Table 1).

and Costello *et al.* (2007). Treating trade flows between all countries as uniform in their probability of becoming pathways of invasions disregards the role of the suitability of receiving habitats – their similarity to the potential invader's native one – as a predictor of invasion success. We try to make a step ahead on this front by weighting trade flows by the degree of bioclimatic similarity between potential source and host countries, measured by means of a Jaffe (2006) index constructed on the base of the Terrestrial Ecoregions geo-referenced database (Olson *et al.* 2001) distributed by WWF.

2. Model structure and data

In this paper we develop and test two analytical models. Both employ the total number of biological invasions per country as dependent variable, explained however by different sets of regressors. The positive integer nature of the dependent variable suggests to use a count data approach (Poisson and negative binomial via maximum likelihood). We assume that in the basic Poisson specification n_i (the number of non-indigenous invasive species recorded in country i) follows the probability distribution:

$$\Pr[n_i] = e^{-\lambda_i} \frac{(\lambda_i)^{n_i}}{n_i!} \tag{1}$$

where the parameter λ_i is linked to the regressors in a loglinear form, $\ln \lambda_i \approx \mathbf{Xb}$.

The disadvantage of the Poisson model is that the mean and variance are imposed to be equal to the parameter value, an assumption usually not respected by empirical datasets that typically exhibit variances larger that the mean. To account for this for each regression we estimate, in addition to the Poisson specification, a negative binomial specification of our models, that allows us to account for overdispersion of variances. In fact, the negative binomial relaxes the delicate assumption on mean and variance by adding a random term ε_i distributed according to a gamma distribution with parameter θ:

$$\ln \lambda_i = \mathbf{Xb} + \ln \varepsilon_i . \tag{2}$$

The analytical solution to integration gives the form:

$$\Pr[n_i] = \frac{\Gamma(\theta + n_i)}{\Gamma(n_i + 1)\Gamma(\theta)} \left(\frac{\lambda_i}{\lambda_i + \theta} \right)^{n_i} \left(\frac{\theta}{\lambda_i + \theta} \right)^{\theta} \tag{3}$$

2.1 The relative weight of socio-economic drivers of invasions

The first model concerns the relationship between the intensity of the phenomenon (the total number of alien invasive species per country), and some relevant indicators of (i) the exposure to invasions due to an economy's openness to international movements of goods and people, and (ii) the level of disturbance to local ecosystems imposed by human activities. The dataset merges indicators taken from different statistical international databases. To facilitate the interpretation and comparison among variables, all variables except dummies have been standardized and expressed in shares, as a ratio between the value of each observation and the maximum, *i.* Hence, the effect of a variation in the share of each regressor has to be interpreted as a beta percent of variation in the expected value of the number of NIS.

The first subset of variables includes quantitative indicators of the extroversion of an economy: *agricultural* and *manufactured imports* (WTO trade statistics, 10^6US$, year 2005), as the components of merchandise trade that are more likely to affect the unintentional transport of biotic materials with invasive potential. The number of *tourists* has been included as well in the subset of openness indicators (World Tourism Data, World Tourism Organization, expressed in 10^3 arrivals, year 2005).

A second subset of regressors pertain to characteristics that may influence a country invisibility: *area* (United Nations Statistic Division 2009) as the total surface of land within the countries boundaries, and *island*, a dummy variable for countries entirely sited on islands; the biological literature ascribes a higher sensitivity to biological invasions to island ecosystems, whose endemic species have evolved in isolation over a long period of time. The variable *protected area* derives from the ratio of total area under ecological and environmental protection over the total surface of a country. It checks for correlation among bioinvasions and land use outcomes of nature conservation policies.

The third subset of regressors represent proxies of several forms of disturbance imposed by economic activities on natural habitats, that may undermine the ability of ecosystems to resist invasions. Disturbance creates open space that may allow alien species to get established. Intermediate levels of disturbance, particularly, offer invaders an edge against the better adapted and therefore usually competitively stronger native species (Connell 1978; Rejmánek 1989; Lodge 1993; Etter and Caswell 1994; Pišek *et al.* 1998; Shigesada and Kawasaki 1997 and references therein). The higher frequency of alien species in disturbed sites, however, may simply reflect the fact that disturbed areas are those where rates of introduction through economic activities are higher (Crawley 1987; Usher *et al.* 1988; and Williamson 1996). It has not been shown yet, in other words, how important disturbance is as a determinant of invisibility – of the chances to get established that a given area offers to an alien species.

For this reason we have chosen to refine the analysis on this front with a broader set of indicators aimed at capturing different forms of anthropogenic disturbance. We have included, as in previous studies, the standard information on aggregate economic and demographic factors imposing pressures on ecosystems: *per capita GDP* (WDI, 106 US$, year 2005), and *population density* (WDI population data, year 2005). We have then added an indicator of economies' impact on local ecosystems due to the supply of food and other agricultural non-energy goods (excluding imports), accounted by means of the EUROSTAT methodology of Material Flow Accounting (Krausmann *et al.* 2008): the variable *biomass extraction* measures the total quantity of harvested biomass within the country boundaries (10^3 tons, year 2000). The pressure imposed on marine ecosystems is represented by the variable *overfishing* (ESI indicators 2005). The variable *ecological deficit* is a dummy equal to one for those countries where the total biocapacity is exceeded by the ecological footprint of consumption, i.e. the quantity of land necessary to supply all consumed environmental goods and services required by an economy (Ewing *et al.* 2008). The *ecological deficit* variable captures also the component of local consumption due to imports, hence including the environmental pressure that a country imposes, through its demand of goods and services, on other countries. It is therefore a mixed indicator of both an economy openness and of the disturbance it imposes on local ecosystems.

