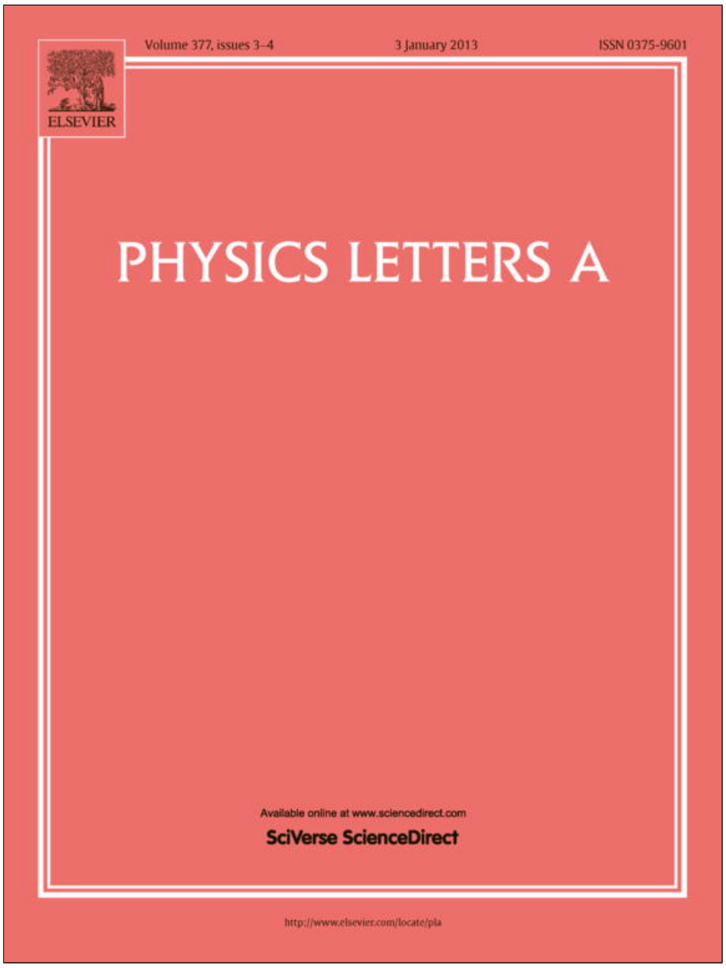
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Ecological analysis of world trade

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ABSTRACT

Ecological systems have a high complexity combined with stability and rich biodiversity. The analysis of their properties uses a concept of mutualistic networks and provides a detailed understanding of their features being linked to a high nestedness of these networks. Using the United Nations COMTRADE database we show that a similar ecological analysis gives a valuable description of the world trade: countries and trade products are analogous to plants and pollinators, and the whole trade network is characterized by a high nestedness typical for ecological networks. Our approach provides new mutualistic features of the world trade.

1. Introduction

Ecological systems are characterized by high complexity and biodiversity [1] linked to nonlinear dynamics and chaos emerging in the process of their evolution [2,3]. The interactions between species form a complex network whose properties can be analyzed by the modern methods of scale-free networks [4–7]. An important feature of ecological networks is that they are highly structured, being very different from randomly interacting species [7,8]. Recently it has been shown that the mutualistic networks between plants and their pollinators [8–12] are characterized by high nestedness [13–16] which minimizes competition and increases biodiversity. It is argued [14] that such type of networks appear in various social contexts such as garment industry [15] and banking [17,18]. Here we apply a nestedness analysis to the world trade network using the United Nations COMTRADE database [19] for the years 1962–2009. Our analysis shows that countries and trade products have relations similar to those of plants and pollinators and that the world trade network is characterized by a high nestedness typical of ecosystems [14]. This provides new mutualistic characteristics for the world trade.

2. Results

The mutualistic World Trade Network (WTN) is constructed on the basis of the UN COMTRADE database [19] from the matrix of trade transactions $M^{p}_{c',c}$ expressed in USD for a given product (commodity) p from country c to country c' in a given year (from 1962 to 2009). For product classification we use 3-digit Standard International Trade Classification (SITC) Rev. 1 with the number of products $N_p = 182$. All these products are described in [19] in the commodity code document SITC Rev. 1. The number of countries varies between $N_c = 164$ in 1962 and $N_c = 227$ in 2009. The import and export trade matrices are defined as $M^{(i)}_{p,c} = \sum_{c'=1}^{N_c} M^{p}_{c,c'}$ and $M^{(e)}_{p,c} = \sum_{c'=1}^{N_c} M^{p}_{c',c}$ respectively. We use the dimensionless matrix elements $m^{(i)} = M^{(i)}/M_{max}$ and $m^{(e)} = M^{(e)}/M_{max}$ where for a given year $M_{max} = max\{max[M^{(i)}_{p,c}], max[M^{(e)}_{p,c}]\}$. The distribution of matrix elements $m^{(i)}$, $m^{(e)}$ in the plane of indexes p and c, ordered by the total amount of import/export in a decreasing order, is shown in Fig. 1 for years 1968 and 2008 (years 1978, 1988, 1998 are shown in Fig. S-1 of Supporting Information (SI)). These figures show that globally the distributions of $m^{(i)}$, $m^{(e)}$ remain stable in time especially in a view of 100 times growth of the total trade volume during the period 1962–2009. The fluctuations of $m^{(e)}$ are visibly larger compared to $m^{(i)}$ case since certain products, e.g. petroleum, are exported by only a few countries while it is imported by almost all countries.

