Global formal live poultry and hatching egg trade network (2004-2016): description and association with poultry disease reporting and presence

L. Awada,[*,†,1] K. Chalvet-Monfray,[‡] P. Tizzani,[*] P. Caceres,[*] and C. Ducrot[§]

[*] *World Animal Health Information and Analysis Department, World Organisation for Animal Health 75017 Paris, France;* [†] *Lyon University, UMR EPIA, INRA VetAgro Sup, 69280, Marcy l'Etoile, France;* [‡] *Clermont Auvergne University, UMR EPIA, INRA VetAgro Sup, 63122, Saint-Genes-Champanelle, France; and* [§] *UMR ASTRE, Montpellier University, CIRAD, INRAE, Montpellier, France*

ABSTRACT As international trade constitutes one of the main spread pathways of diseases, a better understanding of the trade behaviors of countries will help identify strengths and areas for improvement in the approach of national authorities to controlling poultry diseases globally. Using data reported to the United Nations Comtrade and the World Organisation for Animal Health (**OIE**) between 2004 and 2016 by 193 countries, we used a network analysis on trade data of poultry hatching eggs, live poultry of less than 185 g and live poultry of 185 g or more to determine that: 1) quantities traded between countries are substantial, and tend to increase (average increase of 800,000 poultry heads and 21,000 tons of hatching eggs each year equivalent to an increase by 2-fold in 17 yr); 2) the stability of the networks was low (a quarter to half of trade relationships maintained between 2 consecutive years) and the subnetworks favorable to the spread of diseases were in general consistent with regional clustering, trade exchanges being equally at intracontinental and intercontinental levels; 3) countries with highest number of partners were located in the same world regions for the 3 poultry networks - Americas and Europe for export (up to 107 partners) and Africa, Asia and Europe for import (up to 36 partners); 4) for live poultry, biggest exporting countries shared more poultry disease surveillance data, and reported more disease presence than others, which did not stop them from trading. Biggest importers reported less poultry disease surveillance data and reported more disease presence than others; and 5) the main structural and trend characteristics of the international trade networks were in general similar for the 3 networks. The information derived from this work underlines the importance of applying the preventive measures advocated by the OIE and will support countries to reduce the risk of introduction of pathogens causing poultry diseases.

Key words: international poultry trade, network analysis, poultry disease, epidemiology, global health

2021 Poultry Science 100:101322
https://doi.org/10.1016/j.psj.2021.101322

INTRODUCTION

Formal and informal live poultry movements have been identified as a significant pathway for spread of poultry diseases, at local and international level (Van Den Berg, 2009; Soares Magalhães et al., 2012; Zhou et al., 2015; Kurscheid et al., 2017; Radin et al., 2017). It has been estimated that 43% of the highly pathogenic avian influenza (**HPAI**) introductions in Asia and 25% of those in Africa between 1996 and 2006 were due to live poultry trade (Kilpatrick et al., 2006). It has been suggested that, following the introduction of HPAI into Africa in 2006 through migratory birds, regional spread has occurred through live poultry trade, particularly between Nigeria and neighboring countries, because of the lack of border control in West Africa (Gauthier-Clerc et al., 2007; Cattoli et al., 2009; Fasina et al., 2009). Similarly, in 2016, the Food and Agriculture Organization (**FAO**) considered legal movements of live poultry to be an important pathway for the spread of HPAI in the Middle East (Lockhart et al., 2016). Network analysis techniques have been widely used to investigate the risk of the spread of poultry diseases through local poultry movements and more rarely through international or global poultry movements (Soares Magalhães et al., 2012; Fournié et al., 2013; Molia et al., 2016; Radin et al., 2017).

The ongoing global spread of certain poultry diseases, such as HPAI in birds and humans indicates current

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Received December 2, 2020.

Accepted June 4, 2021.

[1] Corresponding author: l.awada@oie.int

surveillance and control measures are insufficient (Awada et al., 2018). As international trade constitutes one of the main potential spread pathways, a better understanding of the trade behaviors of countries will help to identify strengths as well as areas for improvement in the approach of national authorities to controlling transboundary poultry diseases globally. Toward this end, the primary objective of the paper is to contribute to the understanding of the structure and dynamics of the global formal live poultry trade network, and to evaluate associations between trade behaviors and disease presence. To accomplish this, we use 13 yr of international poultry trade data to determine: 1) the quantities of poultry and hatching eggs traded and their evolution between 2004 and 2016; 2) the structural characteristics of the international trade network and its stability over time, from 2004 to 2016; 3) the countries acting as super exporters and super importers in the network, with description of their geographical characteristics; and 4) the associations between behaviors of countries for international trade and poultry disease reporting and presence. Findings are discussed in the context of transboundary spread of poultry diseases.

MATERIALS AND METHODS

Materials

Databases used: United Nations Comtrade and OIE WAHIS. United Nations (UN) Comtrade (United Nations, 2018a) centralizes data on international trade, provided by exporting and importing countries. Countries provide information for each year by product, the direction of exchanges (exporting to importing country), the price of the commodity traded (standardized in US dollars) and the quantity of goods. Annual data have been extracted for the period from 2004 to 2016, for the 193 UN Member States (United Nations, 2018b), with a final update as of 2 May 2018. Among poultry subcategories, data for chickens lighter than 185 g and ducks, geese, guinea fowls, turkeys lighter than 185 g were grouped under the name "live poultry lighter than 185 g"; data for chickens of 185 g or more and ducks, geese, guinea fowls, turkeys of 185 g or more were grouped under the name "live poultry of 185 g or more". These data were available for the entire period of analysis. Data for chicken hatching eggs and hatching eggs of ducks, geese, guinea fowls, and turkeys were only available for the 2012-2016 period. These subcategories were grouped under the name "poultry hatching eggs." It should be noted that data for ostriches and emus were only available for the 2012-2016 period, and were not considered in this analysis, since the corresponding reported international trade exchanges were negligible (1% to 2% of the total number of trade exchanges each year).

Disease reporting data were from the World Organisation for Animal Health (**OIE**), whose mandate is to ensure transparency in the global animal disease situation. These data are submitted to the OIE World Animal Health Information System (**WAHIS**) by the national authorities of 182 Member Countries that have the legal obligation to report data concerning high impact animal diseases listed by the OIE, and more than 20 additional countries and territories that provide information on a voluntary basis. This annual list of diseases contains 13 to 15 diseases of poultry for the period from 2004 to 2016 (World Organisation for Animal Health, 2018a,c). The OIE monitoring system includes data sent every 6 mo by each country and includes absence or presence, changes in the occurrence of all listed diseases, and information of epidemiological significance to the international community.

Countries targeted in the analysis (2004-2016). Of the 193 Member States of the UN, 109 (57%) provided poultry trade data for all years from 2004 to 2016 and 84 (43%) had missing data for at least one year between 2004 and 2016 (Figure S1). However, most of the poultry trade data for these 84 countries could be obtained by cross-checking information provided by their trading partners. The only exchanges for which no information was available were those that occurred between these 84 countries. Since countries within the same world subregion have a high probability of exchanging among themselves, blocks of countries have been set up for the analysis, as described below:

- Block 1: 9 countries in the Caribbean, Central America, and South America (Antigua and Barbuda, Bahamas, Cuba, Dominica, Grenada, Haiti, Honduras, Trinidad and Tobago and Venezuela)
- Block 2: 6 countries in Eastern Africa (Djibouti, Eritrea, Kenya, Somalia, South Sudan and Zambia)
- Block 3: 9 countries in Melanesia, Micronesia, and Polynesia (Kiribati, Marshall Islands, Micronesia (Fed. States of), Nauru, Palau, Papua New Guinea, Solomon Islands, Tuvalu and Vanuatu)
- Block 4: 8 countries in Middle Africa (Angola, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon and Sao Tome and Principe)
- Block 5: 3 countries in Northern Africa (Egypt, Libya, and Sudan)
- Block 6: 4 countries in Central Asia (Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan)
- Block 7: 2 countries in Southern Europe (Montenegro and Serbia)
- Block 8: 12 countries in Western Africa (Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Nigeria, Sierra Leone and Togo)
- Block 9: 7 countries in Western Asia (Iraq, Israel, Kuwait, Lebanon, Qatar, Syria and Yemen)
- Block 10: 5 countries in Southern Asia (Afghanistan, Bangladesh, Bhutan, Iran and Nepal)
- Block 11: 3 countries in South-East Asia (Cambodia, Lao (PDR) and Myanmar).