The last two explanatory variables are aggregate indicators of ecosystem integrity. *System Health* is one of the indicators composing the Environmental Sustainability Index (ESI), calculated via a principal component analysis on a variety of ecological indicators (Esty *et al.* 2005).[2] The *National Biodiversity Index*, although correlated with the System Health indicator, has been included in order to specifically address the role played by biodiversity in affecting susceptibility to biological invasions. It is based on estimates of richness and endemism in the four terrestrial vertebrate classes and vascular plants, adjusted to country area (WCMC 1992).

The extremely high number of alien species recorded in the United States is generally recognized as being influenced by the higher relative surveying and cataloguing effort of the US compared with all other countries. In order to control

[2] System Health is a subcomponent of the Environmental Sustainability Index. It is derived from a principal component analysis, collecting information from five other indicators related to biodiversity and habitat conservation: ECORISK (the percentage of territory in threatened ecoregions), PRTBRD (Threatened bird species as percentage of known breeding bird species in each country), PRTMAM (Threatened mammal species as percentage of known mammal species in each country), PRTAMPH (Threatened amphibian species as percentage of known amphibian species in each country), NBI (National Biodiversity Index).

for this we introduce the number of endemic species that have produced ecological damage as invasives in other countries (*Native sp. invaders elsewhere*), its value linked as well to the accuracy of monitoring and surveying: used as a control variable, it captures some of the bias that would otherwise fall on the other coefficients.

The explanatory variables used are summarized in Table 1.

Table 1. Descriptive statistics for the explanatory variables used.

Variable name	*Unit*	*Data coverage*	*Mean*	*St.Dev.*	*Min Max*
Island	Dummy variable	140	0.11		
Ecological deficit	Dummy variable	140	0.61		
Area	km^2	139	921535.9	2217203	5130 1.71e+07
Tourists	number of arrivals	120	1.26e+07	3.04e+07	9956- 2.41e+08
Agricultural imports	million US$	126	9736.817	22028.72	3.09743 197282.8
Manufactured imports	million US$	126	72864.71	200088	6.27691 1580536
Domestic extraction of biomass	1000 tons	136	132250.1	346342.1	524.6791 2481499
System health (Biodiversity)	-	136	0.0008088	.4814039	-1.99 0.89
National Biodiversity Index	-	139	0.5545324	.1554713	0.22 1
Population density	pop./km^2	139	96.99818	118.6467	1.657249 1013.578
Per capita GDP	US$/pop.	136	8840.167	14122.47	115.8853 66638.51
Protected Area	Protected area/ Total land area	134	0.1181201	0.1072639	0 0.72
Overfishing	-	115	4.699029	1.282116	2 7

2.2 The relationship between invasions and the composition of trade flows by country and bio-geographic region of origin

The second model builds on the results obtained by Costello *et al.* (2007), who showed that bioinvasion risk, in the case of marine non native species that entered the United States prior to 1997 via the San Francisco Bay commercial harbor, varies with trading partners. We aim at investigating whether a similar result is extendable to other invasive species and to other receptors. The ecological information we employ comes from the IUCN Global Invasive Species Database, listing invasive species across all taxa recorded until August 2009 in 227 countries. The constraint of matching economic data enables us to build a matrix of bilateral trade flows (merchandise trade and services imports, 10^6US$, year 2005) for 134 countries (Appendix I). The source of economic data is the IMF Direction of Trade Statistics 2009.

Ecological analyses of biological invasions typically include habitat suitability among the predictors of invasion success (e.g. Williamson 1996). Treating all trade flows as conveying an identical potential of bioinvasion, regardless of the spatial and bio-geographical location of trading partners, runs the risk to be a misleading assumption that weakens the explanatory power of the analysis. To avoid this, in our model imports are weighted according to the degree of bioclimatic similarity of the trading partners. This allows us to highlight the role played by habitat similarity between source and host countries on the bioinvasion risks associated with international trade. Borrowing from innovation economics we use a Jaffe's index, well experimented as a way to build weights expressing a similarity criterion (Jaffe 1986, Moreno *et al.* 2004, Parent and Lesage 2008). We have disaggregated the flows of imports according to the geographical location of the country of origin, then aggregated all the country-level trade flows by geographic regions (as defined in the World Bank classification, WDI 2009), and adjusted them for the degree of bioclimatic similarity. The regions are South Asia (SAS), North America (NA), Middle-East and North Africa (MENA), Latin America and Caribbean (LAC), Europe and Central Asia (ECA), Sub-Saharan Africa (SSA), East Asia and Pacific (EAP).

Revisiting Jaffe's index (1986), our similarity criterion measures the closeness between two regions *i* and *j* based on biome classes:

$$p_{ij} = \frac{\sum_{k=1}^{K} f_{ik} f_{jk}}{\sqrt{\sum_{k=1}^{K} f_{ik}^2 \sum_{k=1}^{K} f_{jk}^2}} \qquad (4)$$

where f_{ik} is the share of biome *k* in the total ecosystem of country *i* (area of biome *k* over total land area of country i), and f_{jk} is the share of biome *k* in country *j*.

Using this formula we build an ecosystem matrix that has 134 rows and 134 columns. In each cell a value $0 \leq P_{ij} \leq 1$ measures the degree of similarity between the composition of the ecosystems of two countries. The closer is P_{ij} to zero, the more dissimilar are the two regions from the point of view of ecosystemic composition.

