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Evaluation of the impact of live pig trade network, vaccination coverage and socio-economic factors in the classical swine fever eradication program in Peru

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ABSTRACT

Classical swine fever (CSF) is a viral infectious disease of swine with significant economic impact in the affected countries due to the limitation of trade, culling of infected animals and production losses. In Latin America, CSF is endemic in several countries including Ecuador, Bolivia, Brazil and Peru. Since 2010, the National Veterinary Services of Peru have been working to better control and eradicate the disease with an intensive vaccination program. The aim of this study was to evaluate the effectiveness of the vaccination program and determine which factors are still contributing to the persistence of the disease in certain regions of Peru. We integrated the data from the vaccination campaign, the live pig movement network and other socioeconomic indicators into a multilevel logistic regression model to evaluate their association with CSF occurrence at district level. The results revealed that high vaccination coverage significantly reduces the risk of CSF occurrence (OR = 0.07), supporting the effectiveness of the vaccination program. Districts belonging to large and medium pig trade network communities (as identified with walktrap algorithm) had higher probability to CSF occurrence (OR = 2.83 and OR = 5.83, respectively). The human development index (HDI) and the presence of a slaughterhouse in the district was also significantly associated with an increased likelihood of CSF occurrence (OR = 1.52 and OR = 3.25, respectively). Districts receiving a high proportion of the movements from districts that were infected in the previous year were also at higher risk of CSF occurrence (OR = 3.30). These results should be useful to guide the prioritization of vaccination strategies and may help to design other intervention strategies (e.g., target education, movement restrictions, etc.) in high-risk areas to more rapidly advance in the eradication of CSF in Peru.

1. Introduction

Classical swine fever (CSF) is a viral disease that affects both wild and domestic pigs; the etiological agent for this disease is the Classical Swine Fever Virus (CSFV) from the *Pestivirus* genus of the family *Flaviviridae*. Some implications of the disease in the affected countries are the trade restrictions, reduction in the swine production and culling of infected animals, which have severe economic consequences and significantly hampers the sustainability and development of the swine industry in the affected countries. The main route of transmission of CSF is via direct contact with infected animals, but the disease can also be transmitted indirectly by contact with contaminated fomites such as vehicles, boots, clothes and other equipment (Elber et al., 1999). Understanding the dynamics of the disease transmission and high risk areas for CSF occurrence are key to prioritize interventions for disease prevention and control.

CSF is endemic in several countries of Latin America, including Ecuador, Bolivia and Peru; other countries such as Chile, Paraguay and Mexico has successfully eradicated the disease and now are recognized as CSF-free by the World Organization for Animal Health (OIE). Currently, Peru is one of the most rapidly growing economies and although the swine industry only represent the 5.4% of the livestock GDP (MINAGRI, 2015), there is a significant demand and opportunity for growth in the coming years (UNDP, 2013). The swine population is mainly concentrated near mountains (76% of swine producers) and the coast (14% of swine producers). Over 70% of the swine population in Peru is concentrated in small backyard producers. Up to 44% of the producers are in poverty or extreme poverty (INEI, 2015), therefore,

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any improvement of the swine industry may lead to important socio-economical benefits for the country.

CSF is considered as endemic in Peru and veterinary services have a stablished protocol for outbreak response. When a farm is suspicious of having CSF there is a restriction of incoming and outgoing movement followed of testing of all the animals in that farm. Animals that tested positive must be sacrificed, the sacrifice of apparently healthy animals is a decision that is taken by the producer, given that there is no compensation for the sacrificed animals. After the confirmation of the disease by the diagnostic laboratory there is a quarantine of at least 30 days and a compulsory vaccination within the 3 km radius from the affected premise. Previously to the end of the 30-day quarantine the animals must be re-tested and test negative before the quarantine is lifted.

National Veterinary Services of Peru have been intensifying their surveillance, control and eradication programs of several OIE listed diseases, some of them with great success, such as Foot-and-mouth disease (Martínez-López et al., 2014b; OIE, 2017). In 2010, an intensive CSF vaccination program started with the goal of more rapidly control and ultimately eradicate CSF from the country. The vaccine used in Peru is a live attenuated Chinese strain, which is highly effective and safe, providing complete clinical and virological protection within a week of vaccination (van Oirschot, 2003); After the implementation of the vaccination program the reduction of CSF outbreaks has been remarkable in several regions, although the disease is still prevalent in some areas, particularly in the coast and near the border with Ecuador. Some of the possible factors contributing to the persistence of the disease have been hypothesized to be associated with poor vaccination coverage in some areas and the trade of infected animals both inside the country and with other neighboring countries. A better understanding of the live pig movement network structure, dynamics and characteristics (e.g., centrality measures), as well as socio-economic factors that may contribute to poor biosecurity and high risk pig management practices, particularly, in those areas with poor vaccination coverage is highly needed. This information could guide more cost-effective, target interventions and suggest strategical changes in the vaccination implementation to significantly reduce the risk of disease transmission.

In this study, we first aimed to describe the yearly live pig trade network in Peru using centrality measures and identifying the key connected communities (i.e., areas highly interconnected that are more likely to share the same CSF status) from 2010 to 2014. Then we quantified the specific role that vaccination coverage, live pig network characteristics and other socioeconomic indicators have in the CSF occurrence in Peru.

Our main hypotheses are that the vaccination program is certainly reducing the risk of CSF occurrence in areas with high coverage. However, this protective effect is highly influenced and varies among regions due to other factors associated with the structure and characteristics of the live pig trade and socio-economic factors that affect the pig herd biosecurity and management. The identification of areas that remain at high risk of CSF occurrence despite the high vaccination coverage can also be targeted to implement additional interventions (e.g. education, movement restrictions and other target preventive and control strategies).

