Quantitative risk assessment of the African swine fever introduction into the Republic of Korea via legal import of live pigs and pig products

Ki-hyun Cho[1], Hyun Joo Kim[1], Yong-Joo Kim[1], Hae Eun Kang[1], Beatriz Martínez-López[2], and Joong-Bok Lee[3]

[1]Animal and Plant Quarantine Agency
[2]UC DAVIS
[3]College of Veterinary Medicine, Konkuk University

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Abstract

There are several routes of African swine fever (ASF) introduction into a country. Among the possible routes of entry, quarantine policies determine the possibility of introduction by legal import of live pigs and pig products. This study aimed at assessing the probability of ASF introduction through legal import of live pigs and pig products during the high risk period (HRP) using a quantitative stochastic approach during 2009-2018. The result indicates that the mean annual probability of ASF introduction by legal import of live pig was 1.58×10-7 (1.52˜1.67×10-7 95% CI). The mean annual probability by legal import of pig products was 1.59×10-10 (1.55˜1.64×10-10 95% CI), of which Poland assumed 87.9% of the mean annual risk. The current import quarantine policy of Korean government may be enough to block the release of the virus via legal import of live pigs and pig products, and it should be continually enforced. This result can help to elucidate source of infection and minimize the catastrophic consequences of the potential ASF reintroduction into South Korea by designing risk mitigation strategies such as risk-based selection of routes to be assessed and prevented and decreased exposure possibility by increased control of food waste and swill feeding practices.

Keywords: *African swine fever; quantitative risk assessment; Republic of Korea; legal import of live pigs and pig products*

INTRODUCTION

African swine fever (ASF) was described by Montgomery in Kenya in 1921 for the first time. Since then, the disease has been considered endemic in most of the Sub-Saharan countries. The first period of ASF epidemics out of Africa started in 1957 in Portugal and lasted until 1999. However, the ASF epidemiological situation dramatically changed in 2007 when an ASF outbreak was unexpectedly reported in Georgia (Rowlands *et al.* , 2008). From there, ASF spread to the other Caucasian countries and to the southern part of the Russian Federation in one year (Gogin *et al.* , 2012). Despite surveillance and control measures in the Russian Federation, ASF continues to spread in the country with significant economic consequences that were estimated to be 0.8-1 billion USD until October 2009 (USDA, 2010). A report indicated that ASFV was isolated from wild boars in Iran in 2008 (Rahimi *et al.* , 2010). The virus also moved to northwestern countries like Ukraine and Belarus in 2012 and 2013, respectively. European Union member states such as Lithuania, Latvia, Estonia and Poland were affected by the movements of the infected wild boars in 2014. There were notifications regarding ASF outbreaks in Romania and in the Czech Republic in 2017. In August of 2018, ASF was introduced in China, a country with particularly close socio-economic ties with South

Korea (OIE, 2019) and other countries like Mongolia, Vietnam, Cambodia, North Korea, and Laos which have just became infected. South Korea reported the first ASF case in 17 September 2019. Until 9 October 2019, 14 cases occurred in the Northern region of the country. In spite of comprehensive epidemiological investigations, the source of infection is not determined yet.

The movement of live animals and their products is an important route of entry and transmission of ASF. Considering this, the World Trade Organization (WTO) and the World Organization for Animal Health (OIE) encourage member countries to refer to the guidelines of the Sanitary and Phytosanitary Measures Agreement (SPS) and create relevant policies after conducting the necessary risk assessments. According to the guidelines of the SPS, live pigs and pig products from ASF infected zones or countries are not allowed to be traded with ASF-free nations or areas (OIE, 2018a). Once a region reports an ASF outbreak, an immediate ban of the movement of live pigs and their products is implemented. However, live pigs and pig products with ASFV can escape freely from the infected region and be imported to other ASF-free countries legally during the HRP (High Risk Period) (i.e., which means the time period from the first ASF case (index case) in one country/region to the detection and notification of the disease in that country/region, before international trade is banned), which is the period of time from the initial infection of the index farm to the official detection and notification of an ASF outbreak (Horst *et al.* , 1998). Only 1 or 2 weeks have been shown to be sufficient for the extensive spreading of FMD and CSF during the HRP through the movements of animals in some European countries in recent epidemics (Bouma *et al.* , 2003; Greiser-Wilke *et al.* , 2000).