To use the methods of ecological analysis we construct the mutualistic network matrix for import $Q^{(i)}$ and export $Q^{(e)}$ whose matrix elements take binary value 1 or 0 if corresponding elements $m^{(i)}$ and $m^{(e)}$ are respectively larger or smaller than a certain trade threshold value μ. The fraction φ of nonzero matrix elements varies smoothly in the range $10^{-6} \leqslant \mu \leqslant 10^{-2}$ (see Fig. S-2 of SI) and the further analysis is not really sensitive to the actual μ value inside this broad range. Indeed, the variation of μ in

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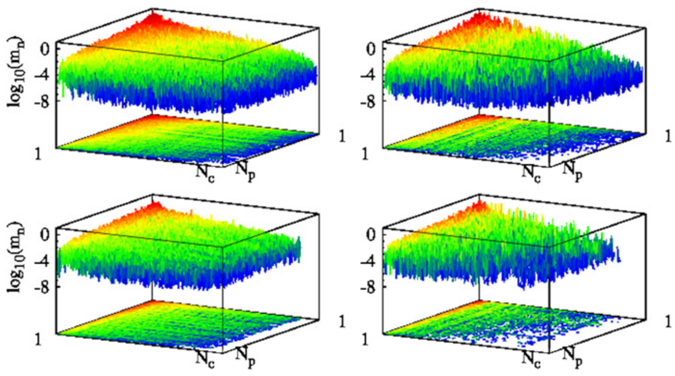

Fig. 1. Normalized import/export WTN matrix elements $m^{(i)}$ and $m^{(e)}$ shown on left/right panels for years 1968 (bottom) and 2008 (top). Each panel represents the dimensionless trade matrix elements $m^{(i)} = M^{(i)}/M_{max}$ and $m^{(e)} = M^{(e)}/M_{max}$ on a thee-dimensional (3D) plot as a function of indexes of countries and products. Here products/countries ($p = 1, \ldots, N_p$ and $c = 1, \ldots, N_c$) are ordered in a decreasing order of product/country total import or export in a given year. The color is proportional to the amplitude of the matrix element changing from red (for amplitude maximum) to blue (for zero amplitude). Each panel shows the 3D distribution and its projection on 2D plane of countries–products in which the amplitude of matrix elements is shown by the same color as in 3D. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

the range $10^{-5} \leqslant \mu \leqslant 10^{-3}$ by two orders of magnitude produces a rather restricted variation of φ only by a factor two.

It is important to note that in contrast to ecological systems [14] the world trade is described by a directed network and hence we characterize the system by two mutualistic matrices $Q^{(i)}$ and $Q^{(e)}$ corresponding to import and export. Using the standard nestedness BINMATNEST algorithm [20] we determine the nestedness parameter η of the WTN and the related nestedness temperature $T = 100(1 - \eta)$. The algorithm reorders lines and columns of a mutualistic matrix concentrating nonzero elements as much as possible in the top-left corner and thus providing information about the role of immigration and extinction in an ecological system. A high level of nestedness and ordering can be reached only for systems with low T. It is argued that the nested architecture of real mutualistic networks increases their biodiversity.

The nestedness matrices generated by the BINMATNEST algorithm [20] are shown in Fig. 2 for ecology networks ARR1 ($N_{pl} = 84$, $N_{anim} = 101$, $\varphi = 0.043$, $T = 2.4$) and WES ($N_{pl} = 207$, $N_{anim} = 110$, $\varphi = 0.049$, $T = 3.2$) from [12,21]. Using the same algorithm we generate the nestedness matrices of WTN using the mutualistic matrices for import $Q^{(i)}$ and export $Q^{(e)}$ for the WTN in years 1968 and 2008 using a fixed typical threshold $\mu = 10^{-3}$ (see Fig. 2; the distributions for other μ values have a similar form and are shown in Fig. S-3 of SI). As for ecological systems, for the WTN data we also obtain rather small nestedness temperature ($T \approx 6/8$ for import/export in 1968 and $T \approx 4/8$ in 2008 respectively). These values are by a factor 9/4 of times smaller than the corresponding T values for import/export from random generated networks with the corresponding values of φ.