The 16 remaining countries that did not provide complete information were surrounded by countries that reported information and were therefore considered individually in the analysis. The analysis of the formal trade data thus covers 125 countries and 11 blocks of countries, which constitutes 136 units. For each country and block of countries, a geographical region was assigned, according to the UN standard classification (United Nations, 2018c).

Estimate of missing data (2004-2016). Annual poultry quantities traded were available in poultry heads for all subcategories, except for hatching eggs, for which quantities were expressed in kilograms (kg). For most annual trade exchanges in each subcategory, 2 types of data, namely the monetary value and the quantity of animals or products traded, were available. However, for 16% of the exchanges across all subcategories, only the monetary value was indicated. For all subcategories, the estimate of missing quantity data was performed by a Bayesian generalized linear model using the “rstanarm” package in the R software 3.5.1 (Gelman and Hill, 2007; R Core Team, 2015; Stan Development Team, 2016), and the following formula with a "Gamma" distribution family: Price per animal ~ Trade Flow + Export region + Import region + Year

With:

- Price per animal expressed in US dollars
- Trade flow having 2 possible values: export or import
- Export region being the geographical region of the exporting country or block
- Import region being the geographical region of the importing country or block
- Year being a value from 2004 to 2016.

All explanatory variables were treated as qualitative variables. The full model was tested for each subcategory (4-variable explanatory model), then variables were removed progressively, comparing the values of the Akaike information criterion (**AIC**) (preferred simplest model if lower AIC value, with at least 2 points of difference). The final model was selected for each subcategory according to the AIC criterion. This final model was used to estimate the missing data for poultry quantities.

Methods

Bearing in mind that the primary objective of the paper was to contribute to the understanding of the global trade network in the context of transboundary spread of poultry diseases, and recognizing that the risk of disease spread associated with poultry differs depending on their age, analyses were performed separately for 3 networks: 1) the network of live poultry lighter than 185 g; 2) the network of live poultry of 185 g or more; and 3) the network of poultry hatching eggs (Boyle et al., 2000; Ellis et al., 2005; McQuiston et al., 2005; Shankar, 2008). Network 1 is for chicken aged from 1 d to approximatively 3 wk, ducks and turkeys aged from 1 d to approximatively 1 wk, and guinea fowls aged from 1 d to approximatively 2 wk (Aggrey, 2002; Nahashon et al., 2006; Osei-Amponsah et al., 2014; Chang et al., 2016; Sogut et al., 2016). Network 2 is for poultry older than that age. Networks 1 and 2 were described for the entire period of analysis (2004 to 2016) and network 3 was described for the period from 2012 to 2016, due to data unavailability before these years.

Poultry quantities traded and their evolution. To identify the poultry subcategories representing the highest number of trade exchanges and highest quantities traded, the following methodology was designed. First, a “directed link” was defined as the existence of one or several trade exchanges between a given exporting country and an importing country during a given year. The number of directed links in the world, the annual poultry quantities traded, and the average poultry quantities traded by directed link were computed and plotted by subcategory using bar charts.

Characteristics of the international trade network over time, general description of the international trade network The 3 annual international formal trade poultry networks were first described using network indicators, including number of directed links, distributions of out-degrees, in-degrees, total degrees and network density. Definitions of selected network indicators are provided in Table S1. The distributions of out-degrees and in-degrees were also plotted for the most recent year (2016). Then, to describe the level of variation of the networks on an annual basis, we calculated the loyalty defined as the fraction of common directed links between each pair of years (Valdano et al., 2015). This loyalty was plotted using strip charts. Finally, groups of countries/blocks that share more relationships, i.e. communities, were identified within the overall cumulated global trade networks.

Identification of countries/blocks acting as super exporters and super importers. For each of the 3 networks, the annual distributions of in-degrees and out-degrees of countries/blocks were computed. For each network and year, countries/blocks were then categorized into 3 groups. Based on the 2 indicators mentioned above, countries/blocks in the category with highest values for all years considered in the analysis were identified and their geographical characteristics were described. Countries/blocks in the category with highest values for in-degrees were considered as super importers, while those in the category with highest values for out-degrees were considered as super exporters.

Poultry disease reporting and presence in potential super exporters and super importers. During the period of analysis, all countries/blocks were required to send information to the OIE each year, for 13 to 15 OIE-listed poultry diseases among the following list: avian chlamydiosis, avian infectious laryngotracheitis, avian infectious bronchitis, avian mycoplasmosis (*M. synoviae*), avian tuberculosis, duck virus enteritis, duck virus hepatitis, fowl cholera, fowl pox, fowl typhoid, HPAI, infectious bursal disease (Gumboro), low pathogenic avian influenza, Marek's disease, mycoplasmosis (*M. gallisepticum*), Newcastle disease, Pullorum disease, and turkey rhinotracheitis.

We first computed for each country/block and year the percentage of poultry OIE-listed diseases with information provided. We tested if there were significant differences between the median percentages of OIE-listed poultry diseases with information provided, between the countries/blocks of the 3 categories (low, medium and high) of out-degrees (indicator for the number of partners for export). We then computed for each country/block and year the percentage of poultry OIE-listed diseases reported present, among those with information. We tested if there were significant differences in the median percentages between the countries/blocks of the 3 categories (low, medium, and high) of out-degrees (indicator for the number of partners for export). We finally tested if there were significant differences in the median percentages between the countries/blocks of the 3 categories (low, medium, and high) of in-degrees (indicator for the number of partners for import).

Statistical analysis. All analyses were done in R (R Core Team, 2015). The correlation between the number of poultry heads traded from 2004 to 2016 and time was measured by the Spearman's rank correlation test. For the 3 networks, analysis of directed links, distributions of out-degrees, in-degrees, total degrees and network density was done using the packages igraph and keyplayer in R (Csardi and Nepusz, 2006; An and Liu, 2016). The theoretical distribution best fitting the observed distributions of out-degrees and in-degrees for 2016 was tested using the "fitdistrplus" package (Delignette-Muller and Dutang, 2015). For the stability analysis, unweighted matrixes were first created for each year. The Jaccard index was then calculated for each pair of matrixes, for each of the 3 networks. The Jaccard index allows understanding the similarities between sample sets and is defined as the size of the intersection divided by the size of the union of the sample sets. The network stability analysis was done using the packages igraph and BiRewire in R (Csardi and Nepusz, 2006; Gobbi et al., 2017). The correlation between the fraction of common directed links and time difference was measured by the Spearman's rank correlation test. For identification of communities within the international trade networks, the first step consisted in transforming the 3 directed networks to undirected networks, using the "collapse" mode. One undirected link was created for each pair of countries/blocks which were connected with at least one directed link. Within each undirected network, communities were then identified using the greedy optimization of modularity (Clauset et al., 2004). This is a bottom-up hierarchical approach that tries to optimize in a greedy manner a quality function called modularity, which is the fraction of the links that fall within the given communities minus the expected fraction if links were distributed at random (Li and Schuurmans, 2011). Initially, every country/block belongs to a separate community, and communities are merged iteratively such that each merge yields the largest increase in the current value of modularity. Results were plotted and described using the package igraph (Csardi and Nepusz, 2006) in R. The dependency between communities containing more than one country and world regions including Africa, Americas, Asia and Europe was tested using a Pearson's chi-squared test on R. Oceania could not be considered in the testing, due to the low number of countries/blocks in this world region. For the identification of super importers and exporters, the in and out-degree analysis was done using the package igraph in R (Csardi and Nepusz, 2006). For each network and year, countries/blocks were then categorized into 3 groups using the Jenks natural breaks classification method in R, with the package BAMMtools (Jenks, 1967; Rabosky et al., 2014). Finally, to test these hypotheses on poultry disease reporting and presence in potential super exporters and super importers, we used the Friedman test (Hollander and Wolfe, 1973), which is a nonparametric test adapted to repeated measurements (in our analysis, yearly measurements). When differences were significant, pairwise comparisons were then performed using the Wilcoxon test (Hollander and Wolfe, 1973).