Considering the historical transcontinental and transboudnary transmissions of ASF, there are several routes of ASF entry that need to be considered: legal or illegal import of live pigs or pig products or feed, introduction of food waste from international airplanes/ships and their use for swill feeding, movement of infected wild boars, other potential contaminated materials carried by foreign workers, vehicles or other fomites. Though the movement of infected wild boars is of major concerns in South Korea now, it is necessary to assess the probability of ASF introduction by each possible route in order to block its entry into the country effectively. This study aimed at assessing the probability of ASF introduction into South Korea through legal import of live pigs and pig products during the high risk period (HRP) using a quantitative stochastic approach during 2009-2018.

MATERIALS AND METHODS

Data source and unit of analysis

This study spanned 10 years from 2009 to 2018. Data for the risk assessment were collected by country and by month. In case of Italy, regions excluding Sardinia was unit of analysis. ASF outbreaks in domestic pigs were based on immediate and follow-up notifications of OIE (OIE, 2019). Data on pig production including the number of pig farms and the pig population, the yields/carcass weight per pig, and the annual pork production were obtained from the OIE (2018b), FAOSTAT (2018), and National Institute of Statistics of Italy (Istat) (2019). The statistics associated with legally imported live pigs and pig products were obtained from the Animal Quarantine Statistics of Animal and Plant Quarantine Agency (APQA, 2019). All data were stored in Microsoft Excel 2016 for the subsequent analysis. A stochastic quantitative risk assessment was conducted with these collected data.

Model specifications for the live pigs imported legally

A quantitative stochastic risk assessment for ASF introduction into South Korea via live pigs imported legally was modelled using an approach similar to that described in previous studies (Herrera-Ibatá*et al.* , 2017; Mur *et al.* , 2012). Canada, Denmark, France, Japan, United Kingdom (UK), and United States of America (USA) exported live pigs to South Korea during the last decade. All these countries have not reported ASF outbreaks in domestic pigs during the study period (Table 1).

To estimate the probabilities, four major assumptions were used: 1) If there were no ASF notifications in the country of origin for the study period, the probability of ASF outbreak in the country was estimated 1 outbreak in 1,000 years as maximum; 2) In order to estimate the number of ASF outbreaks during the HRP, all of the origin countries were assumed to have the same level of surveillance and export animal product quarantine capacity; 3) All imported live pigs have destination to farms; 4) ASFV will be always present in an acute form considering the characteristic of the current ASFV in Eurasia.

Risk analysis for the introduction of infectious agents through imports consists of 3 steps: release, exposure and consequence assessment (OIE, 2010). In this study, the probability of release (P_{re}) and exposure (P_{ex})to a susceptible pig population in South Korea was assessed. The final probability ($P_{f(trade\ of\ live\ pigs)}$) reflects the probability that an ASFV infected pig from country of origin is imported to a country of destination, thus resulting in ASF transmission to local pig population. $P_{f(trade\ of\ live\ pigs)}$ was modelled using a binomial process as suggested by the OIE Risk Analysis handbook (OIE, 2010) as follows:

$$P_{f(trade\ of\ live\ pigs)} = \sum 1 - (1 - P_{\mathrm{re}} \times P_{\mathrm{ex}})^{\ n_{\mathrm{odm}}}$$

In this formulation n_{odm} is the number of imported live pigs from a country of origin o to a country of destination d during the month m .

Release assessment

The probability of release (Pre) means that at least one ASFV infected animal is introduced into the importing country. In our case, it reflects the probability of importing an ASFV infected but undetected pig during the HRP from the country of origin into South Korea at a particular month. P_{re} was estimated with four conditional probabilities: (P_1) the probability of ASFV infection in the country of origin; (P_2) the probability of selecting an ASFV infected pig from the country of origin to be exported to South Korea before detection of ASFV infection in the country of origin (i.e. during the HRP); (P_3) the probability that an ASFV infected pig survives the ASFV infection; (P_4) the probability that the ASFV infected pig survives the transportation from the country of origin to the country of destination.

The probability of ASFV infection in the country of origin (P_1) was estimated using a beta distribution (α1, α2), where the α1 was the number of months with at least one undetected ASF outbreak in the country and α2 was the number of months considered for the analysis (OIE, 2019).

The probability that an ASFV infected pig is selected from the country of origin in a specific month m (P_2) was also modelled using a beta distribution. The shape of this distribution was determined by the number of expected ASFV infected pigs before ASF detection in the country of origin (NI) and the total number of pigs in the country of origin (No). To estimate NI , four independent parameters were multiplied: (Ou) Undetected outbreaks during the HRP for each country/continent which were parameterized using Pert (min, most likely, max) (OIE, 2019); (To) Average size of pig farms in the country, which was calculated with the total number of pig farms and total number of pigs in the country of origin using a normal distribution expressed as an average number (μ) and standard deviation (σ) (OIE, 2018b); (Hp) ASF intraherd prevalence, which was calculated using the minimum, maximum and mean of the proportions of cases vs susceptible animals obtained from the OIE (2019) and was modelled by a Pert distribution for each country. The probability that an ASFV infected pig survives the ASFV infection (P_3) and the transportation (P_4) were modelled using a Pert distribution based on Spickler and Roth (2006) and Murray and Johnson (1998), respectively.