Our division in biomes relies on Olson *et al.* (2001), distributed by WWF, who propose a hierarchical classification of ecosystems in realms, ecoregions and biomes (Figure 1). Through GIS techniques, we overlaid and intersected political boundaries and biomes so as to calculate the shares of each of these 15 ecosystem typologies:

1. Tropical and subtropical moist broadleaf forests;
2. Tropical and subtropical dry broadleaf forests;
3. Tropical and subtropical coniferous forest;
4. Temperate coniferous forest;
5. Temperate broadleaf and mixed forests;
6. Boreal forests/taiga;
7. Tropical and subtropical grasslands, savannahs and shrublands;
8. Flooded grasslands and savannahs;
9. Montane grasslands and shrublands;
10. Tundra;
11. Mediterranean forests, woodlands and scrub;
12. Desert and shrublands;
13. Mangroves;
14. Water bodies.

All imports for country *i* are first weighted by the similarity index (4) to account for bioclimatic similarity at a country level. For each country we then aggregate by region of origin (*h*) the weighted imports $p_{ij} x_{ij}$:

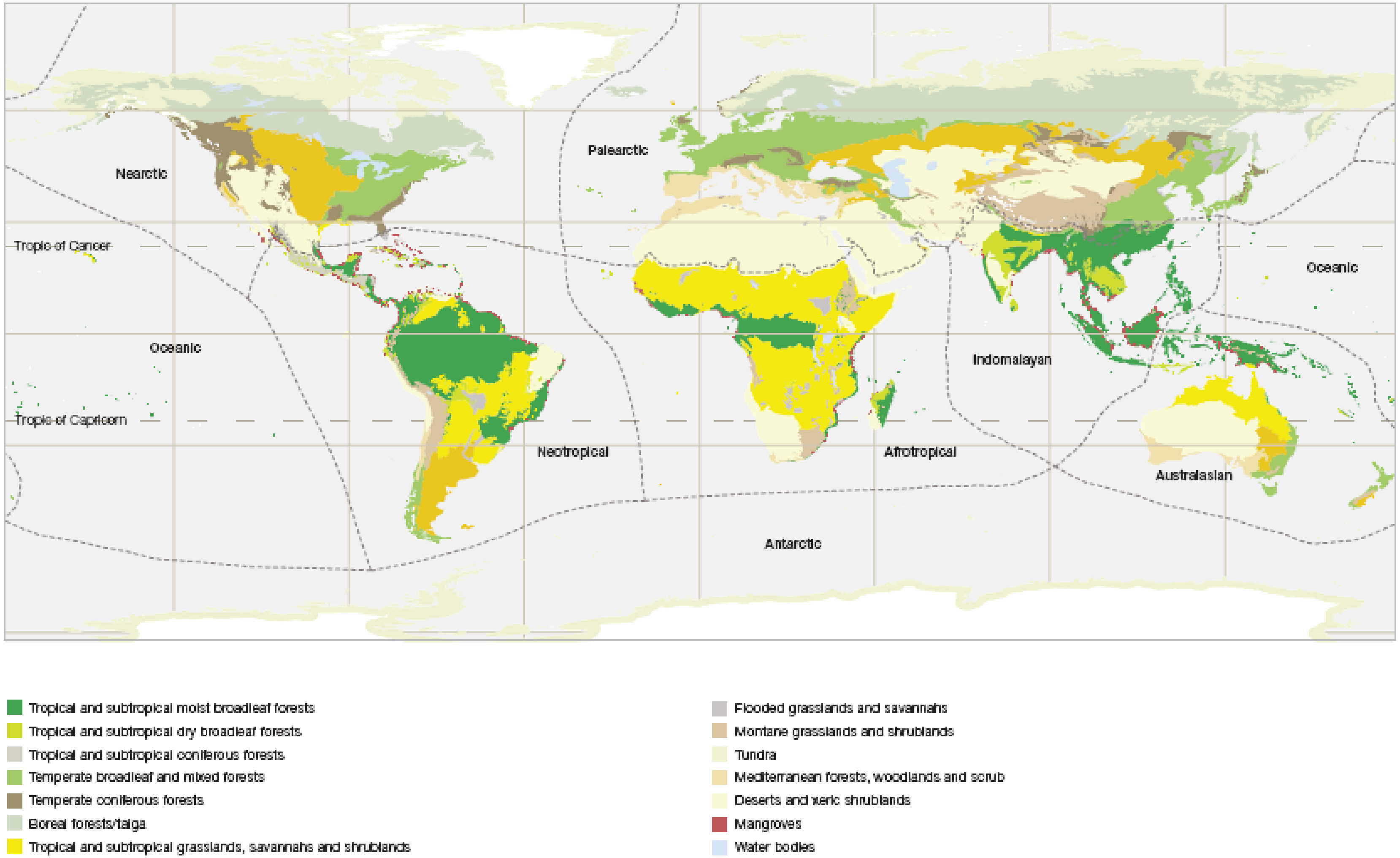
$$W_{ih} = \sum_j p_{ij} x_{ij} \qquad \forall j \in h \tag{5}$$

The specification of the negative binomial, that assumes as dependent the total number of NIS in country i, is:

$$\ln \lambda_i \approx \beta_{SAS} w_{SAS} + \beta_{NA} w_{NA} + \beta_{MENA} w_{MENA} + \beta_{ECA} w_{ECA} + \beta_{SSA} w_{SSA} + \beta_{EAP} w \ + \ln \varepsilon_i \tag{6}$$

The analysis allows us to highlight the association between the number of NIS per country and the imports disentangled by region of origin. We run separate regressions for the models with and without the weight for bioclimatic similarity. The model does not take into account, at this stage, the distance between source and destination country of the trade flow – a refinement that could contribute to further improve its explanatory capacity.

Figure 1. Terrestrial bio-geographic realms and biomes. *Source: Olson et al. 2001*.



