Ecological analysis of world trade

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Ecological systems have a high level of complexity combined with stability and rich biodiversity. Recently, the analysis of their properties and evolution has been pushed forward on a basis of concept of mutualistic networks that provides a detailed understanding of their features being linked to a high nestedness of these networks. It was shown that the nestedness architecture of mutualistic networks of plants and their pollinators minimizes competition and increases biodiversity. Here, using the United Nations COMTRADE database for years 1962 - 2009, we show that a similar ecological analysis gives a valuable description of the world trade. In fact the countries and trade products are analogous to plants and pollinators, and the whole trade network is characterized by a low nestedness temperature which is typical for the ecological networks. This approach provides new mutualistic features of the world trade highlighting new significance of countries and trade products for the world trade.

Ecological systems are characterized by high complexity and biodiversity\textsuperscript{[1]} linked to nonlinear dynamics and chaos emerging in the process of their evolution\textsuperscript{[2, 3]}. The interactions between species form a complex network whose properties can be analyzed by the modern methods of scale-free networks\textsuperscript{[4–7]}. An important feature of ecological networks is that they are highly structured, being very different from randomly interacting species\textsuperscript{[7, 8]}. Recently it has been shown that the mutualistic networks between plants and their pollinators\textsuperscript{[8–11]} are characterized by high nestedness\textsuperscript{[12, 13]} which minimizes competition and increases biodiversity. It is argued\textsuperscript{[12]} that such type of networks appear in various social contexts such as garment industry\textsuperscript{[13]} and banking\textsuperscript{[14, 15]}. Here we apply a nestedness analysis to the world trade network using the United Nations COMTRADE database\textsuperscript{[16]} 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\textsuperscript{[11, 12]}. This provides new mutualistic characteristics for the world trade.

Results

The mutualistic World Trade Network (WTN) is constructed on the basis of the UN COMTRADE database\textsuperscript{[16]} from the matrix of trade transactions $M_{p,c}^{(i)}$ 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-digits Standard International Trade Classification (SITC) Rev.1 with the number of products $N_p = 182$. All these products are described in\textsuperscript{[16]} in the commodity code document SITC Rev1. 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

\[ M_{p,c}^{(i)} = \sum_{c'=1}^{N_c} M_{p,c'}^{(i)} \]

and

\[ M_{p,c}^{(e)} = \sum_{c'=1}^{N_c} M_{c',c}^{(e)} \]

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 $M_{\max} = \max\{\max[M_{p,c}^{(i)}], \max[M_{p,c}^{(e)}]\}$. 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, are shown in Fig. 1 for years 1968 and 2008 (years 1978, 1988, 1998 are shown in Fig. S-1 of Supporting Information (SI)). These Figs. 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 ex-

\[ Q^{(i)} \]

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). 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.
port \( Q^{(e)} \) whose matrix elements take binary value 1 or 0 if corresponding elements \( n^{(i)} \) and \( m^{(e)} \) are respectively larger or smaller than a certain trade threshold value \( \mu \). The fraction \( \varphi \) of nonzero matrix elements varies smoothly in the range \( 10^{-6} \leq \mu \leq 10^{-2} \) (see Fig. S-2 of SI) and the further analysis is not really sensitive to the actual \( \mu \) value inside this broad range. It is important to note that in contrast to ecological systems [12] the 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 BIN-MATNEST algorithm [17] 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 [11, 18]. 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 \( \mu \)-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 \( \varphi \). The detailed data for \( T \) in all years are shown in Fig. 3 and the comparison with the data for random networks are given in Figs. S-4,S-5,S-6 in SI. The data of Fig. 3 show that the value of \( T \) changes by about 30-40% with variation of \( \mu \) by a factor 1000. We think that this is relatively small variation of \( T \) compared to enormous variation of \( \mu \) 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. 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 tempera-

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 [11, 18]. 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 [17], the perfect nestedness is shown by green curves for the corresponding values of \( \varphi \).

The nestedness algorithm [17] 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 [19] (see corresponding data in Fig. 5) or recently proposed democratic ranking of WTN based on the Google matrix analysis [20]. Indeed, in 2008 China is at the top rank for total export volume but it is only at 5th position in
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.

EcoloRank (see Fig. 4, Fig. 5 and Table I in SI). In a similar way Japan moves down from 4th to 17th position while 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 [16] and in Table II in SI.

**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 medpharm (medical-pharmaceutical 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 mate-
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.

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 \cite{17} for import/export with the trade threshold $\mu = 10^{-3}$. Each product is shown by its own symbol with short name written at years 1968, 2008; symbol color marks 1st SITC digit; SITC codes of products and their names are given in Table II of SI.