RESULTS

Poultry Quantities Traded and Their Evolution Between 2004 and 2016

Number of directed links and their evolution. The number of directed trade links for the subcategories for which data were available for the entire period of analysis (2004-2016) is shown in Figure S2a. The total number was close to 1700 in 2004 and 2005, and it then dropped in 2006 to 1374, which is the minimum value observed for the period. The drop was observed for all subcategories (from -12% for "chickens lighter than 185 g" to -26% for "ducks, geese, guinea fowls and turkeys lighter than 185 g"). In the subsequent years, this number slowly and regularly increased up to values close to 1800 in 2015 and in 2016. These values were above the level of exchange observed in 2004 and 2005, before the drop. Concerning all subcategories of live poultry and hatching eggs (Figure S2b), the total number of directed links was stable from 2012 to 2014 (values close to 2800) and then increased to values close to 3000 in 2015 and 2016.

Quantities traded and their evolution. For live poultry (Figure 1A), the total number of heads traded by year increased by 2.6-fold (from 735 million in 2004 to 1 billion 956 million in 2016). This increase with years was significant, as measured by the Spearman's rank correlation test (rho = 0.98; P-value < 2.2e-16). For the subcategory "chickens lighter than 185 g", sudden increases of the quantity of heads traded are observed for the yr 2007, 2014 and a sudden decrease is observed for the year 2015. For live poultry, the annual average quantity by directed link (inset of Figure 1A) suddenly increased between 2005 and 2006, with less variation the following years. For hatching eggs (Figure 1B), the total weight of eggs traded by year ranged between 227 thousand tons (in 2012) and 362 thousand tons (in 2015). The weight of hatching eggs traded had an increasing trend from 2012 to 2015 and a sudden decrease was observed for the year 2016. For the 2 subcategories of hatching eggs (inset of Figure 1B), the annual average weight/directed link had

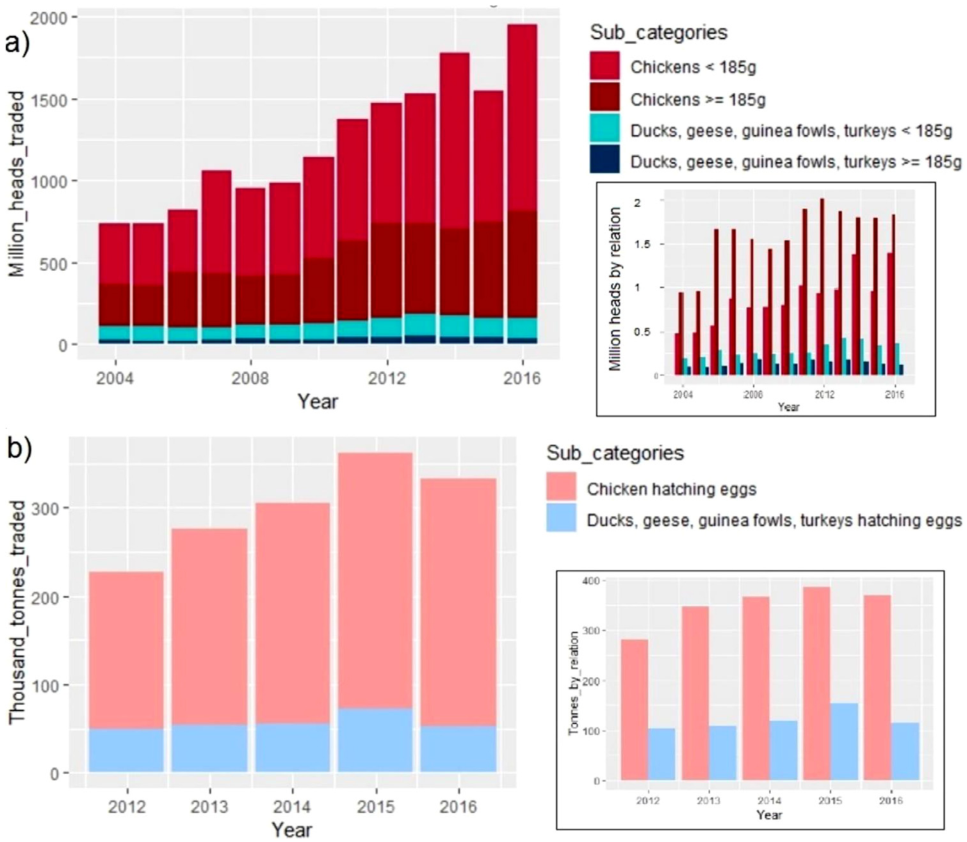


Figure 1. Number of annual quantities traded by poultry subcategory. (A) For live poultry for the period from 2004 to 2016; the average quantity of poultry heads traded by directed link is shown in the inset. (B) For poultry hatching eggs for the period from 2012 to 2016; the average weight of poultry hatching eggs traded by directed link is shown in the inset.

an increasing trend from 2012 to 2015 and a sudden decrease was observed for the year 2016.

Subcategories most traded. Consistently over the period of analysis, chickens lighter than 185 g and chicken hatching eggs were the subcategories with highest numbers of commercial directed links. The subcategory “chickens lighter than 185 g” represented the highest percentage of directed links (45% to 50% of the total each year for live poultry in Figure S2a and 27% to 28% of the total each year for all poultry subcategories in Figure S2b). When considering all poultry (Figure S2b), the second subcategory was “chicken hatching eggs” (22% to 25% of the total each year), while other subcategories (“chickens of 185 g or more”; “ducks, geese, guinea fowls and turkeys of 185 g or more”; “ducks, geese, guinea fowls and turkeys lighter than 185 g” and “hatching eggs of ducks, geese, guinea fowls and turkeys”) accounted for 9% to 18% of the total each year. In addition, consistently across all years, “chickens lighter than 185 g” represented the highest percentage of heads traded and the highest number of heads by directed link (47% to 61% of the total each year in Figure 1A and annual average of 1.63 million heads/directed link in the inset of Figure 1A). Similarly, “chicken hatching eggs” represented the highest percentage of weight traded and the highest weight by directed link (78% to 84% of poultry hatching eggs traded each year in Figure 1B and annual average of 352 tons/directed link in the inset of Figure 1B).

Characteristics of the International Trade Network and Its Stability Over Time

General description of the international formal trade network. The number of nodes was consistent across the period of analysis, as the 136 countries/blocks described in 2.1. were considered each year. Almost all countries/blocks were included in the trade network. Only 2 countries (Liechtenstein and Monaco) were neither connected to the network of hatching eggs nor to the network of live poultry lighter than 185 g. Five countries (Democratic People's Republic of Korea, Iceland, Liechtenstein, Monaco, and San Marino) were not connected to the network of live poultry of 185 g or more.

The largest network sizes (number of directed commercial links between 2 countries) were for the network of live poultry lighter than 185 g (range between 762 and 914 from 2004 to 2016) and for the network of hatching eggs (range between 763 and 901 from 2012 to 2016). The size of the network of live poultry of 185 g or more was smaller (range between 287 and 469 from 2004 to 2016) (Table S2). For both live poultry networks, the number of links between countries/blocks was high in 2004 and 2005 (around 900 for live poultry lighter than 185 g and around 415 for live poultry of 185 g or more) and then suddenly dropped in 2006 to 762 and 309 respectively (Figure S3). The same pattern was observed for the density of the network of live poultry lighter than 185 g. The number of directed links then progressively increased in the next years up to values around 880 for live poultry lighter than 185 g and around 470 for live poultry of 185 g or more in 2016 (Figure S3). For the network of hatching eggs, the number of directed links consistency increased from 796 in 2012 to 901 in 2016.

For all networks and all years during the period of analysis, the median value for in-degrees remained above the median value for out-degree, which shows that, globally, countries/blocks had more diverse partners for import than for export. The difference in the maximum values between out-degrees and in-degrees is also remarkable. Each year, the difference was of 50 to 62 degrees for live poultry lighter than 185, of 13 to 24 degrees for live poultry of 185 g or more, and of 30 to 81 degrees for hatching eggs. It shows that consistently over the period of analysis, some specific countries/blocks had very high numbers of different partners for export and that the maximum values for the number of different partners for import never reached the same level (Figure S3). This difference is very clear on Figure S4, which shows the distributions of out-degrees and in-degrees plotted for 2016 (the plot for 2016 was provided as an example, considering the 3 networks 1) the network of live poultry lighter than 185 g; 2) the network of live poultry of 185 g or more; and 3) the network of poultry hatching eggs).

