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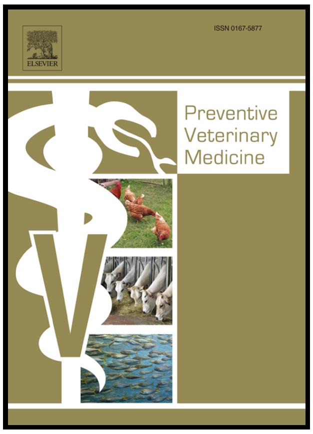

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V. Brusa, M. Durrieu, C.J. Van Gelderen, M.L. Signorini, A. Schudel

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Quantitative risk assessment of FMDV introduction in a FMD free country through bone-in beef and offal importation from a FMD free with vaccination country/zone

Brusa, V.[1]; Durrieu, M.[2]; Van Gelderen, C.J.[2]; Signorini, M.L.[3*]; Schudel, A.[2]

[1] IGEVET – Instituto de Genética Veterinaria "Ing. Fernando N. Dulout" (UNLP-CONICET LA PLATA), Facultad de Ciencias Veterinarias UNLP, Buenos Aires, Argentina

[2] Fundación Prosaia – Ciudad Autónoma de Buenos Aires

[3] IdICaL – Instituto de Investigación de la Cadena Láctea (INTA – CONICET), Rafaela, Santa Fe, Argentina

* Corresponding author.

E-mail address: signorini.marcelo@inta.gob.ar (M.L. Signorini).

ABSTRACT

Quantitative risk assessment was used to estimate the risk of introducing foot-and-mouth disease (FMD) through bone-in beef from Argentina (FMD-free with vaccination status) into other FMD-free countries. A stochastic model was built to characterize all the steps from primary production to bone-in beef export and introduction into an FMD-free country. The probability that bone-in beef from at least one animal infected with the FMD virus (FMDV) was exported during a year was 5.27×10^{-3} (95% CI $<10^{-10} – 5.19 \times 10^{-2}$) or in other words one case in 190 years. The risk of FMDV introduction was sensitive to the probability of an outbreak occurring in Argentina (*r* [Spearman´s rank correlation] = 0.99) and the number of herds affected during an outbreak (*r*= 0.10). Additionally, the probability that susceptible animals in the importing country came into contact with infective material (bones) and generated an outbreak was 6.16×10^{-4} (95% CI $<10^{-10} – 6.20 \times 10^{-3}$) or one FMD outbreak every 1623 years on average. Based on the quantitative risk assessment results, the probability of FMDV introduction into a FMD-free country where vaccination is not practiced from a FMD-free country where vaccination is practiced associated with bone-in beef trade from Argentina was negligible. The risk of an FMD outbreak caused by the potential introduction of the FMDV was associated with the existing conditions in the country. Thus, maintaining the FMD-free status with or without vaccination would not be relevant.

Keywords:

Foot-and-mouth disease; risk assessment; outbreak; beef trade

1. Introduction

Argentina has historically been one of the main food producers and exporters worldwide. The agricultural sector is of great economic and social importance for the country, despite the high variability in its productive, technological, and organizational structure. The agri-food chain accounts for 9.92% of the country´s gross domestic product, generating two out of 10 private jobs nationwide (Instituto Nacional de Estadísticas y Censos [INDEC], 2021). Argentina is the sixth producer of bovine meat worldwide and the fifth world exporter after Brazil, Australia, India, and the United States, with a production of 2.98 million metric tonnes and an export of 803.5 thousand metric tonnes in 2021 (Ministerio de Agricultura, Ganadería y Pesca [MAGYP], 2021).

Foot-and-mouth disease (FMD) has been the main animal health barrier for meat exports from Argentina and the region (de Meneses et al., 2022, Labraga, 2016). The presence of FMD in Argentina has been known since the 18th century, when it was introduced by European cattle (de las Carreras, 1993). It is one of the most important infectious diseases affecting animals due to its high transmissibility (Paton et al., 2018). The disease is produced by a virus from the *Picornaviridae* family, genus *Aphtovirus*. The FMD virus (FMDV) was the first animal virus identified, and seven different serotypes without cross-immunity have been characterized (A, O, C, SAT1, SAT2, SAT3, and Asia 1) (Mort et al., 2005; World Organisation for Animal Health [WOAH], 2008).

Argentina has been officially listed as an FMD-free country by the World Organization of Animal Health (WOAH, former OIE). The country is divided into five zones, three FMD-free where vaccination is not practiced and two FMD-free where vaccination is practiced. To confirm and maintain this status, the requirements established in chapter 8.8.3 of the Terrestrial Code of the WOAH must be complied annually, providing information following the WOAH regulations (WOAH, 2022).

The last FMD outbreak detected in Argentina occurred in the province of Corrientes in 2006. Since then, neither clinical signs of the disease have been detected, nor has evidence of circulation/transmission or infection by the FMDV throughout the country been reported (Rivera et al., 2023; OPS, 2021). Additionally, the WOAH has evaluated annually the information submitted by Argentinean authorities to retain the status of FMD-free with vaccination, corroborating that animals susceptible to the FMDV in Argentina have remained free of infection for more than 16 years (Rivera et al., 2023; OPS, 2021).