Exposure assessment

The probability of an imported ASFV infected pig coming into contact with other domestic pigs in the importing country and resulting in ASFV transmission (P_{ex}) was estimated as follows:

$P_{ex} = P_q + [(1 - P_q) \times P_u]$

In the formulation, P_q is the probability that an imported ASFV-infected pig is not quarantined, $P_u$is the probability that the pig is not detected during the quarantine process. The former was based on the quarantine procedure of the USDA (Herrera-Ibatá *et al.* , 2017) and the latter on the probability that a CSF infected pig is not detected base on the clinical signs during quarantine (Martínez-López *et al.* , 2009), as both diseases have similar clinical manifestations (Sánchez-Vizcaíno, 2006). The parameters and descriptions are shown in Table 2.

Model specifications for the pig products imported legally

A quantitative stochastic risk assessment for ASF introduction into South Korea via pig products imported legally was conducted using an approach similar to that used in the previous studies (Herrera-Ibatá*et al.* , 2017; Mur, 2010). 20 countries which exported pig products to South Korea in the last decade were subjected for the assessment (Table 1).

Similar to the previous pathway, four major assumptions were used: 1) If there were no ASF notifications in the country of origin for the study period, the probability of ASF outbreak in the country was estimated 1 outbreak in 1,000 years as maximum; 2) In order to estimate the number of ASF outbreaks during the HRP, all of the origin countries were assumed to have the same level of surveillance and export animal product quarantine capacity; 3) ASFV will be always present in an acute form based on the characteristic of the current ASFV in Eurasia; 4) ASFV can survive regardless of the types of pig products.

Similar to the live pig pathway, the probability of release (P_{re}) and exposure (P_{ex})to a susceptible pig population was assessed. The final probability ($P_{f(trade\text{ of pig products})}$) here reflects the probability that an ASFV contaminated pig product from a country of origin o is imported to a country of destination$d$ (in this case South Korea) and results in ASFV transmission. This probability was modelled using a binomial process as follows:

$$P_{f(trade\ of\ pig\ products)} = \sum 1 - (1 - P_{\text{re}} \times P_{\text{ex}})^{\,n_{\text{odm}}}$$

In this formulation n_{odm} is the quantity (kg) of pig products (i.e. chilled and frozen pork, pork products, fat, and offal) legally imported from the country of origin to South Korea during the month m . The sterilized pork products with heat treatment at 121 °C for 15-20 min according to Range and criteria for sterilization, pasteurization and process of designated quarantine products (Notification of APQA No. 2018-24, Enforcement on 13 Sep 2018) and hog casings that were treated for at least 30 days either with dry salt or with saturated brine or with phosphate supplemented dry salt at 12 °C above following the procedure outlined by the OIE (2018b) were excluded from this study.

Release assessments

The probability P_{re} was estimated with 2 conditional probabilities: The probability of ASFV infection in a country o (P_1) and the probability of selecting an ASFV contaminated meat during the month m before detection of the infection (P_2). Probability of an ASFV infection in the country o (P_1) was modelled using a beta distribution (α1, α2), where the α1 was the number of months with at least one undetected ASF outbreak in the country and α2 was the number of months considered for the analysis (OIE, 2019).

The P_2 was also estimated with a beta distribution (α3, α4), where α3 was the quantity (kg) of potentially infected pig products in the country o in the month m(Qim) and α4 was the quantity of pig products produced in country$o$ in the month m (Nm). The quantity of infected pig products in the country o (Qim) was calculated with 3 parameters: (NI) estimated number of infected pigs in the country which was calculated by multiplying the number of undetected outbreaks (Ou), average herd size (To), and intraherd prevalence (Hp) similar to the assessment of the ASF introduction by live pig imported legally during the HRP, (Pm) the probability that an ASFV infected pig is transformed into meat and (Mp) the average weight of the products (kg) obtained per slaughtered pig. The probability Pm was estimated as follows:

$$Pm = P_3 \times P_4 \times P_{sm} \times P_{us}$$

In this formula, P_3 is the probability that a pig survives ASFV infection; P_4 is the probability that the ASFV infected pig survives the transportation;P_{sm} is the probability of a pig going to a slaughterhouse during a specific month based on the pig census and monthly proportion of pigs slaughtered on average (EUROSTAT, 2014) and;P_{us} is the probability that an ASFV-infected pig is undetected during the clinical checks in the slaughterhouse.