3. Results

The regression results for the first model are presented in Table 2. They confirm the expected role of both the measures of economies' extroversion and of the level of disturbance to ecosystems in making countries more susceptible to NIS. While most previous studies on the socio-economic drivers of biological invasions focus primarily on international trade, this analysis indicates that the level of disturbance imposed on local ecosystems, or conversely their integrity, play an even more decisive role. Estimated coefficients for overfishing, population density, ecological deficit are all statistically significant and positive. The extraction of biomass alone has more than twice the impact of trade in raising the average number of NIS.

Per capita GDP also has a positive, heavy and statistically significant estimated coefficient. As an aggregate indicator of the scale of human activity, it plausibly captures the environmental damage caused locally by production activities, an important part of which (e.g. atmospheric, water and other forms of pollution before they arrive to threaten species or eco-regions; the absorption of environmental sink services) is not captured by the other indicators of disturbance to local ecosystems included in the analysis.

As to the impact of international trade, agricultural imports appear to carry all the responsibility of conveying invaders. Manufacturing imports exhibit an unexpected negative sign, statistically significant, in all model specifications.[3]

The island status affects positively the average number of NIS, as expected. Contrary to previous studies (e.g. Westphal *et al.* 2008) country area is not significant, independently of the presence or not of the US in the sample.

Countries' endowment in terms of biodiversity confirms to be associated with higher numbers of alien species, as found already in several studies (Westphal *et al.* 2008, Stark *et al.* 2006, Stohlgren *et al.* 1999, Lonsdale 1999). The hypothesis is that at large spatial scales the most species-rich areas have a larger resource heterogeneity, offering more chances of adaptation and establishment to invaders.

Movements of people play a minor role. Tourist arrivals are statistically significant but with a very low positive coefficient. The sensitivity of this result to the choice of explanatory variable has been checked by running alternative regressions including other flows of people movements (immigration) or specific transport modes (plane arrivals), all of them proving not significant.

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[3] The latter result reinforces the hypothesis of per capita GDP exerting an impact on a country's vulnerability to biological invasions due to the disturbance associated with production rather than to the correlation of GDP with the level of international trade.

Table 2. The relative weight of socio-economic drivers of invasions: regression results

	Full sample		Sample without US	
	Negative binomial	Poisson	Negative binomial	Poisson
N observations	115	115	114	114
Loglikelihood	-412.6763	-512.8372	-406.6774	-504.4674
	β [z values]	β [z values]	β [z values]	β [z values]
Island	0,41376	0,3182022	0,4028321	0,2994534
	[2,9]***	[5,45]***	[2,77]***	[5,08]***
Population density	0,109435	0,1833811	0,1112946	0,1953189
	[2,2]**	[7,4]***	[2,22]**	7,82]***
Overfishing	0,3645753	0,3175357	0,3667838	0,3505993
	[2,72]***	[4,32]***	[2,72]***	[4,67]***
Area	-0,1366235	-0,1805766	-0,1343138	-0,1809017
	[-0,41]	[-1,21]	[-0,4]	[-1,19]***
Agricultural imports	1,354154 [2,09]**	0,9927652 [4,86]***	1,565213 [1,98]**	1,579025 [5,63]***
Manufacturing imports	-1,168249	-0,8993558	-1,125347	-0,7230329
	[-2,23]**	[-4,79]***	[-2,08]**	[-3,74]***
Per capita GDP	1,465669	1,48574	1,448397	1,439059
	[6,07]***	[15,94]***	[5,92]***	[15,01]***
Ecological deficit	0,203555	0,2761819	0,2115622	0,3134051
	[1,8]*	[4,64]***	[1,84]**	[5,15]***
Protected areas	0,0800021	0,1005967	0,0799693	0,1015579
	[2,14]**	[5,15]***	[2,13]**	[5,16]***
System Health (Biodiversity)	-0,3245064 [-3,26]***	-0,407545 [-10,14]***	-0,3248648 [-3,25]***	-0,4041561 [-10]***
National Biodiversity Index	1,642182 [5,03]***	1,204256 [8,37]***	1,651325 [5,02]***	1,20677 [8,41]***
Extraction of biomass	2,959832 [9,16]***	3,344119 [21,25]***	2,884928 [8,01]***	3,077669 [16,97]***
Tourists	0,0890555	0,0503941	0,0820021	0,0207797
	[3,43]***	[4,49]***	[2,71]***	[1,39]
Native sp. invaders elsewhere	0,0158795 [1,78]**	0,0173544 [5,02]***	0,0176028 [1,81]***	0,0224057 [5,86]***
/lnalpha	-2,317369		-2,3055	
alpha	0,0985325		0,099712	

*, **, *** for p<0.1, p<0.05, p<0.01

Protected areas show a positive small correlation with the average number of NIS, counterintuitively at first but consistently with previous empirical findings. This has been interpreted as the result of a positive relationship between the number of visitors to protected areas and the number of alien species piggybacked on tourist vehicles (Lonsdale 1999, Vila and Pujadas 2001).

In the second model we investigate the correlation between number of NIS in each country and trade flows. At this stage of our research, total imports are distinct by region of origin, independently of their destination. β coefficients are therefore to be interpreted as indicators of the invasiveness of imports coming from countries belonging to different regions. To a unit increase in the value of imports from region i corresponds a β_i percentage increase in the world average number of NIS per country (Table 3).

Trade flows revealing the highest potential to convey non-indigenous species are those from Sub-Saharan Africa and South Asia. Based on negative binomial estimates with imports weighted by habitat similarity, an increase of one million US dollars in imports from Sub-Saharan Africa is related to a 0,31% increase in the average number of NIS per country. The same increase in imports from South Asia is related to a 0,15% increase in the average number of NIS per country. Much lower the risk of NIS introductions from Latin American and Caribbean countries (0,07%). A further sharp decrease in risk is associated with imports from Europe and Central Asia (0,004%), North America (0,003%) and East Asia and Pacific (0,001%). These results are likely to be driven, at least in part, by the relative weight of the agricultural and natural resource components in trade flows, which in the first part of our analysis have emerged as the imports working as pathways of invasions. Among further economic explanations to be considered is the comparative level of investment in control policies.