The sudden increase in the maximum out-degree value for the network of hatching eggs, between 2014 (56) and 2015 (106) is also remarkable (Figure S3). The Netherlands had around 50 partners for export in 2012 and 2013 and suddenly increased its number of export partners to 106 in 2015 and 107 in 2016. In relation with out-degree distribution for 2016 (Figure S4a), results show that most of the countries/blocks in the networks exported to very few other countries and this is consistent with the medians presented in Table S2 (2 outgoing trade relations for the network of live poultry lighter than 185 g and network of poultry hatching eggs; 1 out-going trade relation for the network of live poultry of 185 g or more). However, the maximum number of partners registered for export is very high (78 for live poultry lighter than 185 g, 47 for live poultry of 185 g or more and 107 for poultry hatching eggs). The data approximated negative binomial distributions (for live poultry lighter than 185 g mu= 6.44 and variance = 121,64, for live poultry of 185 g or more mu= 3.45 and variance = 33.96 and for poultry hatching eggs mu= 6.62 and variance = 135.61). In relation with in-degree for 2016 (Figure S4b), results show that the distribution of countries/blocks is less variable. The medians presented in Table S2 are higher than for out-degree and the maximum number of partners for import is 27 for the 2 live poultry networks and 36 for hatching eggs. The data approximated negative binomial distributions (for live poultry lighter than 185 g mu= 6.44 and variance = 22.09, for live poultry of 185 g or more mu= 3.45 and variance = 15.76 and for poultry hatching eggs mu= 6.62 and variance = 30.83).

Nodes loyalty. Results for the Jaccard index calculated for each pair of matrices are shown in Table S3. The percentage of common directed links contained in networks of 2 consecutive years ranged between 48% and 49% for hatching eggs, 47% and 58% for poultry lighter than 185 g and between 28% and 43% for live poultry of 185 g or more. The percentage of connections that persisted between the 2 most extreme years was 43% for poultry hatching eggs (between 2012 and 2016), 38% for poultry lighter than 185 g (between 2004 and 2016) and 25% for live poultry of 185 g or more (between 2004 and 2016). Figure 2 shows the fraction of common directed links per year time difference. This fraction clearly decreased with increase of time difference. For hatching eggs, the median value decreased from 49% for a year of difference to 43% for 4 yr of difference. This decrease with time was barely significant as measured by the Spearman's rank correlation test (rho = -0.95; *P*-value = 0.05). For poultry lighter than 185 g, the median value decreased from 54.5% for a year of difference to 38% for 12 yr of difference. This decrease with time was significant as measured by the Spearman's rank correlation test (rho = -1; *P*-value = 1.288e-13). For live poultry of 185 g or more, the median value decreased from 40% for a year of difference to 25% for 12 yr of difference. This decrease with time was significant as measured by the Spearman's rank correlation test (rho = -0.99; *P*-value = 9.971e-10). It is interesting to note that for poultry lighter than 185 g and poultry of 185 g or more, there were few preserved links between 2004 and the other years as well as between 2005 and the other years.

Communities within the international trade network. The number of communities identified was of 7 within the network of live poultry lighter than 185 g (5 communities with several countries/blocks and 2 countries not connected to the network as described in 3.2.), 9 within the network of live poultry of 185 g or more (4 communities with several countries/blocks and 5 countries not connected to the network as described in 3.2), and 6 within the network of poultry hatching eggs (4 communities with several countries/blocks and 2 countries not connected to the network as described in 3.2.) (Figure 3 and Table S4). The number of trade relations was the highest (1,605) in the cumulated network of live poultry lighter than 185 g from 2004 to 2016. Among them, 861 (54%) were across communities and the remaining relations were within communities. Then, the cumulated network of poultry hatching eggs from 2012 to 2016 comprised 1,140 trade relations and among them, 542 (47%) were across communities and the remaining relations were within communities. Finally, the cumulated network of live poultry of 185 g or more from 2004 to 2016 comprises 1,072 trade relations and among them, 449 (42%) were across communities and the remaining relations were within communities.

The clustering in communities for the 3 networks is relatively consistent with the regional clustering (Table S4). The dependency between the clustering into the communities and the world regions was confirmed by the Pearson's chi-squared test for the network of live poultry lighter than 185 g (X-squared = 152.05, df = 9, *P*-value < 2.2e-16), for the network of live poultry of

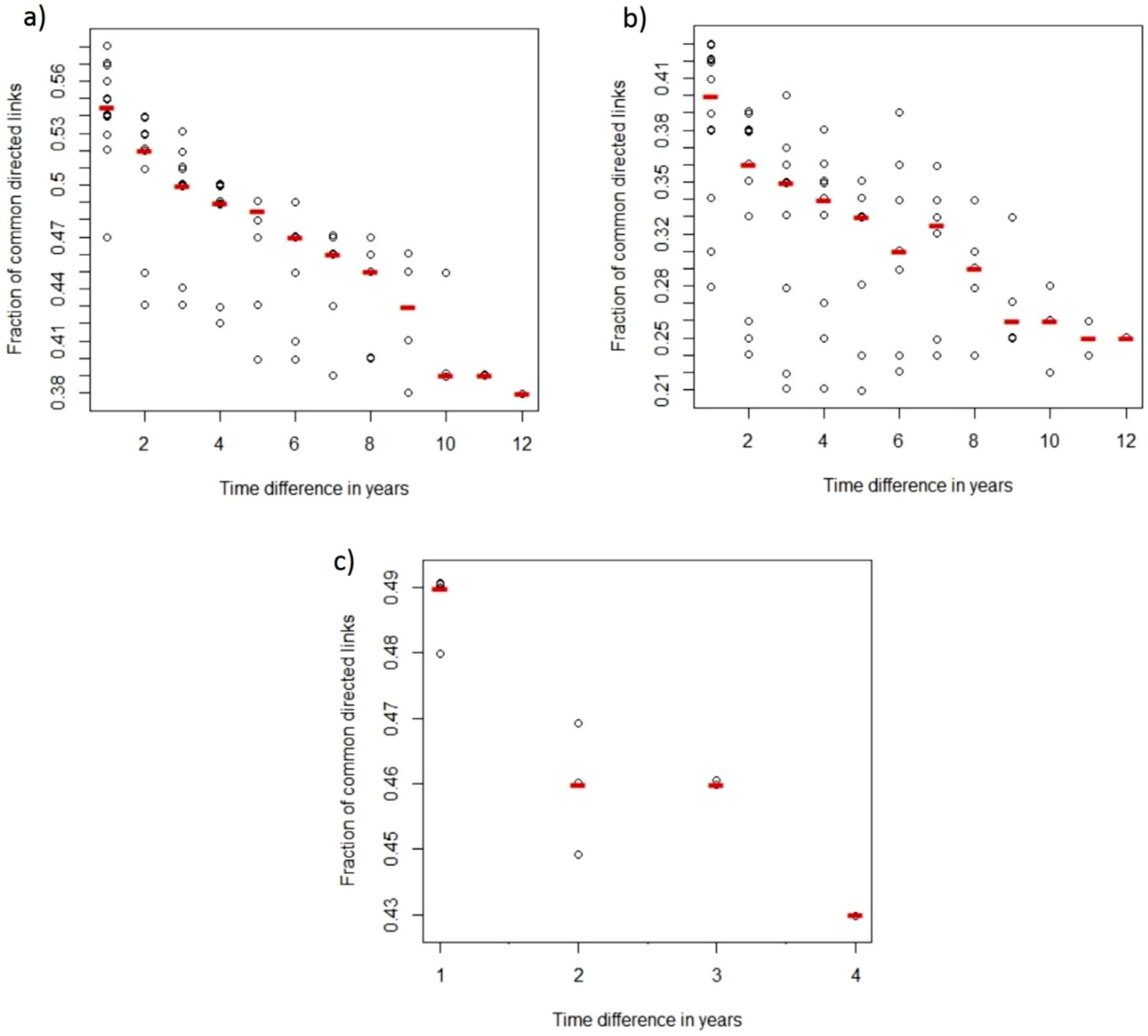


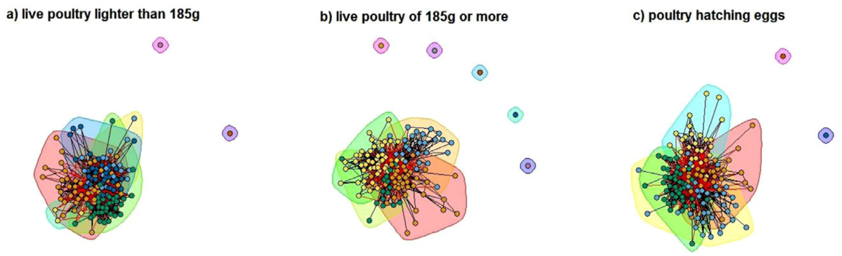
Figure 2. Fraction of common directed links per year time difference (stripcharts) – medians are shown in red – (A) considering live poultry lighter than 185 g from 2004 to 2016; (B) live poultry of 185 g or more from 2004 to 2016; and (C) poultry hatching eggs from 2012 to 2016.