To our knowledge, this is the first study that describes the temporal and spatial patterns of CSF in Peru after initiation of the intensive control program in 2010 as well as the factors contributing to the effectiveness of the vaccination program in the country. Methods and results should be useful to advance with the CSF eradication, not only in Peru, but in other countries in the region.

2. Materials and methods

2.1. Study area and data sources

Data regarding the vaccination program, the live pig movements and the CSF outbreaks between 2010–2014 were provided by the Animal Health Service (SENASA) of Peru. For this study we considered as the pig population the pigs included in the vaccination program. Specifically, we obtained data about the number of pigs included in the vaccination program, the number of pigs vaccinated, date and ID of the herd vaccinated. Live pig movement information was obtained from the CSTI (health certificate for internal movement, from the Spanish "Certificado Sanitario de Transito Interno") which included information of the origin of the movement, the destination, date, number of animals moved, transportation type (such as: truck, train, airplane), ID of the driver and license plate of the vehicle. Information about the CSF outbreaks consisted of location of the outbreak, date, and test used. Additionally, SENASA provided the geocoded location and type (municipality or private) of the slaughterhouses.

Socio-economic information was also gathered from the United Nation Development Program in Peru (UNDP, 2013). Specifically, we obtained the human development index (HDI), which is a summary measure that considers three aspects of human development: health assessed by life expectancy, education assessed by the average number of years of schooling and standard of living measured by gross national income per capita (UNDP, 2016). The HDI was only available for the years 2010–2012, based on this data we made an extrapolation of the data to obtain an estimate of the expected HDI also for 2013 and 2014.

For the extrapolation of the HDI, a simple linear regression model was fitted for each district j using the following equation: $HDI_j = \beta_0 + \beta_1 year_j$

As mentioned before, all the data was analyzed at district level (n = 1834), which is the smallest administration level for the country (mean = 563.59 km^2, SD = 1743 km^2).

2.2. Network definition and construction

We used the information on live pig movements between districts in Peru to construct a directed network for each year and evaluate the properties, dynamics and characteristics of the live pig movement network. We geocoded the districts of origin and destination and generated spatial-explicit directed networks for each year, using districts as the nodes and movements as the edges. Centrality measures such as degree, betweenness and closeness as well as the Euclidean distance for each movement were calculated for each district. Analyses were conducted using the igraph package in R (Csardi, 2006). We used the information provided by SENASA regarding the case reports of CSF to calculate the proportion of movements incoming from districts with positive cases of CSF in the previous year and categorized this variable in 4 groups: communities that not received incoming movements from CSF positive districts in previous years, communities that received less than 20% of their movements from positive districts, communities that received more than 20% and less than 60% of their movements from positive districts, and communities that received more than 60% of their movements from positive districts.

We calculated the giant strong component (GSC) and giant weak component (GWC) per year using the igraph library in R. Briefly, GSC and GWC can be defined as subgraphs of the network where every node can be reached from every other node, via directed paths or indirectly by ignoring the direction of the links, respectively (O'Malley and Marsden, 2008). Then, we used the walktrap algorithm (Pons, 2005) using a simplified network per year to detect communities of districts (i.e., districts highly connected between them). The districts that did not have pig trading during that year were included in the community 0. Then, we selected the largest (community L) and second largest community (community M) and we grouped as "other" all other districts belonging to any other smaller communities.

2.3. Statistical analysis

A multilevel logistic regression model (Eq. 1) was used to evaluate the impact that vaccination coverage, live pig network characteristics and socio-economic factors have in CSF occurrence at district level from 2010 to 2014. We used a random intercept model formulated as follow:

$$y_{ij} \sim Binomial\,(1,\ \pi_{ij})$$

$$logit\,(\pi_{ij}) = \beta_0 + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \ldots \beta_4 X_{kij} + \mu_j$$

Where the y_{ij} is the disease status at time i for the jth district (1 = positive, 0 = negative), π_{ij} is the probability of having a CSF outbreak, β_0 is the intercept, $\beta_1\beta_2 \ldots \beta_k$ represents the slopes for each of the X_k predictors and μ_j is the random effect that is assumed to follow a normal distribution of the form $\mu_j \sim N(0, \sigma)$, where j represents the district.

We first conducted a bivariate analysis to identify potential good predictors using a conservative $p < 0.20$. Then, these potential good predictors were included into the multilevel logistic regression model using year as random effect to account for the multiple observations per district over the study period (i.e., repeated measures design). Selection of the final model was conducted using a manual backward elimination process using AIC as criterion to choose the best model. The AUC of the ROC Curve was also used to evaluate the predictive ability of the model. All analyses were conducted using the packages lme4 (Bates et al., 2015), Epi (Bendix Carstensen et al., 2017), epicalc (Chongsuvivatwong, 2012) and igraph (Csardi, 2006) in R-language (Team, R.C., 2015). Maps for the spatial visualization of results were generated with ARCGIS (version 10.5, ESRI 2017).

3. Results

3.1. Descriptive analysis of the vaccination program, the pig trade patterns and, socioeconomic indicators in Peru from 2010 to 2014

The pig population per district based on the vaccination program highly varied from just one pig to 192,397 pigs (mean = 1,777 SD = 7,946) (Table 1). The areas with higher pig density are concentrated in districts in the coast, such as Moche from the department of La Libertad (2,884 pigs per km^2) and Santa Maria from the department of Lima (1,426 pigs per km^2), and in some districts in the south, such as Alto de la Alianza from the department of Tacna (1,095 pigs per km^2) (Fig. 1).

The CSF vaccination program in Peru was significantly enhanced over the study period. In 2010, 15.33% of the districts were part of the vaccination campaign, but only 7.73% were vaccinating 100% of the pig population. The following year, 2011, the number of districts included in the vaccination campaign greatly increased reaching a total number of 83.95% districts vaccinated, with 39.83% of them having 100% vaccination coverage. Description of the program and spatial distribution of the vaccination coverage per year is presented on Table 2 and Fig. 2, respectively.