Exposure assessments

The probability that domestic and wild pigs in South Korea are exposed to imported pig products (P_{ex}) was estimated as follows:

$$P_{ex} = PW \times PM \times (SF \times IE + LF \times LFw \times Wa)$$

The pig products legally imported into South Korea may be consumed or discarded and become food waste at selling points and at all consumer and distribution levels. In South Korea, food waste at all levels including households, restaurants, meal places at schools and institutions and distribution stage are thrown separately and collected. The pay-as-you-throw food waste management system has been implemented in all sectors of the country since 2010 (Ministry of Environment, 2010). The proportion of food waste (PW) vs supplied food was estimated using a normal distribution (Ministry of Environment, 2017a). The proportion of food (PW) was then multiplied by the proportion of meat (PM) in food waste, which was also parameterized using a normal distribution (Chang *et al.* , 2003).

Once discarded and collected, food waste has different destinations: feeding animals mainly for domestic pigs after heat treatment, production of biogas and fertilizer and disposal in landfills. This model assessed two potential pathways of exposure/contact of pig products with domestic pigs: 1) by swill feeding (SF) and 2) wild boars having access to landfills (LF). The swill feeding practice is applied for swine and poultry farms in South Korea according to the Waste Control Act (Act No. 15103, Enforcement on 29 May 2018) and the Standard and Criteria of Feed (Notification of the Ministry of Agriculture, Food and Rural Development (MAFRA), No. 2017-28, Enforcement on 1 Apr 2017). The proportion of food waste used for feed was estimated using a normal distribution based on the data of the Ministry of Environment (2015, 2016, 2017b). Most of the food waste recycled for feed is used mainly in pig farms after heat treatment at 80 °C for at least 30 min in authorized facilities. However, the process of heating does not ensure the inactivation of the ASFV, based on the conditions of 90 °C for at least 60 min and 100 °C (212 °F) for at least 30 min proposed by the OIE (2018a) and APHIS (2009), respectively. Thus, a certain degree of uncertainty about the inefficiency of the process (IE) was included using a Pert distribution (0.05, 0.1, 0.2).

The other potential pathway of contact with wild boars accessing landfills was estimated with 3 parameters: (LF) The probability that the food waste is disposed in landfills, (LFw) The probability of wild boars being present near landfills, (Wa) The probability of wild boars accessing and feeding in the landfills. Firstly, the proportion of meat in the food waste disposed in landfills (LF) was obtained (Ministry of Environment, 2015; 2016; 2017b). The probability that wild boars are present around landfills (LFw) was estimated using a Pert distribution (0.860, 0.919, 0.978) based on the 4$^{\text{th}}$ investigation on the Environment of South Korea (National Institute of Ecology, 2015) and lists of landfills and incineration facilities (Ministry of Environment, 2011). Wild boars were observed in a 10 km (minimum) and 20 km (maximum) radius from each landfill in ArcGIS for Desktop software (Esri Inc. Redlands, CA, USA) considering the natural home ranges of wild boar are 10-20 km. Data on the probability of wild boar having access and feeding in landfills is currently not available. Therefore, the probability that wild boars have access to landfills (Wa) was assumed conservatively with Pert (0.05, 0.1, 0.2) as proposed by a previous study (Herrera-Ibatá *et al.* , 2017). The parameters and descriptions are shown in Table 3. Event scenarios for the two routes are detailed in Figure 1.

Model construction and sensitivity analysis

The risk assessment models were constructed in R (R-language, version 3.4.4). For the Monte Carlo simulation, the analysis for each country was repeated 1,000 times. The probability of introduction of each country was clustered using the Jenks natural breaks optimization and mapped using the same program.

Sensitivity analysis for both pathways was performed to evaluate the influence of the changes in the value of the input parameters on the model outcomes. A regression coefficient (β_i) was calculated between each input and the probability of ASF introduction by month. The inputs that were most influential were determined and analyzed using spider graphs, which shows the impact that changes in the input parameters from a minimum of a 50% reduction to a maximum of a 50% increase have on the final probability using a linear regression approach. All analyses were conducted in R.