185 g or more (X-squared = 170.76, df = 9, P-value < 2.2e-16) as well as for the network of poultry hatching eggs (X-squared = 201.86, df = 9, P-value < 2.2e-16). Also, the dependency between the clustering into the communities of the networks 2 by 2 was confirmed by the Pearson's chi-squared test: X-squared = 188.07, df = 9, P-value < 2.2e-16 for hatching eggs and live poultry of 185 g; X-squared = 175.4, df = 9, P-value < 2.2e-16 for hatching eggs and live poultry lighter than 185 g; and X-squared = 119.71, df = 9, P-value < 2.2e-16 for live poultry of 185 g or more and live poultry lighter than 185 g.

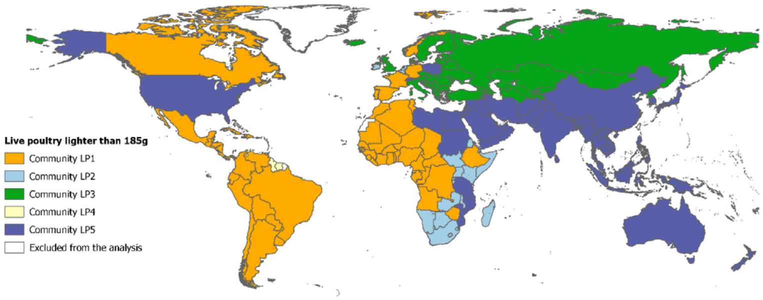
Identification of Super Exporters and Super Importers

Group categorization using the Jenks natural breaks classification method. The categorization was first done based on out-degrees, an indicator for the number of export partners (Table S2). For the network of live poultry lighter than 185 g, and according to the year, the lowest category included exporters with 0 to 14 partners, the medium category 8 to 42 partners, and the highest category 22 to 84 partners. For the network of live poultry of 185 g or more, the lowest category included exporters with 0 to 8 partners, the medium category 4 to 23 partners, and the highest category 13 to 48 partners. For the network of poultry hatching eggs, the lowest category included exporters with 0 to 15 partners, the medium category 10 to 59 partners, and the highest category 31 to 107 partners. For example, on Figure S4a, vertical lines show the Jenks natural breaks used to group exporters in the three 2016 trade networks. In general, 81% of countries/blocks remained in the same category (lowest, medium or highest) over the period of analysis in the network of live poultry lighter than 185 g, 66% in the network of live poultry of 185 g or more and 86% in the network of poultry hatching eggs, which shows high stability of countries/blocks export level during the period of analysis.

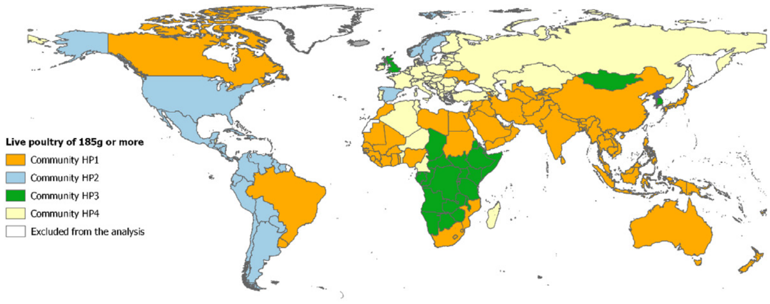
Second, the categorization was done based on in-degrees, an indicator for the number of import partners (Table S2). For the network of live poultry lighter than 185 g and according to the year, the lowest category included importers with 0 to 6 partners, the medium category 4 to 13 partners, and the highest category 9 to 28 partners. For the network of live poultry of 185 g or



d) Communities within the network of live poultry lighter than 185g



e) Communities within the network of live poultry of 185g or more



f) Communities within the network of poultry hatching eggs

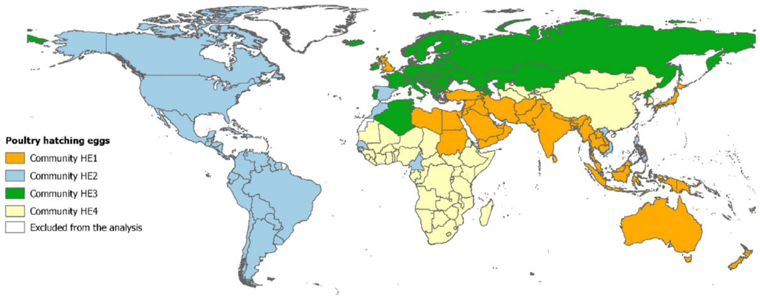
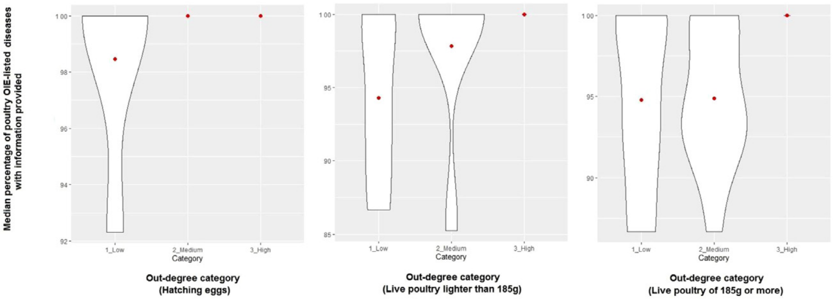


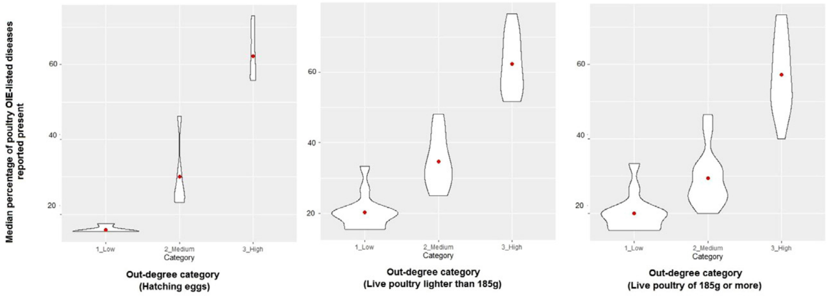
Figure 3. Communities identified in the cumulated global poultry trade network – each color corresponds to a community - (A) seven communities in the trade network of live poultry lighter than 185 g (2004-2016), *community LP1: orange dots, community LP2: light blue dots, community LP3: dark green dots, community LP4: yellow dots, community LP5: purple dots, community LP6: gray dots, community LP7: brown dots* - (B) Nine communities in the network of live poultry of 185 g or more (2004-2016), *community HP1: orange dots, community HP2: light blue dots, community HP3: dark green dots, community HP4: yellow dots, community HP5: purple dots, community HP6: gray dots, community HP7: brown dots, community HP8: light purple dots, community HP9: beige dots* - (C) Six communities in the network poultry hatching eggs (2012-2016), *community HE1: orange dots, community HE2: light blue dots, community HE3: dark green dots, community HE4: yellow dots, community HE5: purple dots, community HE6: brown dots* - (D) Spatial distribution of countries according to their communities in the trade network of live poultry lighter than 185 g (2004-2016), using same colors; (E) Spatial distribution of countries according to their communities in the trade network of live poultry of 185 g or more (2004-2016); (F) Spatial distribution of countries according to their communities in the trade network of poultry hatching eggs (2012-2016), using same colors. The countries/blocks composing the communities are further described in Table 2. Only communities with several countries/blocks are shown on maps (D), (E), and (F).