The detailed data for T in all years are shown in Fig. 3 and the comparison with the data for random networks is given in Figs. S-4–S-6 in SI. The data of Fig. 3 show that the value of T changes by about 30–40% with variation of μ by a factor 1000. We think that this is relatively small variation of T compared to enormous variation of μ that confirms the stability and relevance of ecological analysis and nestedness ordering. The nestedness temperature T remains rather stable in time: in average there is 40% drop of T from 1962 to 2000 and 20% growth from 2000 to 2009. We attribute the growth in last decade to the globalization of trade. Even if the nestedness temperature T may be sensitive to

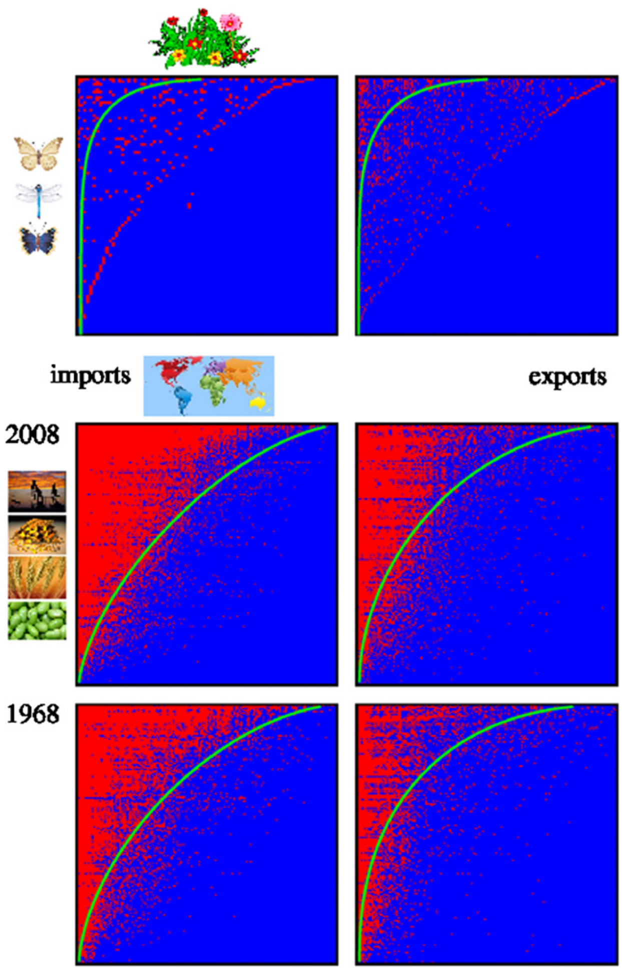

Fig. 2. Nestedness matrices for the plant–animal mutualistic networks on top panels, and for the WTN of countries–products on middle and bottom panels. Top-left and top-right panels represent data of ARR1 and WES networks from [12,21]. The WTN matrices are computed with the threshold $\mu = 10^{-3}$ and corresponding $\varphi \approx 0.2$ for years 1968 (bottom) and 2008 (middle) for import (left panels) and export (right panels). Red and blue represent unit and zero elements respectively; only lines and columns with nonzero elements are shown. The order of plants–animals, countries–products is given by the nestedness algorithm [20], the perfect nestedness is shown by green curves for the corresponding values of φ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

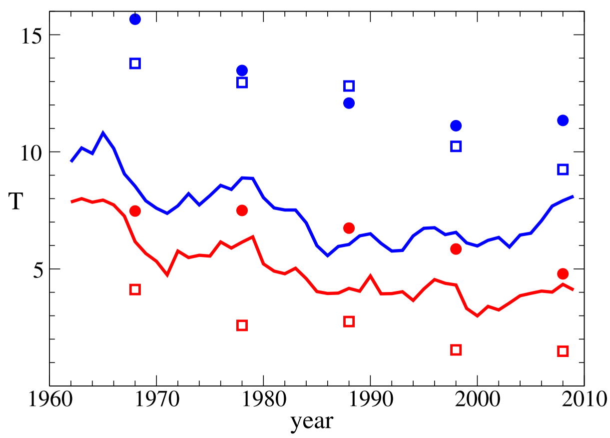

Fig. 3. Nestedness temperature T as a function of years for the WTN for $\mu = 10^{-3}$ (curves), 10^{-4} (circles), 10^{-6} (squares); import and export data are shown in red and blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

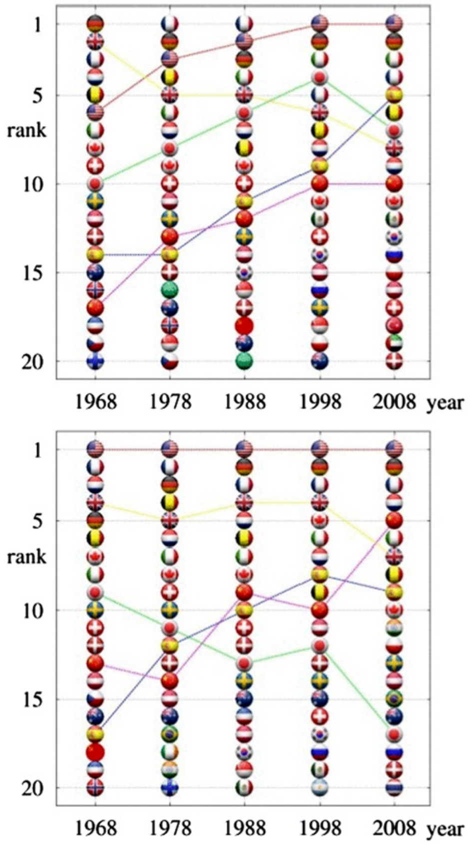

Fig. 4. Top 20 EcoloRank countries as a function of years for the WTN import/export on top/bottom panels. The ranking is given by the nestedness algorithm [20] for the trade threshold $\mu = 10^{-3}$; each country is represented by its corresponding flag. As an example, dashed lines show time evolution of the following countries: USA, UK, Japan, China, Spain. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