3.2. Live pig trade network in Peru

During the period analyzed, 501 (32.5%) districts were involved in the shipment or reception of pigs to/from other districts, accounting for a total of 129,678 pig movements between 2010–2014. From these movements, we removed the movements that were destined to slaughterhouse, as the risk for CSF spread was considered to be negligible, and considered only all other live pig movements to define the network per year (n = 7785). Movements to other destinations besides slaughterhouses accounted for 6% of the total movements in the database, and were classified as trade, consumption, fattening, exhibition and reproduction. Trade movements were the ones between premises for commercial purposes, consumption the movements that go from one premise to another facility for posterior sacrifice and consumption, fattening are the movements destined to other premises for growing and finishing, exhibition movements are the ones destined to fairs, and reproduction movements where movements with breeding purposes. (Fig. 3)

The mean, standard deviation and maximum number of pig movements per month were 130, 25 and 193, respectively. The overall network density for the time period analyzed was 0.04%. The values of the centrality measures, distance and number of pigs moved per shipment are presented in Table 3. Lima and Puno were the most active departments in terms of live pig movements. Santa Maria, Huaura from the department of Lima was the district with higher outdegree (i.e., outgoing pig shipments) followed by Ilave, El Collao from the department of Puno, with 1,212 and 735 movements, respectively. The districts with higher indegree (i.e., incoming pig shipments) during the period of the study were Puno from the department of Puno, with 823 incoming shipments, and Chilca from the department of Lima with 808. The median distance covered by movement was 18.09 km with a standard deviation of 107.12 km and a range from 1.03 km to 1,524 km. As mentioned before, most of the incoming and outgoing movements were within a short distance (mainly between the departments of Lima and Callao), but there were also some movements registered between distant districts such as El Algarrobal and La Victoria, which are 1,524 km apart. Districts such as Santa Maria, Callao and Lurin showed the highest betweenness (i.e., how often the district is in the shortest path between any pair of districts), suggesting an important trading role of those districts.

The yearly live pig trade networks in Peru did not form any GSC but did form GWC including, on average, 84.57% of the districts per year. Large and medium communities per year were relatively stable (i.e., same districts included in those communities over the years) (Fig. 4). Main composition and descriptive statistics of the communities are shown in Table 4.

Table 1
Summary statistics of the swine population and the vaccination coverage (per district per year, n = 4610 observations).

	Mean	Median	SD	Min-Max
Number of pigs	1777	439	7946	1-192,397
Vaccination coverage (%)	96.83	100	9	0-100
Pig density (number of pigs per km^2)	14.95	2.41	92.43	> 1-2884

3.3. HDI extrapolation

A linear regression model was fitted for each of the districts in Peru. The distribution of the residuals for all those models is shown in Fig. 5. The mean value of the residuals for the linear model was 1.01×10^{-19} with a SD of 3.99×10^{-03} (min = -2.69, max = 2.14×10^{-02}), showing overall a good fit for most of the districts. Some of the districts with better fit and worst fit are shown in Fig. 5.

3.4. Multilevel logistic regression model

A total of 4,597 observations were analyzed using a multilevel logistic regression model, each observation representing a district at a specific year. Final model included vaccination coverage as a strong protective factor (OR = 0.07) and the risk factors were presence of slaughterhouse (OR = 3.25), scaled HDI (OR = 1.52), and the presence of the district in a large, medium and other community (OR = 2.83, OR = 5.83 and OR = 2.66, respectively). The incoming movements from CSF positive districts in previous year was significant when the incoming movements were more than 60% from CSF positive districts (OR = 3.30) (Table 5). The AUC for the final model was 97.70%. Fig. 6 shows the spatio-temporal distribution of the observed cases and the prediction values and residuals of the model.

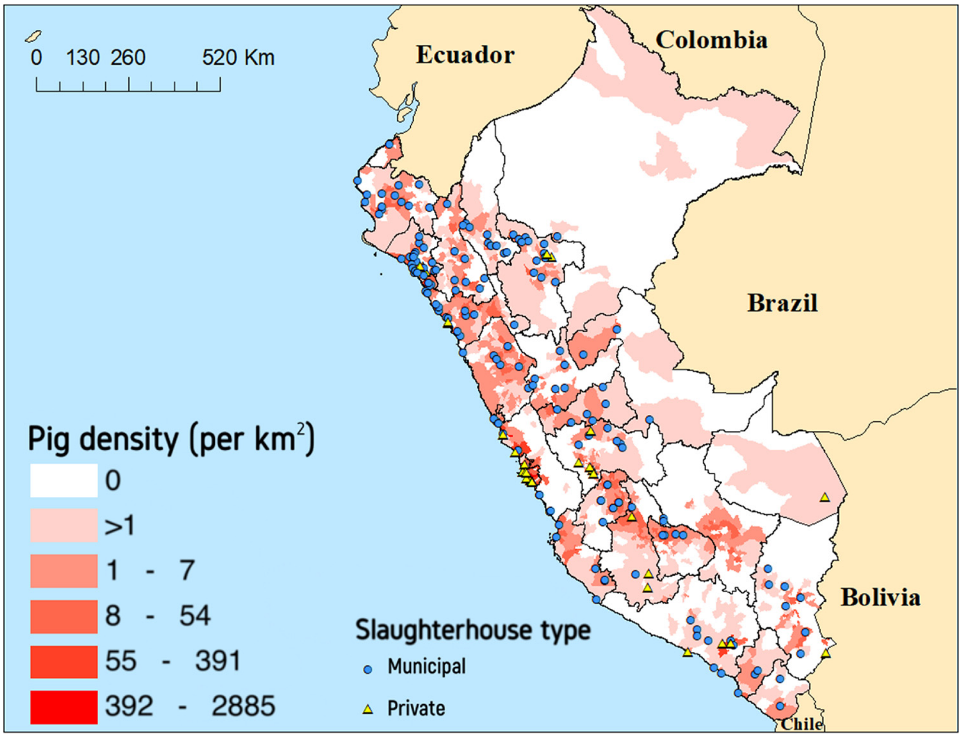

Fig. 1. Spatial distribution of the pig density with location of the slaughterhouses in Peru in 2014. Categories for the pig density were selected using natural breaks in ArcGIS 10.5. (The reader is referred to the web version of this article for the interpretation of the different colors of this figure.)