more, the lowest category included importers with 0 to 4 partners, the medium category 2 to 14 partners, and the highest category 6 to 28 partners. For the network of poultry hatching eggs, the lowest category included importers with 0 to 7 partners, the medium category 4 to 16 partners, and the highest category 12 to 36

a) Poultry OIE-listed diseases with information provided, according to category of export



b) Poultry OIE-listed diseases reported present, according to category of export



c) Poultry OIE-listed diseases with information provided, according to category of import

d) Poultry OIE-listed diseases reported present, according to category of import

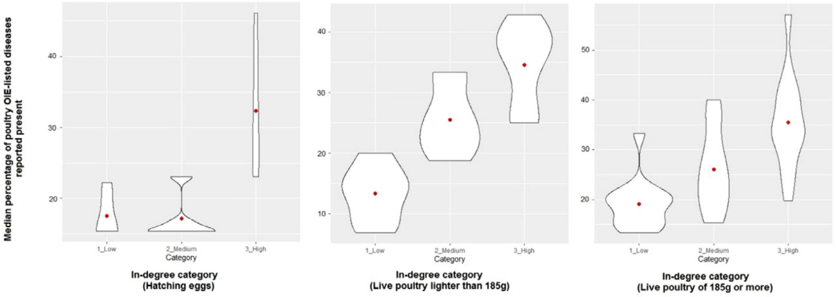


Figure 4. Poultry OIE-listed diseases with information provided, and poultry OIE-listed diseases reported present, according to category of export and import. Violin plots show the distributions of annual median values and the red dot shows the median value across all years (2004-2016 pour live poultry and 2012-2016 for poultry hatching eggs).

partners. For example, on Figure S4b, vertical lines show the Jenks natural breaks used to group importers in the three 2016 trade networks. In general, only 27% of countries/blocks remained in the same category (lowest, medium or highest) over the period of analysis in the network of live poultry lighter than 185 g and 21% in the network of live poultry of 185 g or more. This shows little stability of countries/blocks import level during the period of analysis for these 2 networks. In the network of poultry hatching eggs, about half of the countries/blocks (51%) remained in the same category between 2012 and 2016, which shows some stability for this category only.

Geographical characteristics of super exporters and super importers. Based on out-degrees and in-degrees consistently over the period of analysis, and for all poultry categories, The Netherlands was in the highest category each year, which makes it super exporter and super importer for the whole period of analysis, for all trade networks (Table 1). Based on out-degrees,

Table 1. Distribution of countries/blocks across the period of analysis, by Region – (A) by out-degree category and (B) by in-degree category. All results are detailed separately for the 3 networks: live poultry lighter than 185 g from 2004 to 2016, live poultry of 185 g or more from 2004 to 2016 and poultry hatching eggs from 2012 to 2016.

A. By out-degree category (Regions with super exporters are highlighted)

Region	Network	Always in the lowest category	Medium or lowest category depending on years	Highest or medium or lowest category depending on years	Highest or lowest category depending on years	Always in the medium category	Highest or medium category depending on years	Always in the highest category
Africa	**Poultry<185g**	22	7	0	0	0	0	0
	Poultry≥185g	21	5	2	0	0	1	0
	Hatching eggs	27	1	0	0	1	0	0
Americas	**Poultry<185g**	23	1	1	0	1	0	1
	Poultry≥185g	20	5	1	0	0	1	0
	Hatching eggs	24	0	0	0	2	0	1
Asia	**Poultry<185g**	26	6	0	0	0	0	0
	Poultry≥185g	21	10	0	1	0	0	0
	Hatching eggs	27	5	0	0	0	0	0
Europe	**Poultry<185g**	26	4	0	0	3	5	4
	Poultry≥185g	19	11	1	0	3	6	2
	Hatching eggs	22	6	0	0	7	6	1
Oceania	**Poultry<185g**	4	2	0	0	0	0	0
	Poultry≥185g	4	2	0	0	0	0	0
	Hatching eggs	5	1	0	0	0	0	0

B. By in-degree category (Regions with super importers are highlighted)

Region	Network	Always in the lowest category	Medium or lowest category depending on years	Highest or medium or lowest category depending on years	Always in the medium category	Highest or medium category depending on years	Always in the highest category
Africa	**Poultry<185g**	3	13	3	3	5	2
	Poultry≥185g	6	18	3	0	2	0
	Hatching eggs	15	11	0	1	1	1
Americas	**Poultry<185g**	7	13	5	0	2	0
	Poultry≥185g	6	20	1	0	0	0
	Hatching eggs	15	9	0	2	1	0
Asia	**Poultry<185g**	4	9	4	1	12	2
	Poultry≥185g	2	20	5	0	4	1
	Hatching eggs	5	15	0	7	4	1
Europe	**Poultry<185g**	5	11	2	0	19	4
	Poultry≥185g	7	16	3	3	12	1
	Hatching eggs	5	13	0	5	10	9
Oceania	**Poultry<185g**	5	1	0	1	0	0
	Poultry≥185g	3	3	0	0	0	0
	Hatching eggs	3	3	0	0	0	0

Table 1A shows that consistently over the period of analysis, several other countries in Europe and one country in the Americas were in the highest category each year, which make them super exporters for the whole period of analysis. In Europe, France was a super exporter for live poultry (both lighter than 185 g and of 185 g or more), and Germany and United Kingdom were super exporters for live poultry lighter than 185 g. In the Americas, United States of America was a super exporter for live poultry lighter than 185 g as well as poultry hatching eggs. In addition, concerning export, 6 other European countries (Belgium, Czech Republic, Denmark, Hungary, Italy and Spain), one other American country (Canada), one Asian country (Brunei Darussalam), and 3 African countries (Senegal, South Africa and Tanzania) were in the highest category certain years but not all.

Based on in-degrees, Table 1B. shows that consistently over the period of analysis, several countries in Africa, Asia and Europe were in the highest category each year, which make them super importers for the whole period of analysis. Block 9 composed of 7 countries in Western Asia was a super importer for all poultry networks. In Africa, block 8 composed of 12 countries in Western Africa was a super importer for live poultry lighter than 185 g as well as poultry hatching eggs, and block 5 composed of 3 countries in Northern Africa was a super importer for live poultry lighter than 185 g. In Asia, block 10 composed of 5 countries in Southern Asia was a super importer for live poultry lighter than 185 g. In Europe, Germany and Hungary were super importers for live poultry lighter than 185 g as well as poultry hatching eggs. Romania was a super importer for live poultry lighter than 185 g, while Denmark, France, Italy, Poland, Russia, and United Kingdom were super importers for poultry hatching eggs. In addition, concerning import, 8 other African countries/blocks, 7 American countries/blocks, 18 other Asian countries/blocks, and 16 other European countries/blocks were in the highest category certain years but not all.

Poultry Disease Reporting and Presence in Potential Super Exporters and Super Importers

Percentage of OIE-listed poultry diseases with information provided, according to number of partners for export. Results are presented in Figure 4A. The percentage of OIE-listed poultry diseases with information provided by countries increased with the number of their commercial partners for export, and these medians were significantly different for live poultry lighter than 185 g (Friedman $\chi^2_2 = 9.54$, P-value = 0.008) and live poultry of 185 g or more (Friedman $\chi^2_2 = 10.889$, P-value = 0.00432). Concerning the network of live poultry lighter than 185 g between 2004 and 2016, the pairwise comparison test showed that the values of the lowest category (countries /blocks that exported to the smallest number of partners) were significantly different (P-value = 0.01368) and lower than the values of the highest category (countries/blocks that exported to the higher number of partners). Concerning the network of live poultry of 185 g or more between 2004 and 2016, the pairwise comparison test showed that the value of the lowest category and the value of the medium category were significantly different (P-value = 0.0206 and 0.008969 respectively) and lower than the value of the highest category. No significant differences were shown in the network of poultry hatching eggs.

Percentage of OIE-listed poultry diseases reported present, according to number of partners for export. Results are presented in Figure 4B. The percentage of OIE-listed poultry diseases reported present by countries increased with the number of their commercial partners for export and these medians were significantly different for live poultry lighter than 185 g (Friedman $\chi^2_2 = 26$, P-value = 2.26e-06) and live poultry of 185 g or more (Friedman $\chi^2_2 = 23.804$, P-value = 6.777e-06). Concerning the network of live poultry lighter than 185 g between 2004 and 2016, and the pairwise comparison test showed that the values of the lowest category and the values of the medium category were significantly different (P-value = 0.001651 and P-value =0.0002441 respectively) and lower than the values of the highest category. It also showed that the values of the lowest category were significantly different (P-value = 0.001656) and lower than the values of the medium category. Concerning the network of live poultry of 185 g or more between 2004 and 2016, the pairwise comparison test showed that the values of the lowest category and the values of the medium category were significantly different (P-value = 0.001656 for both tests) and lower than the values of the highest category. It also showed that the values of the lowest category were significantly different (P-value = 0.003252) and lower than the values of the medium category. No significant difference was shown in the network of hatching eggs.