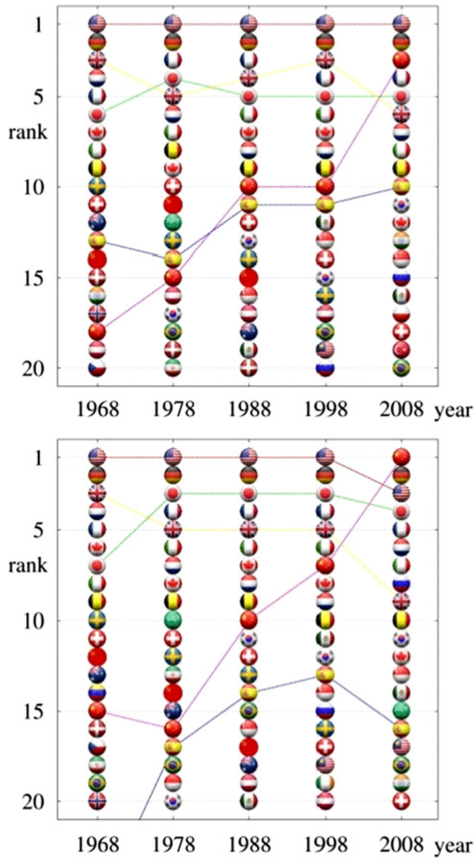

Fig. 5. Top 20 countries as a function of years ranked by the total monetary trade volume of the WTN in import/export on top/bottom panels respectively; each country is represented by its corresponding flag. Dashed lines show time evolution of the same countries as in Fig. 4.

variation of φ the data of Figs. S-2 and S-6 show that in the main range of $10^{-5} \leqslant \mu \leqslant 10^{-3}$ the variation of φ and T remains rather small. The comparison with the randomly generated networks also shows that they have significantly larger T values compared to the values found for the WTN (see also discussion of Figs. S-4–S-6 in SI).

The small value of nestedness temperature obtained for the WTN confirms the validity of the ecological analysis of WTN structure: trade products play the role of pollinators which produce exchange between world countries, which play the role of plants. Like in ecology the WTN evolves to the state with very low nestedness temperature that satisfies the ecological concept of system stability appearing as a result of high network nestedness [14].

The nestedness algorithm [20] creates effective ecological ranking (EcoloRanking) of all UN countries. The evolution of 20 top ranks throughout the years is shown in Fig. 4 for import and export. This ranking is quite different from the more commonly applied ranking of countries by their total import/export monetary trade volume [22] (see corresponding data in Fig. 5) or recently proposed democratic ranking of WTN based on the Google matrix analysis [23]. Indeed, in 2008 China is at the top rank for total export volume but it is only at 5th position in EcoloRanking (see Figs. 4, 5 and Table 1 in SI). In a similar way Japan moves down from 4th to 17th position while the USA raises up from 3rd to 1st rank.

The same nestedness algorithm generates not only the ranking of countries but also the ranking of trade products for import and export which is presented in Fig. 6. For comparison we also show there the standard ranking of products by their trade volume. In Fig. 6 the color of symbol marks the 1st SITC digit described in [19] and in Table 2 in SI.

3. Discussion

The origin of such a difference between EcoloRanking and trade volume ranking of countries is related to the main idea of mutualistic ranking in ecological systems: the nestedness ordering stresses the importance of mutualistic pollinators (products for WTN) which generate links and exchange between plants (countries for WTN). In this way generic products, which participate in the trade between many countries, become of primary importance even if their trade volume is not at the top lines of import or export. In fact such mutualistic products glue the skeleton of the world trade while the nestedness concept allows to rank them in order of their importance. The time evolution of this EcoloRanking of products of WTN is shown in Fig. 6 for import/export in comparison with the product ranking by the monetary trade volume (since the trade matrix is diagonal in product index the ranking of products in the latter case is the same for import/export). The top and middle panels have dominate colors corresponding to machinery (SITC 7; blue) and mineral fuels (3; black) with a moderate contribution of chemicals (5; yellow) and manufactured articles (8; cyan) and a small fraction of goods classified by material (6; green). Even if the global structure of product ranking by trade volume has certain similarities with import EcoloRanking there are also important new elements. Indeed, in 2008 the mutualistic significance of petroleum products (SITC 332), *machindus* (machines for special industries 718) and