The case of imports from Middle-East and North Africa is the most dubious. The negative value of β_{MENA}, meaning that a unit increase in imports from that area is associated to a (very small) decrease in the average number of NIS per country, becomes statistically not significant when the United States are removed from the sample.

Weighting imports by bioclimatic similarity always causes the estimated association between imports and NIS to increase, a result particularly marked in the case of Sub-Saharan Africa. A comparison between the two specifications (weighted and non-weighted trade flows) by Likelihood-ratio tests confirms, with an increase in log-likelihood maximization of the weighted model compared to the non-weighted one, a significant contribution to the explanatory power on the part of weighted models. Examples of bilateral flows whose weight has been emphasized on the ground of bioclimatic similarity are New Zealand-France (p=0.93), Canada-Russia (p=0.95), Haiti-India (p=0.81), Madagascar-Guatemala (p=0.82), Algeria-Australia (p=0.85). This offers some novel evidence to the debate on the importance of habitat suitability as a factor determining the success rate of invasions, one of the open questions in biological invasions theory (Williamson 1996) – and an element for evaluating and forecasting the risk of introductions associated with different trading partners and for targeting preventive measures.

Excluding the United States, a control for the sampling bias potentially due to the very large number of NIS recorded in the US compared to any other country which is due also to a comparatively very high monitoring effort, does not lead to noticeable differences in the outcome of the regressions, except causing a loss of significance for the North American and Middle East coefficients.

4. Conclusions

We developed two models of the introduction of non-indigenous invasive species. The first looks at the socio-economic drivers of biological invasions. We used it to estimate the relative weight of the two classical priors of biological invasions theory that identifies propagule pressure (deriving from the openness of a country to the international movement of goods and people) and the level of disturbance to local ecosystems as concurrent determinants of the level of biological invasions in a country. Our estimates support the theoretical hypothesis that international trade is an important determinant of the level of NIS in a country and indicate that agricultural and natural resource imports are the actual pathway much more than manufactured imports. This may represent a useful information for cost-effective design of preventive measures. However, the estimated coefficients of indicators of the level of stress imposed on local ecosystems (extraction of biomass, overfishing, population density, ecological deficit) underline the fundamental role played by the environmental quality of the receiving country in determining its vulnerability to biological invasions. The analysis also sheds some light on open questions like the role of biodiversity of receiving ecosystems, of the movement of people and of protected areas.

The second model estimates the potential to convey non-indigenous species of trade flows from the different world regions. In addition, the regression analysis confirms the theoretical hypothesis that habitat similarity affects invasion success, showing the superiority of the model accounting for the bio-geographical location of trading partners over that treating all trade flows as involving an identical potential of bioinvasions.

The novel contributions of this papers to the status quo of the economic literature on biological invasions are:

(i) the extension of the analysis to all taxonomic groups of potential invaders. Empirical studies currently available focused on one class (e.g. insects), or on only one environmental medium (e.g. marine species). Our analysis considers how introductions of all (including marine, terrestrial, mammals, amphibian, insects, plants, etc.) non native species depend on different socio-economic drivers and on the composition of international trade flows by trading partner;

Table 3. The relationship between NIS and merchandise imports disaggregated by source country.

	Full sample including USA				**Restricted rejecting USA**			
	Weighted for similarity		NOT Weighted for similarity		Weighted for similarity		NOT Weighted for similarity	
	Negative Binomial	Poisson	Negative Binomial	Poisson	Negative Binomial	Poisson	Negative Binomial	Poisson
N observations	136		136		135		135	
Log-likelihood	-832.87	-7857.389	-841.34	-8238.1003	-808.50	-8134.07	-811.30	-8229.88
	β	β	β	β	β	β	β	β
ALIEN	[z values]	[z-values]	[z-values]	[z-values]	[z values]	[z-values]	[z-values]	[z-values]
South Asia (SAS)	0.0015678	.0002219	0.0009245	0.0001072	0.0013445	0.0000157	0.000992 [3.34	0.0001024
	[2.49]**	[10.91]***	[3.2]***	[10.31]***	[2.46]**	[0.31]	]***	[8.89]***
North America (NA)	0.00003	.000042	-0.0000335 [-	0.000024	0.000038	0.000043	-0.000079 [-	0.0000176
	[1.24]	[63.12]***	1.43]	[59.32]***	[0.95]	[64.5]***	3.65]***	[16.57]***
Middle-East and North	-0.0000392	.0002181	-0.000104	0.0000569	0.0001044	0.0002974	-0.0001795 [-	0.0000597
Africa (MENA)	[-0.22]***	[39.4]***	[-1.31]	[24.57]***	[0.49]	[39.49]***	2.11]***	[26.83]***
Latin America and	0.0007888	-.0001516	0.0002212	-0.0000558	0.0011573	0.0002398	0.0005416	0.00000739
Caribbean (LAC)	[4.21]***	[-28.99]***	[2.82]***	[-53.98]***	[4.62]***	[8.57]***	[4.27]***	[0.77]***
Europe and Central Asia	0.0000447	9.70e-06	0.0000195	0.00000382	0.0000413	0.000013	0.0000143	0.00000347
(ECA)	[4.29]***	[40.07]***	[2.88]***	[31.98]***	[4.08]***	[40]***	[2.33]***	[25.48]***
Sub-Saharan Africa (SSA)	0.0031097	.0011533	0.000000119	0.0000658	0.003091	0.0006052	0.0001283	-0.000000851
	[3.2]***	[38.24]***	[0]	[8.73]***	[3.32]***	[11.42]***	[0.49]	[-0.06]***
East Asia and Pacific	0.0001265	-.0000195	0.0000758	0.00000143[2.2	0.0001776	-0.0000661	0.0001067	-0.00000135
(EAP)	[2.35]**	[-8.32]***	[3.04]***	3]***	[2.85]***	[-16.87]***	[3.82]***	[-1.86]***
/lnalpha	2.068972		2.135748		1.940814		1.961635	
Alpha	7.916683		8.463372		6.964417		7.110945	