Table 2
Number of districts covered by the CSF vaccination program in Peru per year and percentage of districts reaching 100% vaccination coverage (per district, n = 4610 observations).

Year	# of districts vaccinated (%)	# of districts with 100% vaccination coverage (%)
2010	236 (15.33)	119 (7.73)
2011	1292 (83.95)	613 (39.83)
2012	1216 (79.01)	762 (49.51)
2013	674 (43.79)	470 (30.53)
2014	1177 (76.47)	882 (57.30)

4. Discussion

This is the first study to describe the CSF evolution in Peru after the implementation of the intensive control program in 2010. Our results highlight the value of the vaccination program to effectively reduce the incidence of the disease, although also suggest the potential value of other interventions to better control CSF outbreaks likely associated to the flow of infected animals through trade. Previous studies have used Social Network Analysis (SNA) to describe the trade network of animal movements for different countries and even integrating the centrality measures in regression models to predict outcomes such as disease status (Lee et al., 2017; Sintayehu et al., 2017). In this study we have evaluated not only the potential role that the pig trade network may have in CSF transmission using SNA but also have considered other demographic and socioeconomic characteristics of the districts, which we believe allows to better identify factors that may be contributing to CSF persistence even in areas with high vaccination coverage.

According to the vaccination campaign records during the study period, the mean vaccination coverage per district was good (96.86%). Since the start of the vaccination campaign, there was a notable increase in the vaccination efforts from only 236 districts vaccinated in 2010, to 1292 districts in 2011. There was also a notable reduction of the districts vaccinated in 2013, due to some problems with the vaccine distribution during that year (SENASA personal communication) and that is why the vaccination efforts were reduced that year. In Fig. 2 we can see that most of the coastal area near Ancash, Callao and Lima are receiving high vaccination coverage, but other areas near the southern part of Peru such as Moquegua, Madre de Dios showed low vaccination coverage during the study period.

We included HDI in the model in part because previous studies have found a relationship between the lack of education and a higher transmission of disease (Martínez-López et al., 2014a; Leslie et al., 2016) and we believe that the other socioeconomic indicators (i.e., income and life expectancy) could be also proxies related with different pig production systems and CSF transmission dynamics. Interestingly, our model shows that there is a positive association between an increased HDI and a higher probability of CSF occurrence. We believe that this is because underserved communities might be less likely to register movements between farms because the production systems are usually familiar with backyard animals for self-consumption and more likely to have informal trade, which is not captured in our model. On the other side, more developed areas, such as Lima have more resources reflecting a higher complexity of the trade system, potentially including the presence of more markets and centers where a higher diversity of shipping come together, and therefore, an increased risk for infectious diseases transmission if biosecurity measures are not continuously implemented.

Only 32.5% of districts with pig population registered active trade, while the other districts did not register live pig movements during the time period analyzed (2010–2014). We observed an increased trend in the pig movements during the study period as well as a higher number of movements concentrated in the last months of the year. The increase of movements over the study period could be explained, at least in part by an intensification of the notification/registration of pig movements or the increase of trading between districts over the time period. We also observed an intensification of movements during the last months of the year, particularly December, which could be associated with an increased in pork consumption in festivities such as Christmas and New Year.