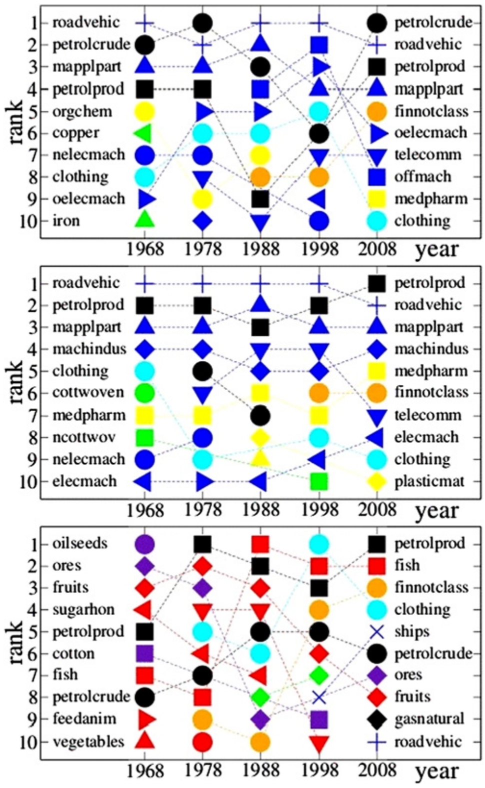

Fig. 6. Top 10 ranks of trade products as a function of years for the WTN. Top panel: ranking of products by monetary trade volume; middle/bottom panels: ranking is given by the nestedness algorithm [20] for import/export with the trade threshold $\mu = 10^{-3}$. Each product is shown by its own symbol with short name written for years 1968, 2008; symbol color marks 1st SITC digit; SITC codes of products and their names are given in Table 2 of SI. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

medpharm (medical–pharmaceutic products 541) is much higher compared to their volume ranking, while petroleum crude (331) and office machines (714) have smaller mutualistic significance compared to their volume ranking.

The new element of EcoloRanking is that it differentiates between import and export products while for trade volume they are ranked in the same way. Indeed, the dominant colors for export (Fig. 6, bottom panel) correspond to food (SITC 0; red) with contribution of black (present in import) and crude materials (2; violet), followed by cyan (present in import) and more pronounced presence of *finnotclass* (commodities/transactions not classified 9; brown). EcoloRanking of export shows a clear decrease tendency of dominance of SITC 0 and SITC 2 with time and increase of importance of SITC 3, 7. It is interesting to note that petroleum products SITC 332 is very vulnerable in volume ranking due to significant variations of petroleum prices but in EcoloRanking this product keeps the stable top positions in all years showing its mutualistic structural importance for the world trade. EcoloRanking of export shows also importance of fish (SITC 031), clothing (SITC 841) and fruits (SITC 051) which are placed on higher positions compared to their volume ranking. At the same time *roadvehic* (SITC 732), which are at top volume ranking, have relatively low ranking in export since only a few countries dominate the production of road vehicles.

It is interesting to note that in Fig. 6 petroleum crude is at the top of trade volume ranking e.g. in 2008 (top panel) but it is absent in import EcoloRanking (middle panel) and it is only on 6th position in export EcoloRanking (bottom panel). A similar feature is visible for years 1968, 1978. On a first glance this looks surprising but in fact for mutualistic EcoloRanking it is important that

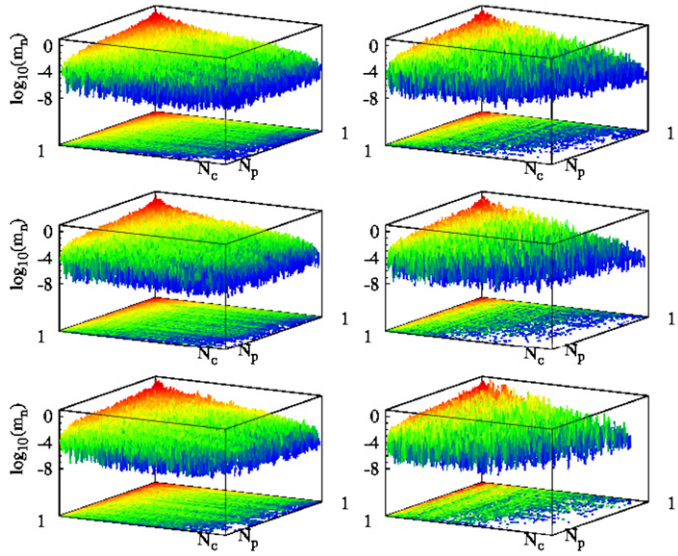

Fig. S-1. Same type of WTN matrix data as in Fig. 1 shown for years 1978, 1988, 1998 in panels from bottom to top respectively.

a given product is imported from top EcoloRank countries: this is definitely not the case for petroleum crude which practically is not produced inside top 10 import EcoloRank countries (the only exception is the USA, which however also does not export much). Due to that reason this product has low mutualistic significance.