RESULTS

Probability of ASF introduction into South Korea via the legal import of live pigs

The overall mean annual probability of ASF introduction into South Korea via the legal import of live pigs was estimated as 1.58×10^{-7}(1.52˜1.65×10^{-7} 95% Confidence Interval, CI). This value approximately corresponds with an outbreak of ASF every 6.31×10^{6} years (6.05˜6.59×10^{6} years 95% CI). Canada took 80.8% of mean annual probability followed by France (9.1%), Denmark (5.1%), and USA (4.4%) (Figure 2).

Probability of ASF introduction into South Korea via the legal import of pig products

The total annual probability of ASF introduction into South Korea via the legal import of pig products was found to be very low, and was estimated to be 1.59×10^{-10}(1.55˜1.64×10^{-10} 95% CI), which approximately corresponds to an outbreak every 6.27×10^{9} years (6.10˜6.47×10^{9} years 95% CI). Among the 20 assessed countries, the mean annual probability of ASF introduction into South Korea by Poland had the highest contribution (87.9%) followed by New Zealand (4.8%) and Sweden (1.4%) in descending order of probability (Figure 2).

Maps with 5 categories based on Jenks natural break optimization with the probability of ASF introduction into South Korea via both pathways are shown in Figure 3. There was a slight difference among the monthly distributions by country via the both routes (Data not shown).

Sensitivity analysis

For the probability of ASFV introduction by the legal import of live pigs and pig products, the probability of selecting an ASFV infected pig/pig product from the country of origin in a specific month $m$during the HRP (P_2) was the most influential input for the final result ($\beta_i = 1.16 \times 10^{-4}$ and 5.99×10^{-5}, respectively,p $value < 0.001$) (Figure 4).

DISCUSSION

The probability of ASF introduction into South Korea via legal imports of live pigs and pig products was found to be negligible. The number of countries eligible to export live pigs and pig products to South Korea is currently 11 and 22 countries, respectively (Regions with an import ban on designated quarantine products, Notification of MAFRA No. 2019-37, Enforcement on 30 July 2019). All import health requirements (IHRs) for both items imported to South Korea stipulate that the importing countries should be ASF-free for at least 3 years prior to shipping. Of the assessed countries which exported live pigs and pig products to South Korea, only two countries have suffered from ASF outbreaks. In Italy ASF is restricted only to Sardinia and South Korea imports pig products from the unaffected regions of the country. In Poland with the highest probability via legal import of pig products ASF has been present since 2014. However, an import ban on pig products from Poland has been imposed immediately after the first ASF outbreak notification in wild boars in February 2014. Countries with ASF outbreaks are only allowed to import sterilized pig products to South Korea (Regions with an import ban on designated quarantine products, Notification of MAFRA No. 2019-37, Enforcement on 30 July 2019; Range and criteria for sterilization, pasteurization and process of designated quarantine products, Notification No. 2018-24 of APQA, Enforcement on 13 Sep 2018). This policy may also play an important role in blocking the ASF risk of introduction through the legal imports of pig products.

The probabilities of release through the analyzed pathways were very low, but the possibility of exposure to the pig population cannot be ignored. In South Korea, swill feeding after heat treatment at 80 °C for 30 min is permitted. This heat treatment is below the recommendation of the OIE (90 °C for 60 min) and, therefore, is more than likely not sufficient to inactivate ASFV in the food scraps used for feed. In addition, a high density of wild boars inhabits the country. Thus, ASFV can be exposed to wild boar populations if they are able to access landfills or other areas used for food disposal. To mitigate this probability of exposure, heating food scraps at higher temperatures and for longer time periods to feed pigs should be reinforced for a short term. The proportion of food waste used for swill feeding and landfills should be decreased and replaced with the production of biogas in the long term.

Totally 14 ASF cases occurred during September-October 2019 in the domestic pig farms of northern region of South Korea around the border with North Korea. Pre-emptive slaughter and culling of domestic pig farms in the infected region were conducted, while 485 cases have been confirmed in wild boar population there from 2 October 2019 to 6 April 2020. The control of infected wild boars to block the further transmissions to domestic pig population is of major concerns in the country now. In spite of ongoing investigations, source of infection is not specified yet. However, there is possibility of ASF introduction via other routes like illegal import of live pigs or pig products, import of feed, introduction of food waste from international airplanes/ships and their use for swill feeding, and potential contaminated materials carried by foreign workers, vehicles or other fomites. These pathways need to be assessed and subsequent preventive measures should be followed for the efficient concentration of limited quarantine personnel and financial resources.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in [repository name] at [URL], reference number [reference number].

ETHICAL CONTRIBUTIONS

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required as this is an article about risk assessment.

CONFLICT OF INTEREST STATMENT

The authors declare no conflict of interest.

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