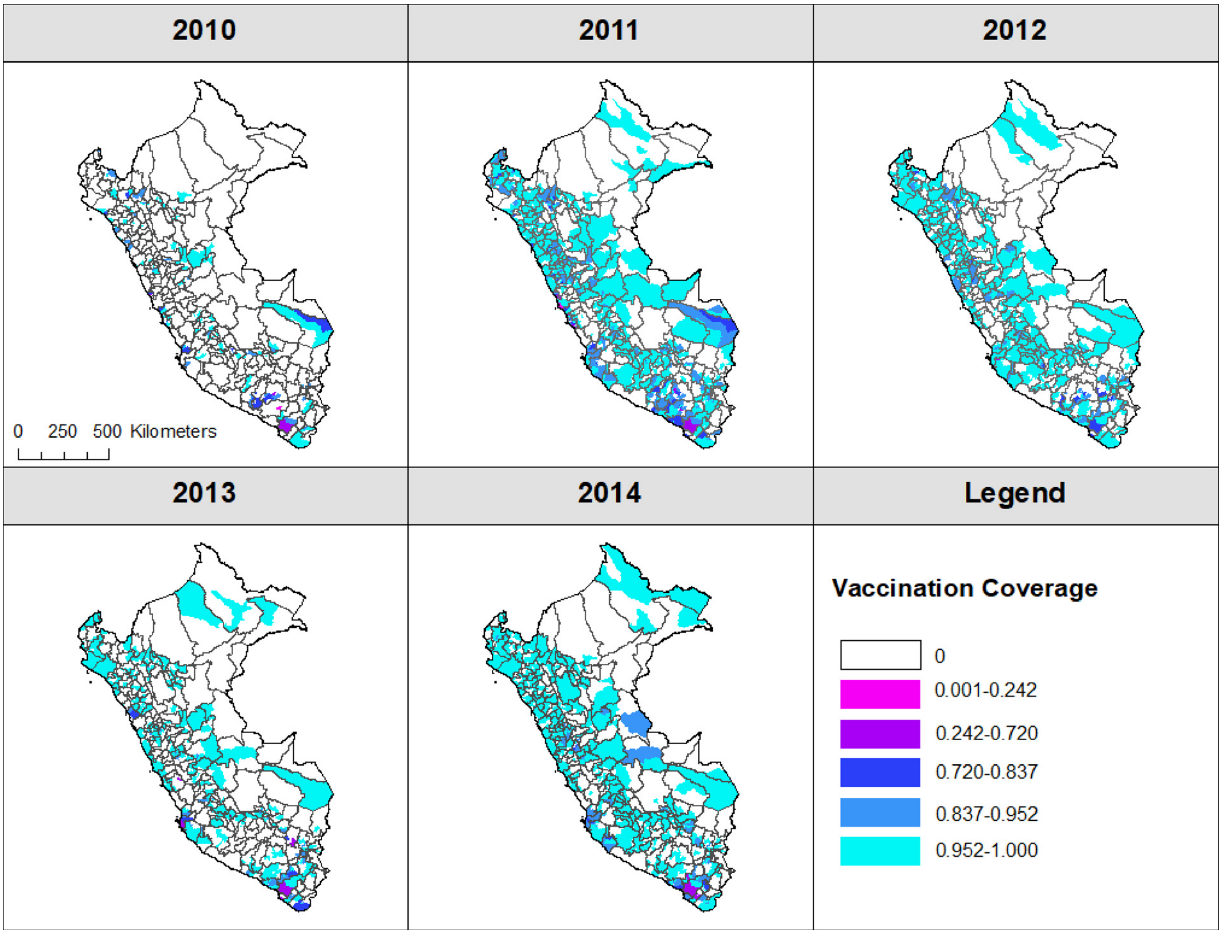

Fig. 2. Spatial distribution of the vaccination coverage per year. Categories were selected using natural breaks in ArcGIS 10.5. (The reader is referred to the web version of this article for the interpretation of the different colors of this figure.)

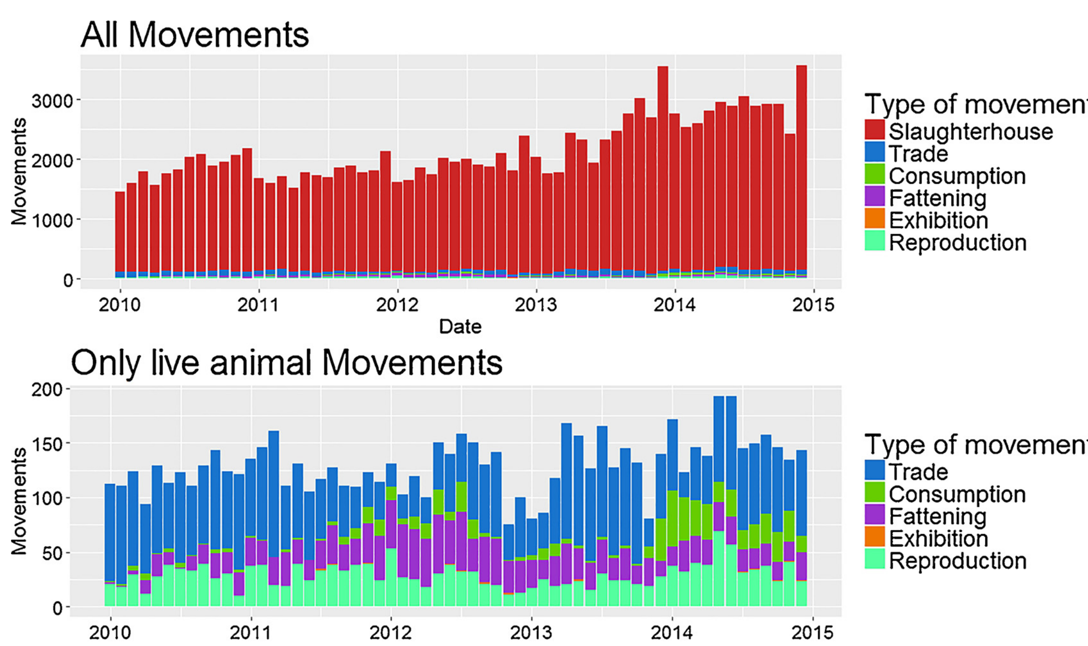

Fig. 3. Temporal distribution of the live pig movements in Peru from January 2010 to December 2014. (The reader is referred to the web version of this article for the interpretation of the different colors of this figure.)

Table 3
Summary statistics for the network centrality measures of the live pig trade network in Peru from 2010–2014 (Per district, n = 4610 observations).

Centrality measure	Mean	Median	SD	Min-max
Indegree	1.24	0	10.67	0-333
Outdegree	1.32	0	12.57	0-312
Betweeness	0.60	0	5.61	0-156.10
Distance (km)	52.88	18.09	107.12	1.03-1524
# pigs moved per shipment	33.93	20	37.69	1-900

Previous studies have found a positive association between indegree and the risk of infection (Sintayehu et al., 2017). In our study, the overall indegree was not significantly associated to CSF occurrence, only the indegree associated to incoming shipments from districts that recently had outbreaks. This highlights the need to intensify the surveillance and more strictly control potential high-risk pig movements in

Table 4
Summary statistics, composition and characteristics of the communities identified for the live pig trade network in Peru from 2010 to 2014. NC = districts not belonging to any community; 1 st = districts belonging to the largest community; 2nd = districts belonging to the second largest community; other = districts belonging to other smaller communities; HDI = Human Development Index;

Variable	NC	1st	2nd	other
Mean vaccination coverage (%)	0.97	0.94	0.97	0.94
Mean indegree	0.06	9.38	17.42	7.87
Mean outdegree	0.07	11.70	15.02	8.40
Number of observations with slaughterhouse	405	62	25	135
Number of CSF positive cases	125	32	24	54
Number of incoming shipments from communities with CSF positive status in previous year	43	256	289	238
Mean HDI	0.33	0.49	0.48	0.47