The mutualistic concept of product importance is at the origin of significant difference of EcoloRanking of countries compared to the usual trade volume ranking (see Figs. 4, 5). Indeed, in the latter case China and Japan are at the dominant positions but their trade is concentrated in specific products which mutualistic role is relatively low. In contrast the USA, Germany and France keep top three EcoloRank positions during almost 40 years clearly demonstrating their mutualistic power and importance for the world trade.

In conclusion, our results show the universal features of ecologic ranking of complex networks with promising future applications to trade, finance and other areas.

Acknowledgements

We thank Arlene Adriano and Matthias Reister (UN COMTRADE) for provided help and friendly access to the database [19]. This work is done in the frame of the EC FET Open project "New tools and algorithms for directed network analysis" (NADINE No. 288956).

Appendix A. Supporting information

Here we present the Supporting Information (SI) for the main part of the Letter, it includes Figs. S-1–S-6, Table 1, Table 2.

In Fig. S-1, in a complement to Fig. 1, we show the normalized WTN matrix for import $m^{(i)}$ and export $m^{(e)}$ at additional years 1978, 1988, 1998. As in Fig. 1 all products and countries are ordered in a decreasing order of product ($p = 1, \ldots, N - p$) and country ($c = 1, \ldots, N_c$) import (left panels) and export (right panels) in a given year. These data show that the global distribution remains stable in time: indeed, the global monetary trade volume was increased by a factor 100 from year 1962 to 2008 (see e.g. Fig. 5 in [20]) but the shape of the distribution remained essentially the same.

The dependence of the fraction φ of nonzero elements of the mutualistic matrices of import $Q^{(i)}$ and export $Q^{(e)}$ on the cutoff threshold μ is shown in Fig. S-2. In the range of $10^{-6} \leqslant \mu \leqslant 10^{-2}$ there is a smooth relatively weak variation of φ with μ.

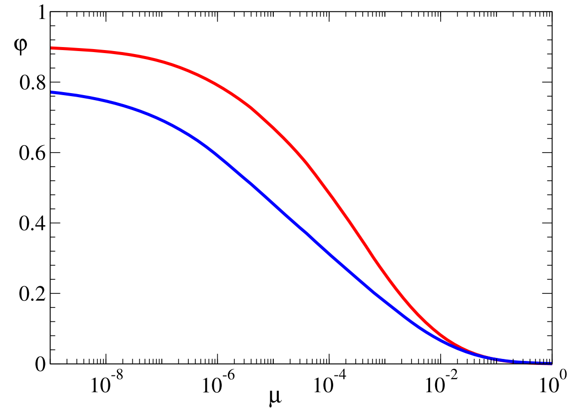

Fig. S-2. The fraction φ of nonzero matrix elements for the mutualistic network matrices of import $Q^{(i)}$ and export $Q^{(e)}$ as a function of the cutoff trade threshold μ for the normalized WTN matrices $m^{(i)}$ and $m^{(e)}$ for the year 2008; the red curve shows the case of import while the blue curve shows the case of export network. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

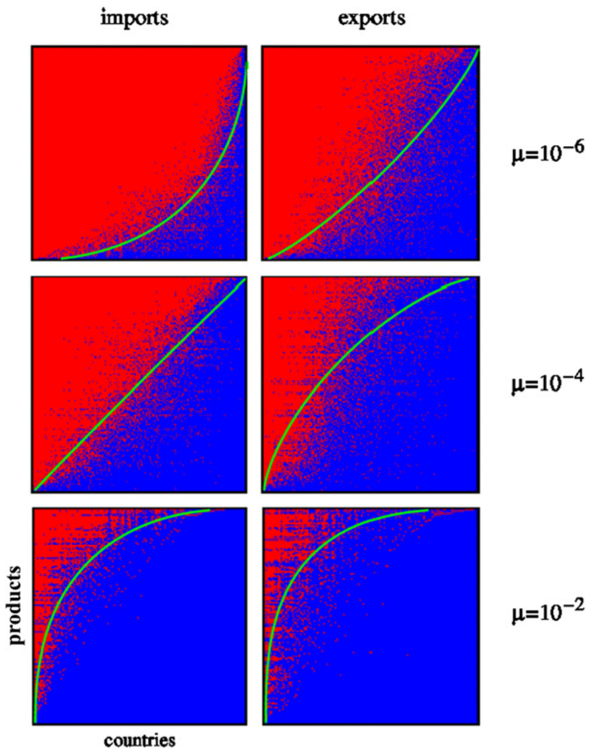

Fig. S-3. Same as in Fig. 2: nestedness matrix for the WTN data in 2008 shown for the threshold values $\mu = 10^{-6}, 10^{-4}, 10^{-2}$ (from top to bottom); the perfect nestedness is shown by green curves for the corresponding values of φ taken from Fig. S-2. (For interpretation of the reference to color in this figure legend, the reader is referred to the web version of this Letter.)