Percentage of OIE-listed poultry diseases with information provided, according to number of partners for import. Results are presented in Figure 4C. The percentage of OIE-listed poultry diseases with information provided by countries decreased with the number of their commercial partners for import, and these medians were significantly different for live poultry lighter than 185 g (Friedman $\chi^2_2 = 7.6818$, P-value = 0.02147) and live poultry of 185 g or more (Friedman $\chi^2_2 = 16.311$, P-value = 0.0002871). Concerning the network of live poultry lighter than 185 g between 2004 and 2016, the pairwise comparison test showed that the values of the lowest category and the values of the medium category were significantly different (P-value = 0.0328 and P-value = 0.01253, respectively) and higher than the values of the highest category. Concerning the network of live poultry of 185 g or more between 2004 and 2016, the pairwise comparison test showed that the value of the lowest category and the value of the medium category were significantly different (P-value = 0.001555 and 0.004991 respectively) and higher than the value of the highest category. No significant difference was shown in the network of hatching eggs.

Percentage of OIE-listed poultry diseases present, according to number of partners for import. Results are presented in Figure 4D. The percentage of OIE-listed poultry diseases reported present by countries increased with the number of their commercial partners for import, and these medians were significantly different for live poultry lighter than 185 g (Friedman $\chi^2_2 = 26$, P-value = 2.26e-06) and live poultry of 185 g or more (Friedman $\chi^2_2 = 17.077$, P-value = 0.0001958). Concerning the network of live poultry lighter than 185 g between 2004 and 2016, the pairwise comparison test showed that the value of the lowest category and the value of the medium category were significantly different (P-value = 0.001656 and P-value =0.0002441 respectively) and lower than the value of the highest category. It also showed that the value of the lowest category was significantly different (P-value = 0.0002441) and lower than the value of the medium category. Concerning the network of live poultry of 185 g or more between 2004 and 2016, the pairwise comparison test showed that the value of the lowest category and the value of the medium category were significantly different (P-value = 0.001656 and P-value = 0.002441 respectively) and lower than the value of the highest category. It also showed that the value of the lowest category was significantly different (P-value = 0.006104) and lower than the value of the medium category. No significant difference was shown in the network of hatching eggs.

DISCUSSION

The main results of this study are: 1) the number of annual trade relationships and quantities traded between countries are substantial, and tend to increase (average increase of 800,000 poultry heads and 21,000 tons of hatching eggs each year equivalent to an increase by 2-fold in 17 yr); 2) the stability of the global network was low as only a quarter to half of trade relationships were maintained between 2 consecutive years in each poultry network, and the subnetworks favorable to the spread of poultry diseases within the international trade network were in general consistent with regional clustering, trade exchanges being equally distributed between subnetworks (intercontinental) and within subnetworks (intracontinental); 3) countries with the highest number of partners were located in the same world regions for the 3 poultry networks, namely Americas and Europe for export (up to 107 partners) and in Africa, Asia, and Europe for import (up to 36 partners); 4) for live poultry, biggest exporter countries shared more poultry disease surveillance data to the OIE, and reported more disease presence than others, which did not stop them from trading. Biggest importers reported less poultry disease surveillance data to the OIE and reported more disease presence than others; and 5) the main characteristics of the international trade networks were in general similar for hatching eggs, live poultry of less than 185 g and live poultry of 185 g and more, in terms of structure and trend. The information derived from this work shows that the risk of poultry disease spread through trade is both at global and regional levels.

The data used in this study are mainly based on official reporting to the UN Comtrade and 43% of the countries considered in the analysis had missing data for at least one year between 2004 and 2016. In addition, several countries only provided information on monetary values of trade exchanges but not on quantities. The gaps of information were partially solved using "mirror data" from trade partner countries, grouping nonreporting countries from the same subregion into blocks (with the assumption that neighboring countries within the same world subregion are more likely to trade together compared with distant countries) and estimate of missing quantities. These methods are consistent with methods described by the United Nations Conference on Trade and Development (Muryawan, 2012) and with the method later developed in the context of the UN Comtrade upgrade plan in 2019. In both cases, estimated values are derived from mirror statistics (data reported by trading partners) or from the value/quantity or value/weight ratio of the properly reported data (United Nations, 2019). It should be kept in mind that these corrections allow to analyze global trends but may not be accurate when looking at specific countries. In addition, data reported from national authorities have limitations due to the variability among countries in national customs institution and other national systems, which, in general, may lead to underreporting. However, the global quantities discussed in this analysis are consistent with previous estimates, which reinforce the confidence in our results (Food and Agriculture Organization of the United Nations, 2011).

The poultry commodities are grouped into categories that are based on United Nations Harmonized Commodity Description and Coding Systems and are not risk based (United Nations, 2017). Bearing in mind that the primary objective of the paper was to contribute to the understanding of the global trade network in the context of transboundary spread of poultry diseases, and recognizing that the risk of disease spread associated with poultry differ depending on their age, analyses were performed separately for 3 networks. However, this network categorization does not allow to isolate day-old chicks, that weight about 40 g, and is known to have lower risk of disease transmission than other live poultry (Jiang and Yang, 2007; Food and Agriculture Organization of the United Nations, 2020). To complete this analysis, it would be interesting for relevant international organization such as UN Comtrade to collect custom data on import and export on more specific groups of animals, based on risk categories. Despite this limitation, the 3 categories considered in the analysis allowed to obtain significant results, meaningful to understand global trends. Moreover, the main characteristics of the 3 international trade networks were in general similar, in terms of structure and trend. The temporal trends for poultry traded and trade relationships were similar, the structure in terms of importing and exporting countries/blocks and their geographical regions were similar and the clustering of the 3 networks into communities was similar. Also, for live poultry networks, similar results were obtained concerning poultry disease reporting and presence in potential super exporters and super importers. The main differences between networks were related to the size of the networks (the network of live poultry of 185 g or more being smaller than the other ones) and the stability of the networks (the network of live poultry of 185 g or more being more instable than others throughout years). Another difference was concerning poultry disease reporting and presence in potential super exporters and super importers: the network of hatching eggs has shown no significant association conversely to the others, potentially due to the fact that data were only available for 5 yr for hatching eggs, vs. 13 yr for live poultry networks.

The poultry disease data used in this study are based on mandatory reporting to the OIE. Disease data reported from national authorities have limitations due to the variability among countries in animal disease surveillance systems and transparency, which, in general, can lead to underreporting which varies between countries. However, it should be kept in mind that this data was used to analyze global trends and not looking at specific countries. Also, among the list of OIE-listed diseases considered in the analysis, few are specific to chickens or ducks, and few others are specific to certain age categories of poultry. However, most diseases considered can affect several poultry species and poultry ages in the different networks considered in the analysis (World Organisation for Animal Health, 2019c). For example, HPAI, Newcastle disease, and avian mycoplasmosis should be considered likely to be spread though trade in hatching eggs, although most poultry diseases are more likely to be spread through live birds. For disease to be spread by poultry hatching eggs, the pathogen must be able to spread through vertical transmission or penetrate the eggshell and contaminate its contents after the egg has been laid. (Swayne and Thomas, 2008; Cobb, 2011). Therefore, despite these limitations, the data considered in the analysis allowed to obtain significant results, meaningful to understand global trends.

Another methodological limitation concerns the identification of communities within the global trade networks, using the greedy optimization of modularity. This method was selected because it is well adapted to big networks (Clauset et al., 2004). Results obtained using this approach were compared with the ones obtained using other methods - community detection based on edge betweenness and community detection based on propagating labels - and the number of communities and grouping of countries slightly differed (Newman and Girvan, 2004; Raghavan et al., 2007). Results using the greedy optimization of modularity method were however considered to make sense as communities were relatively consistent with the regional clustering, as expected.