*, **, *** for p<0.1, p<0.05, p<0.01

(ii) the geographical coverage. The analysis is extended to a set of 115 countries (for the first model) and 134 countries (for the second model) in all continents;

(iii) the employment of a set of specific indicators of local pressure on ecosystems, that allows us to refine previous analyses on socio-economic drivers of invasions based only on more generic proxies of anthropogenic disturbance such as GDP or population density.

(iv) the consideration of the bio-geographic features of the source and destination countries, obtained by weighting trade with an index of bioclimatic similarity.

This study is still work in progress. The next step will be estimating a further version of the model in which the trade flows between countries belonging to the same region are excluded. That would allow us to estimate the introductions of NIS associated with imports coming from, say, South Asia, and destined anywhere in the world except to countries in South Asia. Comparing the results with those presented above will allow us to separately estimate the role of intercontinental, regional and local dispersal of NIS – and hence to evaluate whether and how the scale of international trade affects the risk of biological invasions. This could carry valuable policy implications since global, regional and local dispersal are controlled by different mechanisms. Also the ecological effects of invasions are scale-dependent, ranging from altered local community diversity and homogenization of global ecosystems, to modified biogeochemical cycles and disturbance regimes at regional or global scales (Pauchard and Shea 2006, Havel and Medley 2006). Insights on the scale dimension of the invasion processes would therefore also contribute to establishing priorities in designing control policies.

Being ours a cross-country analysis, we have chosen not to not take into account the fact that, as cumulative import volumes increase over time, they may involve a declining risk of new introductions – an important aspect built into times series studies such as Costello *et al.* (2007). This remains however an important factor that would be advisable to integrate in future developments, particularly in an ideal panel analysis of worldwide invasion trends. Indeed, it would be interesting to treat the issue of non-constant marginal impact of trade flows from any one source, rather than as a concavity prior, as a coefficient to be estimated through non parametric regressions.

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Appendix 1. Total imports of countries by WDI regions

country	SA_IMP	NA_IMP	MENA_IMP	LAC_IMP	EUA_IMP	AFR_IMP	EAP_IMP
ALBANIA	17.2281	53.37051	45.40664	80.77553	3526.873	0.289781	321.4448
ALGERIA	462.9342	2616.083	443.565	1822.764	16344.47	134.0601	4182.457
ANGOLA	289.9117	1493.779	36.29523	1575.524	6455.923	115.8485	1888.153
ARGENTINA	440.106	5644.585	288.516	18815.85	8407.634	6.926	7577.207
ARMENIA	30.39722	157.0412	191.5077	48.70927	2364.235	6.67447	357.5892
AUSTRALIA	1614.032	24146.39	1981.65	2759.665	40643.41	160.7809	75132.45
AUSTRIA	407.9128	4151.409	2258.223	741.6017	144854	197.2047	6684.913
AZERBAIJAN. REP. OF	84.7037	290.3606	37.2304	138.8535	4257.928	12.5534	619.4934
BANGLADESH	2872.604	720.885	1930.054	377.7478	2658.08	79.1675	5017.129
BELARUS	102.8606	441.7425	67.2907	243.1371	25616.12	19.9132	1219.068
BELGIUM	5957.498	25364.63	8202.783	9286.188	306098.4	3012.869	35850.87
BENIN	272.4229	329.1976	53.86605	51.60237	1056.84	378.2035	2799.38
BOLIVIA	9.871503	321.2895	5.783796	2224.719	325.3432	0.072406	192.4531
BOSNIA & HERZEGOVINA	6.75369	27.73973	5.991229	10.94317	7532.505	0.202962	69.12354
BRAZIL	2483.013	22670.57	6174.02	22613.46	35611.36	7556.85	24917.84
BULGARIA	93.3928	361.3446	158.3581	999.5388	26540.52	41.8812	1140.718
BURKINA FASO	30.82031	50.2783	77.27657	2.125327	571.3732	554.1757	70.50049
BURUNDI	17.09318	5.38022	59.8637	0	85.2353	87.05842	30.81112
CAMBODIA	77.51055	158.7989	5.126083	6.501713	250.5504	0.132069	4061.141
CAMEROON	163.4287	166.693	64.62158	173.0905	1723.592	623.8699	477.6033
CANADA	2972.573	226411	10133.94	29466.06	61167.28	2081.515	66111.38
CENTRAL AFRICAN REP.	2.383179	22.14325	5.691564	0.297519	128.9326	51.76748	15.74396
CHAD	19.42876	93.0889	38.80586	0.6083	316.1372	149.4126	79.31993
CHILE	294.7517	8272.774	107.8218	13918.22	7195.351	1244.278	7585.214
CHINA.P.R.: MAINLAND	15940.86	80972.6	25678.92	47761.23	147294.4	24341.62	253609.9
COLOMBIA	528.7771	9279.914	186.0852	8934.215	4640.049	59.9189	5145.794
CONGO. REPUBLIC OF	180.3854	180.5973	44.09919	171.5085	1721.285	135.779	582.299
CONGO. DEM. REP. OF	7.70753	164.4141	24.0806	33.84315	992.3207	1013.129	151.6553
COSTA RICA	40.33828	5123.154	39.9731	2693.259	1544.41	0.913763	1503.193
COTE D IVOIRE	209.9091	191.1628	110.8062	133.0318	2526.007	1838.023	911.0162
CROATIA	156.203	537.729	169.923	350.838	21242.2	22.174	2310.78
CUBA	24.36293	1072.234	356.5914	1013.472	2593.831	45.9025	1913.886
CZECH REPUBLIC	312.2212	1769.745	342.504	295.8698	103761.4	43.2205	9550.385
DENMARK	855.9299	3701.643	228.0117	1462.695	80519.14	134.5714	7592.348
DOMINICAN REPUBLIC	59.39911	6684.846	21.30186	3463.983	1446.016	33.33768	1071.665
EGYPT	1484.059	6240.754	3690.627	2150.656	20461.93	607.8519	8607.146
EL SALVADOR	49.70744	3209.015	12.66213	3461.47	631.7825	6.836819	704.3866
ESTONIA	35.0788	208.7486	16.5616	36.7721	14564.34	6.5469	597.0015
ETHIOPIA	495.4122	264.3554	739.6866	111.6694	1337.824	62.98024	1650.196
FINLAND	259.6911	2601.336	142.2592	1799.121	66579.34	266.9211	7918.885
FRANCE	4572.224	30248.15	19670.4	9487.557	471004.9	9013.046	41352.53
GABON	26.64049	546.1903	28.31538	61.8256	1463.338	194.088	235.0507
GAMBIA. THE	46.6235	22.77024	43.18388	77.11019	190.7543	161.0758	269.5251
GEORGIA	33.5825	216.1529	51.56777	92.2615	4194.308	18.38856	289.1867
GERMANY	9066.367	51253.35	11863.96	20739.79	798896.3	5102.783	110900.6
GHANA	849.2075	621.286	90.4841	470.1735	2787.253	1839.001	2129.704
GREECE	758.3391	1937.858	3770.311	1109.265	53393.16	258.7036	6579.939