In Fig. S-3, in addition to Fig. 2, we show the nestedness matrices of WTN at various values of the cutoff threshold μ. The data at various μ values show that in all cases the nestedness algorithm [17] correctly generates a matrix with nestedness structure.

The variation of the nestedness temperature T with time is shown in Fig. 3 at several values of the trade threshold μ. These data show that in average the value of T for export is higher than for import. We attribute this to stronger fluctuations of matrix elements of $m^{(e)}$ compared to those of $m^{(i)}$ that is well visible in Figs. 1, S-1. As it is pointed in the main part, we attribute this

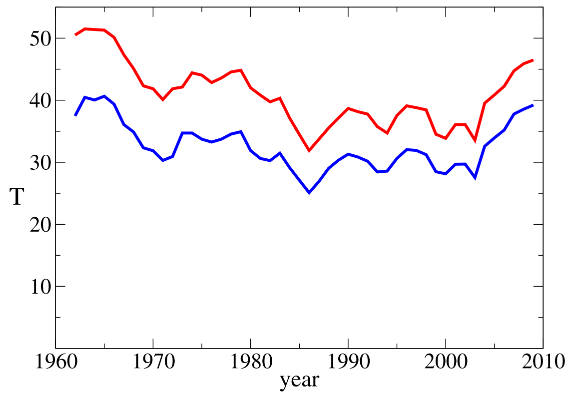

Fig. S-4. Nestedness temperature T for the model given by random generated networks; here T is computed with 500 random realizations of network for each year using N_p, N_c and φ of the corresponding WTN data in this year at $\mu = 10^{-3}$; import/export data are shown by red/blue curves respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

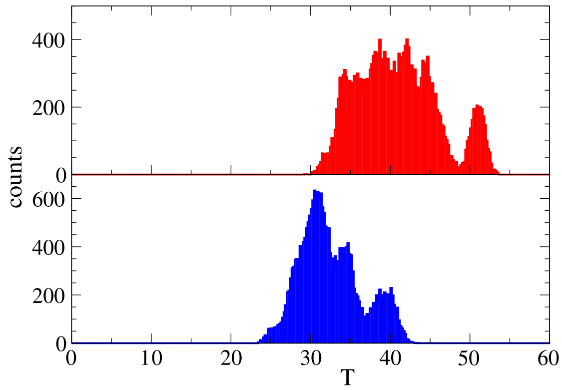

Fig. S-5. Histogram of temperatures for 500 random generated networks per year (from 1962 to 2009). Top (bottom) panel represents import (export) data; here the parameter values of N_p, N_c and φ are as for the corresponding WTN years at $\mu = 10^{-3}$.

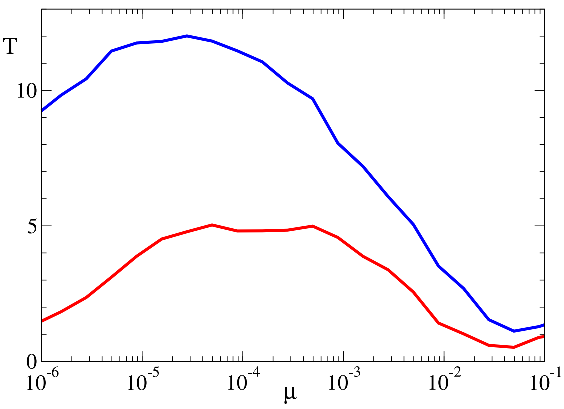

Fig. S-6. Nestedness temperature in the WTN for the year 2008 as a function of threshold μ; import/export networks are shown by red/blue curves respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

to the fact that e.g. only a few countries export petroleum crude while the great majority of countries import this product.

In Fig. S-4 we show the nestedness temperature dependence on time for the case of random generated networks which have the same fraction of nonzero matrix elements φ as the WTN in the given year and $\mu = 10^{-3}$. These data, compared with those of Fig. 3, really demonstrate that the real WTN has values of T

Table 1
Top 20 ranks of countries for import and export with ranking by the monetary trade volume and by the nestedness algorithm at two threshold values μ (year 2008).

Rank	Import			Export		
	Money	$\mu = 10^{-3}$	$\mu = 10^{-2}$	Money	$\mu = 10^{-3}$	$\mu = 10^{-2}$
1	USA	USA	USA	China	USA	USA
2	Germany	Germany	Germany	Germany	Germany	Germany
3	China	Italy	France	USA	France	China
4	France	France	UK	Japan	Netherlands	France
5	Japan	Spain	Italy	France	China	Italy
6	UK	Belgium	Netherlands	Netherlands	Italy	Netherlands
7	Netherlands	Japan	Belgium	Italy	UK	Belgium
8	Italy	UK	Japan	Russian Federation	Belgium	UK
9	Belgium	Netherlands	China	UK	Spain	Japan
10	Canada	China	Spain	Belgium	Canada	Spain
11	Spain	Canada	Canada	Canada	India	Canada
12	Republic of Korea	Mexico	Russian Federation	Republic of Korea	Poland	Switzerland
13	Russian Federation	Republic of Korea	Republic of Korea	Mexico	Sweden	India
14	Mexico	Russian Federation	Switzerland	Saudi Arabia	Austria	Republic of Korea
15	Singapore	Poland	Austria	Singapore	Brazil	Poland
16	India	Austria	Poland	Spain	Australia	Turkey
17	Poland	Switzerland	Sweden	Malaysia	Japan	Czech Republic
18	Switzerland	Turkey	Mexico	Brazil	Russian Federation	Austria
19	Turkey	United Arab Emirates	India	India	Denmark	Thailand
20	Brazil	Denmark	Singapore	Switzerland	Thailand	Denmark