The number of annual directed links and quantities traded between countries were substantial and increasing during the whole period of analysis. The trend observed during the period of analysis would lead to an increase by 2-fold of quantities traded in 17 yr, which is substantial, and can be a source of concern in relation with the risk of diseases spread if not followed by a similar increase in countries sanitary surveillance capacities. Small variations were observed. The number of directed links dropped between 2004/2005 and 2006 for live poultry networks, and then increased regularly in subsequent years to reach in 2016 the same level than in 2004, while the quantities traded substantially increased from 2004 to 2016 (+166% of live poultry traded) with no major drop observed. This drop between 2004/2005 and 2006 also had an impact on nodes loyalty results in the live poultry networks. The lowest percentage of common directed links contained in networks of live poultry of 2 consecutive years was observed between 2005 and 2006 (which shows that the relations in the networks were reorganized that year) and a density drop was observed in the networks of live poultry. This drop might be partially explained by the global HPAI crisis (Nicita, 2008). It is interesting to note that despite the 2006 drop in the number of commercial relationships between countries, the quantities traded continued to increase that year, with a marked increase of the quantities traded by relation. This might suggest discrepancies in trust with trading partners in this context of global sanitary crisis. Indeed, the trade network can impact the spread of avian diseases, but diseases can also impact this network. As previously described by several authors, sanitary constraints, particularly those related to avian influenza, have significantly influenced commercial networks over the last 15 yr (Nicita, 2008; Van Horne and Achterbosch, 2008; Chmielewski and Swayne, 2011). The main difference between the 3 networks in terms of structure was about the size and the number of total degrees distribution. The number of directed links was lower for poultry of 185 g or more compared with other networks, but the quantity of animals traded by directed link was higher. This shows that countries have less partners for trade in that network compared with others.

As mentioned above, the stability of the global poultry trade network was relatively low as only half of trade relationships were maintained between 2 consecutive years in the networks of hatching eggs and live poultry of less than 185 g. The stability was lower in the network of live poultry of 185 g or more, with only a quarter of trade relationships maintained between 2 consecutive years. This is below expectations, as it could have been assumed that countries tend to build trust with partners over time. This variability in trade relationships might be explained by economic and political factors as well as sanitary factors such as trade bans resulting from disease events (Davis, 2015). It may also be partly resulting from data unavailability in the database analyzed. This variability is an interesting result in the context of international efforts to control transboundary poultry diseases, as the resulting increase in number of different partners might increase the probability of exposure to diseases and therefore the risks of disease spread.

In this analysis, subnetworks favorable to the spread of poultry diseases within the international trade networks were identified. These subnetworks (or communities) were consistent with regional clustering in all networks and the communities were similar in the 3 poultry networks analyzed. Our results also show that exchanges were equally distributed between intracontinental (within subnetworks) and intercontinental (between subnetworks) trade. This suggests that the pathways for disease spread through trade are substantial within regions, but also between world regions, at a global scale. When looking at international trade data in general (not only poultry data), intraregional trade is dominant in Asia and Europe and represents more than 15% of the exports in Africa and the Americas, which shows the existence of strong intraregional trade communities (United Nations, 2018d). This is consistent with what has been observed in this analysis.

This paper also poses the questions of identifying countries most at risk for poultry disease spread and introduction via poultry trade, in case of insufficient implementation of preventive and control measures. First, we demonstrated that, similarly for the 3 networks analyzed, super exporters were mainly located in Europe and Northern America, while super importers were mainly located in Africa, Asia, and Europe. Several Western European countries were at the same time super exporter and super importers. We showed that for export, most countries tended to remain with comparable numbers of partners across years, while this was less stable for import.

For live poultry networks, we also demonstrated that the super exporters sent more information on OIE-listed poultry diseases to the OIE than other countries, consistently over years. This was expected, given that transparency is a key requirement for export, as most countries' Veterinary Authorities of importing countries require the presentation of an international veterinary certificate attesting that recommended surveillance and control measures are implemented in their partner exporting countries. This is as recommended by the OIE and shows the importance of transparency for trade. We demonstrated that the super exporters have more OIE-listed poultry diseases reported present than other countries, consistently over years. This was against our initial hypothesis, as we expected that countries free from diseases would be more likely to export live poultry and poultry hatching eggs. It shows that disease presence is not a barrier for export, when proper disease control is implemented and documented, as recommended by the OIE. The Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) seeks to strike a balance between the right of World Trade Organization (WTO) Members to protect health on the one hand, and to avoid unnecessary barriers to trade on the other hand. This agreement highlights science-based principles, such as risk assessment, regionalization, and equivalence. Appropriate preventive and control measures are described in the OIE standards on risk analysis, disease prevention and control, trade measures, import/export procedures and veterinary certification (World Organisation for Animal Health, 2019a,b). These standards apply to countries free from diseases and to affected countries, so that they can mitigate the risk of disease spread and safely import and export live animals and animal products. In addition, several countries that have the highest numbers of partners for export also have the highest numbers of partners for import - especially in Europe − and, we demonstrated that the super importers have more OIE-listed poultry diseases reported present than other countries consistently over years. This was as initially expected, as diversity in the number of partners for import can increase the risk of exposure. Lastly, we showed although a high number of poultry diseases are circulating in super importers, these countries sent less information on OIE-listed poultry diseases to the OIE than other countries, potentially due to lack of resources or transparency. Several super importers are in developing world regions and their reporting systems may not be as extensive and regulated as other countries in other parts of the world. All these associations were significant for live poultry networks. For the hatching eggs network, only the association between disease presence and exporting categories was significant. However, it is likely that the association for other hypotheses could not be demonstrated, due to the lack of data for years 2004 to 2011, which reduced the sample size. It is also possible that hatching egg trade is less associated with disease presence than live poultry.

Import and export levels are highly correlated with poultry density, which is known to be a factor increasing the probability of disease presence (Pavade et al., 2011). Indeed, biggest traders of live poultry are also the highest producers of live poultry. Other factors potentially correlated with trade levels such as implementation of surveillance and control measures or detection and diagnosis capacities impact the probability of disease presence. Therefore, when interpreting results, these correlations should be kept in mind, and a follow-up analysis with a complete model would be interesting to assess the role of each factor, since they may have synergic effects on disease spread.

Considering these findings, especially the increasing quantities of poultry traded over years, all countries must be vigilant to the risk of introduction of pathogens causing poultry diseases, and apply the necessary preventive measures in response to permanent changes in the structure of the global network, such as the measures advocated by the competent international organization, namely the OIE (World Organisation for Animal Health, 2018b). The OIE standards, recognized by the WTO under the SPS Agreement for animal health and zoonoses-related matters, contribute effectively to global regulatory approaches to safeguard public good while limiting unnecessary impediments. In addition, existing tools aiming at monitoring trade and disease evolutions at global level in nearly real-time or real-time, such as the UN Comtrade and the OIE WAHIS disease early warning and monitoring components, constitute important decision tools for countries to identify situations at risk for disease spread (United Nations, 2018a; World Organisation for Animal

Health, 2018a). Interconnection of such databases could be very useful for controlling international spread of animal diseases. This analysis provides an interesting insight of the recent global situation to identify strengths as well as areas for improvement in the approach of national authorities to controlling transboundary poultry diseases globally and this approach could be applied to any animal disease likely to be spread by international trade of animals and animal products.

To complete this analysis, it would be interesting to analyze whether informal trade represents a significant pathway for spread of poultry diseases at international level. To do so, viral analysis has been used in several parts of the world to determine the sources of introduction (Van Den Berg, 2009). Although data on informal trade are very difficult to obtain, several examples in history in different world regions tend to prove its importance, such as the 2016 HPAI event in Lebanon, in connection with the massive influx of refugees, several HPAI events in Asia and Africa in 2006, in 2003/2004 with in particular the fighting cocks, that had probably introduced the disease into Malaysia (Sims et al., 2005; Kilpatrick et al. al., 2006; Gauthier-Clerc et al., 2007; Lockhart et al., 2016). Most of these examples suggest that the importance of informal trade for disease spread would be relevant between neighboring countries, but there is not enough data to assess its importance over longer distances. Finally, to build over this analysis, it would be interesting to overlap the international trade network with the evidence of international spread of poultry diseases over the same period (2004−2016), so that the role of international poultry trade in transboundary historical introductions of the diseases can be further assessed.

DISCLOSURES

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The views and opinions expressed in this article are those personal of the authors and do not necessarily reflect the official policy or position of the World Organization for Animal Health (OIE). The authors declare that they have no conflict of interest.

ACKNOWLEDGMENTS

Ethical statement: The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered. No ethical approval was required.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.psj.2021.101322.

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