GUATEMALA	105.3284	4865.085	30.9212	4394.071	1255.792	27.7226	1332.647
GUINEA	152.4232	91.8678	53.66397	45.963	820.8014	150.5394	395.5998
GUINEA-BISSAU	16.05863	7.603981	2.73512	10.07604	99.73124	54.08987	15.9152
HAITI	32.28418	814.4337	9.246209	909.0826	158.879	0.129475	198.3124
HONDURAS	127.7536	4961.162	15.8672	2627.191	621.2091	10.91935	570.1632
HUNGARY	334.1363	1438.853	171.9857	316.4119	76679.59	22.4487	11445.29
INDIA	1684.815	20631.89	38145.93	5756.21	52311.01	10848.65	52577.06
INDONESIA	1719.728	5853.08	6029.246	1538.096	9957.647	1106.718	30694.18
IRAN. I.R. OF	1726.911	297.382	840.4937	742.4214	20500.35	4.020615	6542.92
IRAQ	339.5075	2003.318	1191.269	119.5279	5454.214	0.029072	1172.714
IRELAND	433.0198	9819.263	336.6716	647.9671	60015.81	180.353	5550.541
ISRAEL	1726.2	8281.7	150.3	1197.2	26646.6	67.4	6272.1
ITALY	6181.311	17293.22	41520.27	13830.63	353201.8	4585.551	45892.44
JAMAICA	32.01392	2861.78	18.17853	1767.89	518.5434	31.3924	584.3231
JAPAN	4792.994	82186.04	49489.57	21934.32	83788.61	4912.541	239428.3
KAZAKHSTAN	139.2766	1017.058	123.4744	169.857	26665.45	50.40162	8514.025
KENYA	1785.771	712.8116	1108.602	132.2285	2345.276	285.052	1986.08
KUWAIT	891.1859	2849.828	1580.59	459.4649	7266.295	5.059065	4373.392
KYRGYZ REPUBLIC	13.0483	118.8222	1.865295	12.5129	1818.878	1.14617	385.8805
LAO PEOPLE S DEM.REP	3.890848	15.34489	0.039476	0.185742	89.00534	0.170187	1840.256
LATVIA	36.2683	199.5266	29.081	30.4331	14252.29	5.2802	462.2428
LEBANON	145.6308	979.6166	1054.196	323.2833	6186.9	56.64237	1379.667
LIBERIA	28.81006	92.11017	17.78424	21.49826	1466.977	121.145	2237.064
LIBYA	167.3492	771.415	329.7653	477.8863	7698.257	5.641385	1666.727
LITHUANIA	52.0219	561.8345	77.3376	103.0364	22469.59	7.319	916.5669
MACEDONIA. FYR	15.80282	53.1181	12.12011	56.72699	4204.174	8.503162	104.5708
MADAGASCAR	140.2119	104.1889	33.18626	46.90275	570.9113	19.12924	693.2141
MALAWI	67.88996	62.04601	3.488562	9.7086	161.9136	155.2331	76.94047
MALAYSIA	2208.6	16677.4	2840.838	2581.281	19652.53	1132.106	60469.81
MALI	44.27963	43.14079	36.15468	5.1606	788.1978	778.5506	176.726
MAURITANIA	36.25399	121.763	72.73019	119.8095	839.5614	66.93743	254.2847
MEXICO	1638.974	162701.1	1767.413	15182.71	39612.69	462.5151	62538.52
MOLDOVA	11.51984	59.57045	19.16568	40.3398	4689.655	1.579389	63.36877
MONGOLIA	9.4706	66.3824	5.9968	10.0143	1041.267	0.0004	766.8372
MOROCCO	338.6162	2145.404	3081.746	1241.313	20967.19	212.8393	887.8458
MOZAMBIQUE	178.375	101.449	24.036	66.297	737.236	39.064	329.589
MYANMAR	202.1283	10.92078	10.80673	2.114669	299.5773	1.892536	3699.308
NEPAL	1506.243	43.7936	43.64947	1.240919	128.0869	0.03248	581.1704
NETHERLANDS	3882.409	39716.47	16112.19	20447.1	290383.4	5552.717	87275.41
NEW ZEALAND	268.0785	3413.855	605.5639	340.1447	5509.301	65.07349	16330.89
NICARAGUA	36.03957	812.0277	6.603652	1702.936	213.1218	0.163674	460.1017
NIGER	83.38078	82.91521	22.28066	8.359201	450.3111	237.8551	57.69146
NIGERIA	1239.476	3254.507	354.6236	2133.992	13679.19	1093.089	5910.407
NORWAY	467.0148	7290.61	296.6799	1679.295	58977.16	180.5858	7766.319
PAKISTAN	2127.421	2694.402	6562.454	296.7996	6883.737	514.0713	11879.2
PANAMA	13.606	2171.144	8.56	1370.616	491.718	0	752.38
PAPUA NEW GUINEA	18.34839	76.08427	1.836785	6.482168	101.6111	5.065637	2293.238
PARAGUAY	48.82813	1369.476	13.27768	2920.141	356.6245	0.583288	628.3054
PERU	258.6856	4572.69	60.89959	7832.121	2782.653	574.8395	3407.798
PHILIPPINES	545.6536	8106.921	3843.15	869.7565	5765.152	12.18631	18689.71
POLAND	665.2092	2352.317	513.5767	1494.48	143967.5	486.0501	9723.344
PORTUGAL	657.8659	1468.216	3142.089	2996.213	60260.1	2249.682	2785.8