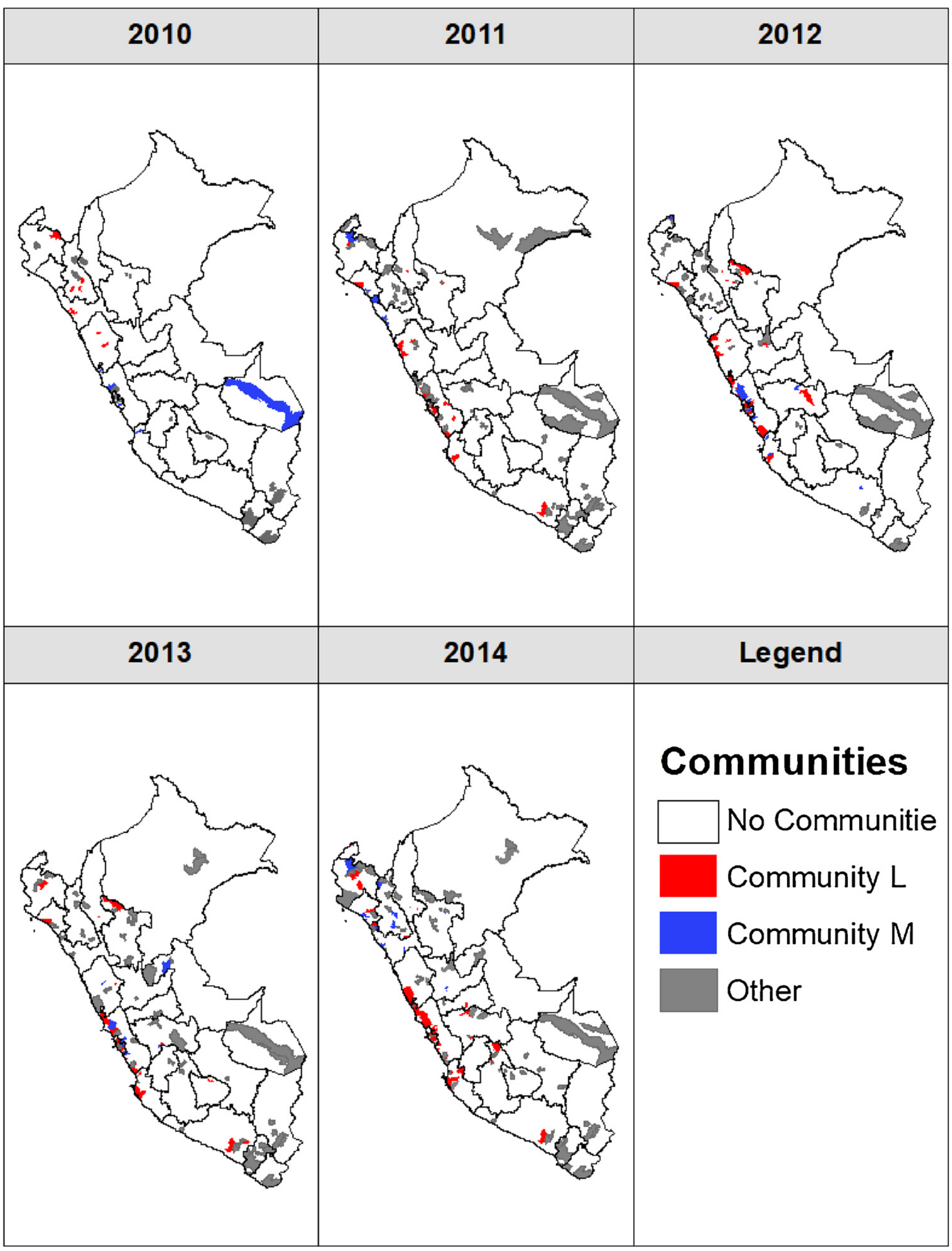

Fig. 4. Spatial distribution of the districts belonging to the large, medium and other communities of live pig trade in Peru from 2010 to 2014. (The reader is referred to the web version of this article for the interpretation of the different colors of this figure.)