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 SITC0 and SITC2 with time and increase of importance of SITC3,7. It is interesting to note that petroleum products SITC332 is very vulnerable in volume ranking due to significant variations of petroleum prices but in EcoMetricRank 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 (SITC031), clothing (SITC841) and fruits (SITC051) which are placed on higher positions compared to their volume ranking. At the same time roadvehic (SITC732), 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 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 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 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 Fig. 4, Fig. 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 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.

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SUPPORTING INFORMATION

Here we present the Supporting Information (SI) for the main part of the paper.

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 year 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.

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.

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

In Fig. S-3, in addition to Fig. 2, we show the nestedness matrices of WTN at various values of the cutoff threshold $\mu$. The data at various $\mu$ values show that in
The fraction $\varphi$ 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 $\mu$ 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.

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 and several values of the trade threshold $\mu$. 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 $m^{(e)}$ that is well visible in Figs. 1, S-1.

As it is pointed in the main part, we attribute this 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 $\varphi$ as the WTN at the given year and $\mu = 10^{-3}$. These data, compared with those of Fig. 3, really demonstrate that the real WTN has values of $T$ by a factor 5 (export) to 10 (import) smaller comparing to the random networks. This confirm 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 $\mu$ for the WTN data in year 2008. We see that there is only about 10-20% of variation of $T$ for the range $10^{-5} \leq \mu \leq 10^{-3}$. Even for a much larger range $10^{-6} \leq \mu \leq 10^{-2}$ 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 $\mu$. 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 I for EcoloRanking of countries at two different values of
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 $\varphi$ are as for the corresponding WTN years at $\mu = 10^{-3}$.

$\mu$ in year 2008 confirm the stability of this nestedness ordering. At the same time larger values of $\mu$ 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 I we present trade volume ranking and EcoloRanking of top 20 countries for import/export of WTN in year 2008.

In Table II we give the notations and symbols for Fig. 6 with corresponding SITC Rev1 codes and names. The list of all SITC Rev1 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 Rev1 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 (Manufact 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).
TABLE I: 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 $\mu$ (year 2008).

| Rank | Country (Import) | Country (Export) |
|------|------------------|------------------|
| 1    | USA              | USA              |
| 2    | Germany          | Germany          |
| 3    | China            | Italy            |
| 4    | France           | France           |
| 5    | Japan            | Spain            |
| 6    | UK               | Belgium          |
| 7    | Netherlands      | Japan            |
| 8    | Italy            | UK               |
| 9    | Belgium          | Netherlands      |
| 10   | Canada           | China            |
| 11   | Spain            | Canada           |
| 12   | Rep. of Korea    | Mexico           |
| 13   | Russian Fed.     | Rep. of Korea    |
| 14   | Mexico           | Russian Fed.     |
| 15   | Singapore        | Austria          |
| 16   | India            | Austria          |
| 17   | Poland           | Switzerland      |
| 18   | Switzerland      | Turkey           |
| 19   | Turkey           | U. Arab Emir.    |
| 20   | Brazil           | Denmark          |

| Rank | Country (Import) | Country (Export) |
|------|------------------|------------------|
| 1    | USA              | USA              |
| 2    | Germany          | Germany          |
| 3    | China            | Italy            |
| 4    | France           | France           |
| 5    | Japan            | Spain            |
| 6    | UK               | Belgium          |
| 7    | Netherlands      | Japan            |
| 8    | Italy            | UK               |
| 9    | Belgium          | Netherlands      |
| 10   | Canada           | China            |
| 11   | Spain            | Canada           |
| 12   | Rep. of Korea    | Mexico           |
| 13   | Russian Fed.     | Rep. of Korea    |
| 14   | Mexico           | Russian Fed.     |
| 15   | Singapore        | Austria          |
| 16   | India            | Austria          |
| 17   | Poland           | Switzerland      |
| 18   | Switzerland      | Turkey           |
| 19   | Turkey           | U. Arab Emir.    |
| 20   | Brazil           | Denmark          |
| Symbol | Code | Abbreviation | Name |
|-------|------|--------------|------|
| ♦ | 001 | animals | Live animals |
| ■ | 031 | fish | Fish, fresh & simply preserved |
| ♦ | 051 | fruits | Fruit, fresh, and nuts excl. Oil nuts |
| ▲ | 054 | vegetables | Vegetables, roots & 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 & 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 & pharmaceutical products |
| ♦ | 581 | plasticmat | Plastic materials,regenerd. cellulose & resins |
| ▲ | 599 | chemmat | Chemical materials and products, nes |
| • | 652 | cottwoven | Cotton fabrics, woven ex. narrow or spec.fabrics |
| ■ | 653 | ncottwov | Text 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 classd. accord.to kind |