Table 2
Product names for SITC Rev. 1 3-digit code used in Fig. 6.

Symbol	Code	Abbreviation	Name
●	001	animals	Live animals
■	031	fish	Fish, fresh and simply preserved
♦	051	fruits	Fruit, fresh, and nuts excl. oil nuts
▲	054	vegetables	Vegetables, roots and tubers, fresh or dried
◀	061	sugarhon	Sugar and honey
▼	071	coffee	Coffee
▶	081	feedanim	Feed. stuff for animals excl. unmilled cereals
●	221	oilseeds	Oil seeds, oil nuts and oil kernels
■	263	cotton	Cotton
♦	283	ores	Ores and concentrates of non-ferrous base metals
●	331	petrolcrude	Petroleum, crude and partly refined
■	332	petrolprod	Petroleum products
♦	341	gas	Gas, natural and manufactured
●	512	orgchem	Organic chemicals
■	541	medpharm	Medicinal and pharmaceutical products
♦	581	plasticmat	Plastic materials, regenerated cellulose and resins
▲	599	chemmat	Chemical materials and products, n.e.s.
●	652	cottwoven	Cotton fabrics, woven ex. narrow or spec. fabrics
■	653	ncottwov	Textile fabrics, woven ex. narrow, spec., not cotton
♦	667	pearlsprec	Pearls and precious and semi precious stones
▲	674	iron	Universals, plates and sheets of iron or steel
◀	682	copper	Copper
●	711	nelecmach	Power generating machinery, other than electric
■	714	offmach	Office machines
♦	718	machindus	Machines for special industries
▲	719	mapplpart	Machinery and appliances non-electrical parts
◀	722	elecmach	Electric power machinery and switchgear
▼	724	telecomm	Telecommunications apparatus
▶	729	oelecmach	Other electrical machinery and apparatus
+	732	roadvehicles	Road motor vehicles
×	735	ships	Ships and boats
●	841	clothing	Clothing except fur clothing
●	931	finnotclass	Special transactions not class. accord. to kind

by a factor 5 (export) to 10 (import) smaller comparing to the random networks. This confirms the nestedness structure of WTN being similar to the case of ecology networks discussed in [12]. It is interesting to note that for random generated networks the values of T for import are larger than for export while to the WTN we have the opposite relation. The histogram of distribution of T for random generated networks for all years 1962–2009 is shown in Fig. S-5. Even minimal values of T remain several times larger than the WTN values of T.

In Fig. S-6 we show the dependence of T on the trade threshold μ for the WTN data in year 2008. We see that there is only about 10–20% of variation of T for the range $10^{-5} \leqslant \mu \leqslant 10^{-3}$. Even for a much larger range $10^{-6} \leqslant \mu \leqslant 10^{-2}$ the variation of T remains smooth and remains in the bounds of 100%. This confirms the stability of nestedness temperature in respect to broad range variations of μ. We present the majority of our data for $\mu = 10^{-3}$ which is approximately located in the flat range of T variation in year 2008. The data of Table 1 for EcoloRanking of countries at two different values of μ in year 2008 confirm the stability of this nestedness ordering. At the same time larger values of μ stress the importance of countries with a large trade volume, e.g. the position of China in export goes up from rank 5 at $\mu = 10^{-3}$ to rank 3 at $\mu = 10^{-2}$.

In Table 1 we present trade volume ranking and EcoloRanking of top 20 countries for import/export of WTN in year 2008.

In Table 2 we give the notations and symbols for Fig. 6 with corresponding SITC Rev. 1 codes and names. The list of all SITC Rev. 1 codes is available at [16] (see file http://unstats.un.org/unsd/tradekb/Attachment193.aspx). The colors of symbols in Fig. 4 mark the first digit of SITC Rev. 1 code: 0 – red (Food and live animals); 1 – does not appear in Fig. 4 (Beverages and tobacco); 2 – violet (Crude materials, inedible, except fuels); 3 – black (Mineral fuels, lubricants and related materials); 4 – does not appear in Fig. 4 (Animal and vegetable oils and fats); 5 – yellow (Chemicals); 6 – green (Manufactured goods classified chiefly by material); 7 – blue (Machinery and transport equipment); 8 – cyan (Miscellaneous manufactured articles); 9 – brown (Commod. and transacts. not class. accord. to kind).

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