ROMANIA	378.8716	1100.935	492.0487	830.6527	61955.86	66.5575	3248.165
RUSSIAN FEDERATION	1767.428	10723.2	1078.627	7378.931	123891.6	745.9576	41728.61
RWANDA	16.07976	19.50628	10.15721	0.095293	172.9189	282.9149	55.56204
SAUDI ARABIA	4182.262	12152.36	2366.019	2424.448	34706.56	484.2831	21692.16
SENEGAL	208.0734	204.1709	127.0876	296.7548	2925.79	402.8355	717.9045
SERBIA & MONTENEGRO	17.29227	0	461.9279	0.468278	800.6458	2.351401	358.6981
SIERRA LEONE	45.81282	73.278	13.60231	7.163015	192.9119	75.79594	121.7931
SLOVAK REPUBLIC	146.4036	393.9779	68.3559	69.9437	52250.82	3.4005	3389.023
SLOVENIA	133.9081	472.6022	323.0788	414.0564	27408.39	24.7364	896.2596
SOUTH AFRICA	2153.434	7583.94	4734.741	4780.136	38433.67	5753.705	21084.41
SPAIN	3923.802	12734.94	23048.28	16309.13	269975.7	8358.532	35434.29
SRI LANKA	2799.183	491.5637	229.208	42.57913	1410.794	11.68339	2393.903
SUDAN	601.94	317.74	1287.54	139.851	1590.22	113.73	3251.74
SWEDEN	983.8832	5269.331	401.2286	1794.961	127736.1	96.4584	11712.22
SWITZERLAND	1011.874	10296.08	2629.588	1840.501	130820.8	655.5786	8691.065
SYRIAN ARAB REPUBLIC	790.3488	463.6906	6642.111	414.9589	8135.193	106.5564	3061.791
TAJIKISTAN	9.3	38.8	4.1	68.6	1955.6	0	282.1
TANZANIA	594.9682	239.8482	198.9982	52.43285	1283.114	589.597	1188.689
THAILAND	2205.428	10287.33	5809.508	2323.85	15633.06	823.2739	68246.66
TOGO	224.5831	331.8778	54.52239	51.45034	1582.979	177.0225	1803.967
TRINIDAD AND TOBAGO	145.7594	2189.855	31.30509	1399.945	942.0426	464.2125	698.1008
TUNISIA	160.1385	555.015	1424.721	402.5668	15862.22	63.10163	780.004
TURKEY	3136.875	9011.73	7769.933	2959.668	105614.6	917.9694	21974.54
TURKMENISTAN	41.2168	211.0498	49.79347	2.1824	1875.691	0	443.509
UGANDA	362.8347	126.0629	109.7469	32.58892	819.8214	540.4574	624.6456
UKRAINE	516.8404	1533.074	205.3439	669.8404	48992.19	526.3526	5574.369
UNITED ARAB EMIRATES	18674.71	13952.33	4919.257	1896.882	49946.5	809.3921	38267.06
UNITED KINGDOM	10913.37	65086	9722.203	11319.08	392250	2867.858	80206.69
UNITED STATES	34854.8	317604	101128.6	308439.4	417943.2	57165.6	598591.4
URUGUAY	57.93888	730.5245	29.90161	3563.694	1242.084	436.2809	831.8176
UZBEKISTAN	46.82567	105.7088	30.48007	6.035629	4458.289	3.46E-06	963.7639
VIETNAM	1447.5	1987.7	247.1	1005.3	6859.3	79.9	28499.1
YEMEN. REPUBLIC OF	1201.432	734.4	1296.102	292.9084	2236.734	54.1192	2182.095
ZAMBIA	166.5584	82.6991	14.05758	12.85397	697.5162	415.3811	352.4707
ZIMBABWE	36.92896	122.801	79.36548	0.112761	241.8822	303.679	271.2962