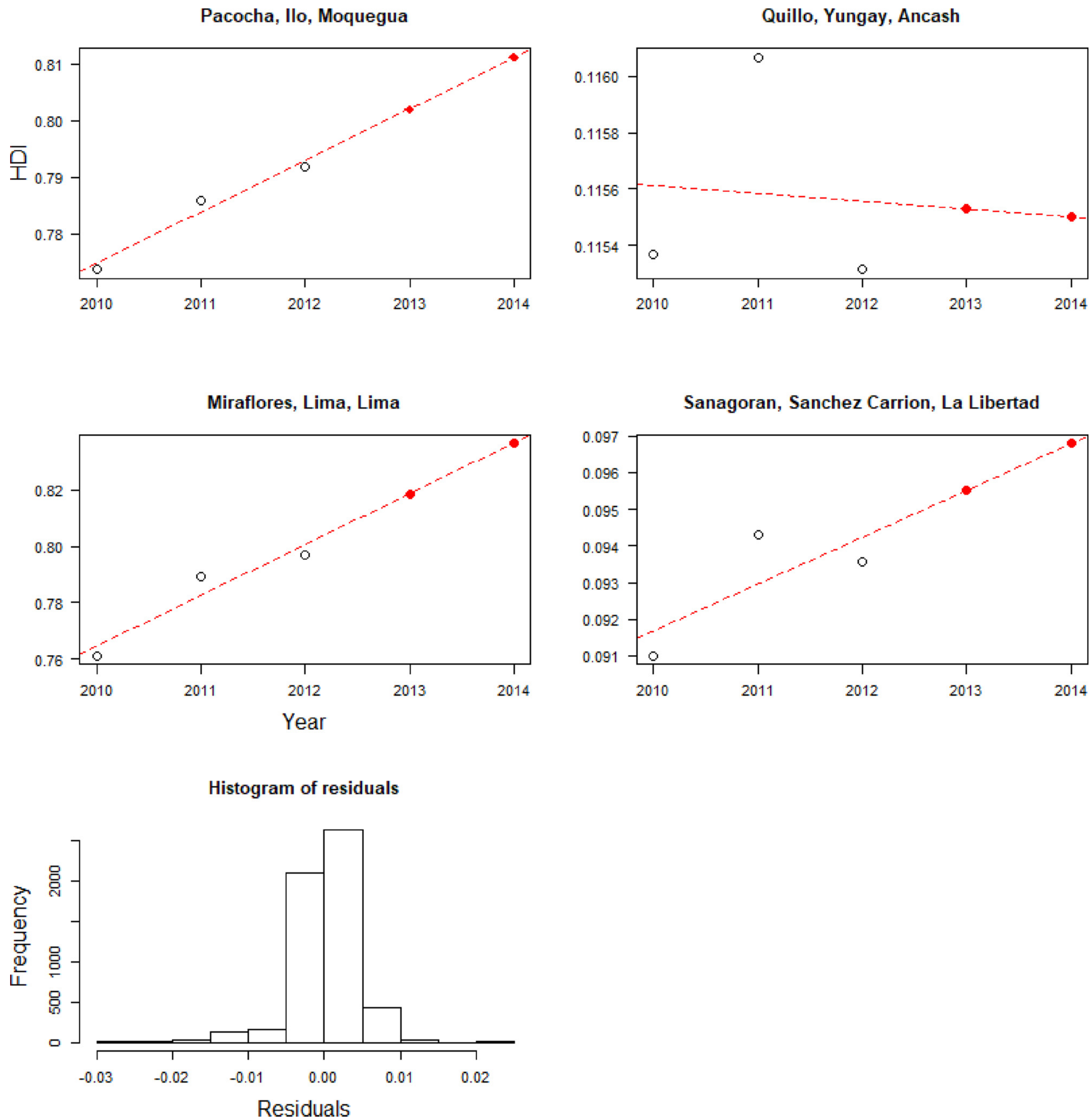

Fig. 5. Illustration of the regression line and prediction values (red dots) for the HDI models for four districts and histogram of the residuals (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

affected regions.

Most of the detected communities were small, including only 2–10 districts. The largest detected community was in 2014 including 46 districts. The districts tend to form the largest trading communities in the regions of the coastal area, near the department of Lima but in some years the communities extended to the north-west part of the country near the border with Ecuador. Districts belonging to the same community are more likely to share CSF and, therefore, could benefit from a common vaccination and control strategy. However, the communities are very dynamic and change over the years making difficult to identify the districts that are more closely related. For that reason, here we only identified the districts that were part of a large or medium community for each year and used that information to try to evaluate the association between being part of a large or medium community and the higher probability of CSF occurrence. A more detailed analysis of the community structure may help to characterize the network connectivity and identify districts that are playing a key role for the dissemination of the disease. According to our model, the medium communities are more likely to have CSF outbreaks. The largest community for each year were near Lima, where the register of the movements and vaccination campaign is more constant. This may indicate more intensive (and likely effective) control by the veterinary authorities to reduce CSF outbreaks in this area.

Other variables considered for the model were pig density, and other centrality measures such as indegree, closeness and betweenness. However, we didn't find any association between the pig density for each district and CSF occurrence. Indegree, betweenness and closeness centrality measures were also tested as potential variables, but, again, only the incoming shipments from districts with recent outbreaks explained well the CSF occurrence. Other socioeconomic variables such as

Table 5
Variables included in the final multilevel logistic regression model for CSF in Peru.

Parameter	Estimate	SE	OR (95%CI)	P-value
Intercept	−3.4635	0.7461		< 0.001
Vaccination coverage	−2.5532	0.6850	0.07 (0.02-0.29)	< 0.001
No incoming from district with cases (ref)	–	–	–	–
< 20%	1.2003	0.7715	3.32 (0.73-15.06)	0.119
20%-60%	0.0165	0.6963	1.01 (0.25-3.98)	0.981
> 60%	1.1961	0.5363	3.30 (1.15-9.46)	0.025
No community (ref.)	–	–	–	–
Community L	1.0415	0.4068	2.83 (1.27-6.29)	0.003
Community M	1.7645	0.4683	5.83 (2.33-14.62)	< 0.001
Other community	0.9799	0.3124	2.99 (1.44-4.91)	< 0.001
Scaled HDI	0.4193	0.1461	1.52 (1.14-2.02)	0.004
Presence of slaughterhouse	1.1798	0.3327	3.25 (1.69-6.24)	< 0.01

Variance:5.46.
AUC: 97.70%.

education level, GDP and poverty index were also evaluated, but the HDI seems to summarize well all this information and to have better predictive ability for CSF occurrence. The interaction between variables was also explored, but the only significant interaction detected was between vaccination coverage and HDI, this interaction was highly correlated with the main effects so we decided not to include it in the final model to avoid problems of collinearity.

This study also had several limitations. For example, we are using district level instead of farm level. Unfortunately farm level data for the pig industry is not available and for that reason we used district level, which is the unit used for decision making in the vaccination program and is the smallest administrative unit of the country. We believe that

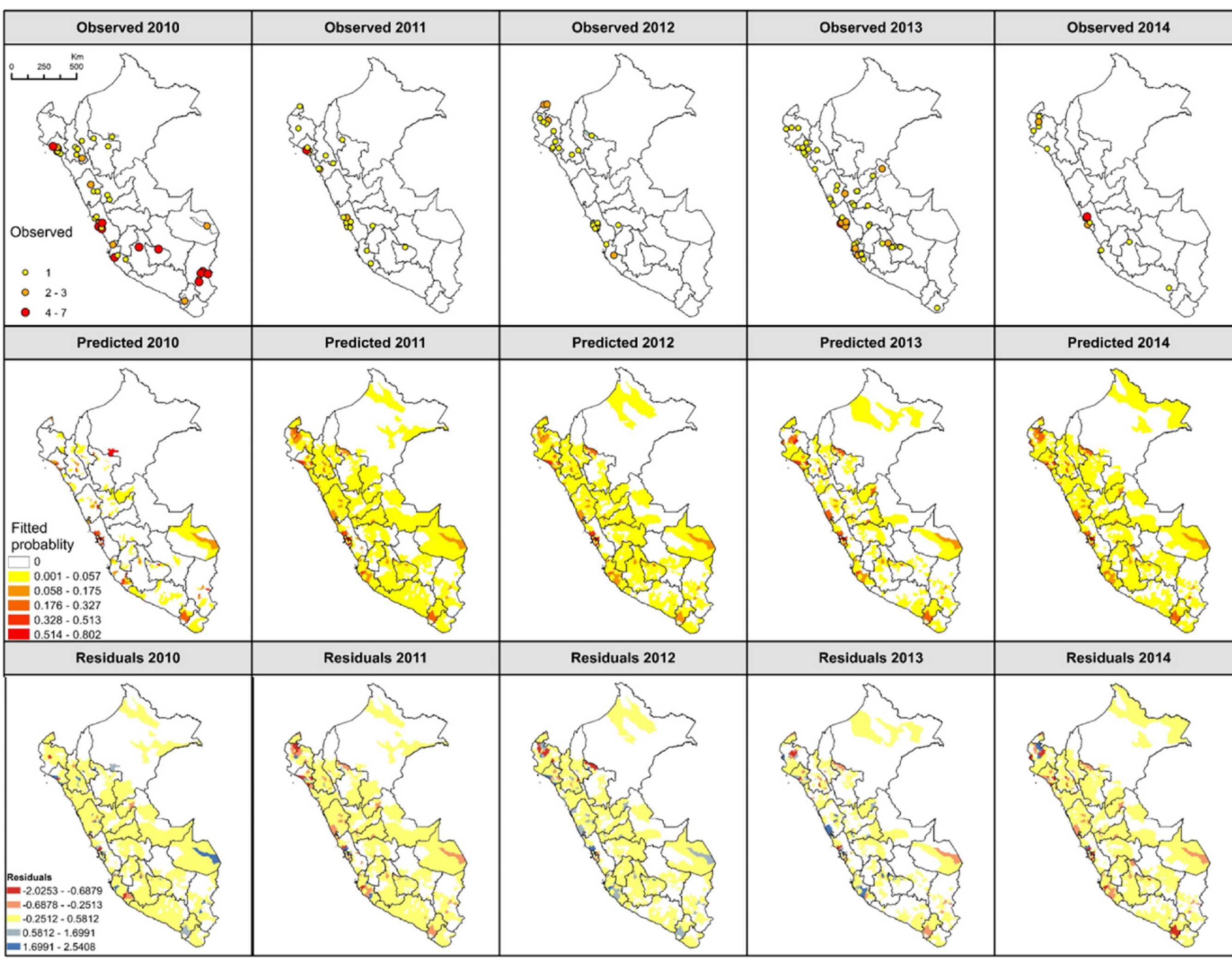

Fig. 6. Spatio-temporal distribution of the number of observed CSF outbreaks (top) and the predicted value of the probability of CSF occurrence (medium) and the residuals (bottom) by district as result of the multilevel logistic regression model for CSF in Peru from 2010 to 2014. (The reader is referred to the web version of this article for the interpretation of the different colors of this figure.)

this level of analysis minimizes the ecological bias and allows to use socioeconomic and pig demographic factors that are only gathered at this level while offers the best resolution to support decision making.

One of the assumptions we are making in this study is that the CSF status of each district is constant during the year. The data we obtained was rounded to yearly observations, when an outbreak was reported for a given district we assumed that the district remained CSF positive during all the year and we used that information for the variable of incoming shipments from CSF positive districts, which is not always a reasonable assumption, but for this study it was the most accurate information we could obtain.

Other important part of information that we are missing in our model is the different type of farms and production systems involved in the pig movements. Previous studies have shown that there is a difference in the network structure depending to the type of farms, which can lead to different risk of disease transmission (Arruda et al., 2016; Relun et al., 2016; Lee et al., 2017). Some of the districts such as Santa Maria have a high number of movements (n = 1212), but only the 0.01% of these movements are incoming shipments. Districts like this might suggest that the main type of farms found here could be more related with reproduction. Additional information regarding the composition of the types of farms for the districts would be valuable to identify if there is an association between the size and types of farms and the risk of CSF occurrence. Another important aspect to mention is that the pig population estimates we used are based on the vaccination registers, therefore, may underestimate the swine population in some areas. The CSF surveillance in Peru is a passive-active surveillance, which means that only regions with previous CSF reports have an active surveillance for the detection of the disease; similar to the population estimates per year, it is possible that there is an underestimation of the CSF case reports because there might be regions where there is not an adequate diagnosis and identification of positive animals.

According to our model the regions of the coast near Lima, the north west area near the border to Ecuador and the southern region near the borders with Bolivia and Chile are constantly at more risk of CSF occurrence, suggesting the need to reinforce the surveillance and vaccination program in these regions to better prevent and control future CSF outbreaks. The more cost-effective allocation of resources and prioritization of the vaccination program in the key high risk districts identified in this study should contribute to the advance and faster eradication of CSF from Peru.

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