Meat, bones, lymph nodes, viscera, and unprocessed blood, from countries or zones where FMD is present, are considered risk products (WOAH, 2022; Astudillo et al., 1997). For imports of bone-in beef from FMD-free country or zone where vaccination is practiced, the WOAH recommends to ensure that the animal has been kept in an FMD-free country/zone with vaccination and that it has been satisfactorily evaluated in *ante*- and *post-mortem* examinations to detect the disease (Table 1, based on WOAH Terrestrial Code Chapter 8.8.21). Consequently, the WOAH code anticipates the possibility of the introduction of bone-in beef from a FMD-free country or zone where vaccination is practiced to another FMD-free country or zone where vaccination is not practiced. However, some importing countries maintain the restrictions on bone-in beef trade, based on the possibility that vaccinated animals and their products may contain the FMDV and pose a risk when introduced into FMD-free countries or zones where vaccination is not practiced (Labraga, 2016).

Bone-in beef is one of the most important products exported by Argentine (IPCVA 2023). Considering Argentina's FMD-free with vaccination status, authorization for the export of bone-in beef would be the last barrier to overcome with importing countries to be on an equivalent condition to countries/zones free from FMD without vaccination, as established by the WOAH and the World Trade Organization (WTO). The objective of this study was to quantitatively assess the risk of FMD introduction through bone-in beef from Argentina (FMD-free with vaccination) to other countries with FMD-free where vaccination is not practiced. The hypothesis was that the risk of bone-in beef import from Argentina was equivalent to the import of these same products from FMD-free countries/zones where vaccination is not practiced.

2. Materials and methods

2.1. Model development

The biological conceptual model upon which the stochastic model was based on is depicted in Figure 1. The variables included in the model, the equations and the probability distributions used are detailed in Table 2. The model was created in Microsoft Excel 2007 with the add-in package @Risk (version 7.5, Palisade Corporation, New York, USA). The Monte Carlo model simulation technique (applying 5000 iterations) was used to create the output distributions, which reflect the inherent uncertainty and variability in each input variable. The number of iterations provided adequate convergence of the simulation statistics (<1%).

2.1.1. Probability of an FMD outbreak in Argentina with the current epidemiological status ($P_{(Br)}$)

Argentina obtained the FMD-free status with vaccination in 2002. From that date to the present, two FMD outbreaks occurred (2003 and 2006) according to official data reported by the National Animal Health and Agrifood Quality Service (SENASA, for its Spanish acronym). In 2003, an FMD outbreak was detected 40 km from the northern border, in Tartagal, San Martín Department (province of Salta), which was associated with the presence of clinical manifestations of the disease in Paraguay (Pozo Hondo, Boquerón Department, July 2003) and Bolivia (Chuquisaca, La Paz, Potosí, Tarija, July 2003). The FMD-free status with vaccination of Argentina was suspended and restored on January 18th, 2005. In 2006, the last FMD outbreak in Argentina was detected in an establishment in the Department of San Luis del Palmar, province of Corrientes. On that occasion, all sick animals and contacts were slaughtered (SENASA, 2011).

Since 2006, the National Surveillance System of Argentina has not detected clinical signs of the disease or evidence of circulation/transmission and/or infection with the FMDV. It could be therefore considered that the probability of an FMD outbreak in Argentina is negligible. Likewise, since the outbreak in 2003, 38 consecutive vaccination campaigns have been performed. According to SENASA's annual sampling, these campaigns conferred vaccination coverage levels of over 90% and high levels of protection, increasing the level of resistance and prevention of the bovine population in the event of a possible re-emergence of FMD. The vaccination program in Argentina includes all bovines and buffaloes with two annual vaccinations; pigs and sheep are not vaccinated and are used as sentinels. The vaccines used are of maximum purity and potency against 3 types of virus A, O, and C, and all the series are controlled according to the procedures recommended by the WOAH (Terrestrial Code). Vaccination is practiced in all establishments in the three FMD-free zones where vaccination is practiced under the supervision of the National Veterinary Service. At the same time, the active and passive surveillance program is carried out according to the recommendations of the WOAH. The vaccination program is covered by the private sector, which actively participates in the process (SENASA, 2023).

The status free of FMD with vaccination is verified by Argentinean authorities following the WOAH guidelines according to article 8.8.3 of the Terrestrial Code. Basically, Argentina has a record of regular and prompt animal disease reporting, implements a surveillance system to detect clinical signs of FMD, implements measures for the prevention and early detection of FMD, carries out a compulsory systematic vaccination in the target population, and this vaccination is performed following appropriate vaccine strain selection. Annually, Argentinean authorities send a declaration to the WOAH stating that there has been no case of FMD during the past two years and there has been no evidence of FMDV transmission during the past 12 months. Argentina supplies documentation to support that the surveillance system has been implemented to detect clinical signs of FMD and demonstrate no evidence of infection with FMDV in unvaccinated animals and FMDV transmission in vaccinated animals. Finally, Argentina has to demonstrate that the vaccination was applied and achieve adequate coverage and population immunity. Annually, the WOAH has revised and accepted this information and has maintained the FMD status, corroborating that animals susceptible to the FMDV in Argentina have remained free of infection for more than 16 years.

Despite all the results reported up to now have been negative for the clinical and serological presence (circulation/transmission) of the FMDV, the probability of a re-emergence of an FMD outbreak cannot be eliminated as a potential scenario. Accordingly, this probability was modeled with a gamma distribution that contemplates the number of outbreaks that occurred from the moment the FMD-free status with vaccination was obtained until the present (two outbreaks in 20 years).

2.1.2. Probability that FMD cases are detected in an export eligible herd ($P_{(R+)}$)

The information reported by Argentina on the FMD outbreaks from 2002 to the present was used. For this risk assessment, the epidemiological data of the 2006 outbreak were taken into account, given that the country had a status of FMD-free with vaccination, similar to the current one and which motivates this risk assessment. This information is available on the World Animal Health Information System database of the WHOA (WAHIS-WOAH). To estimate the probability of FMD cases in a herd before the National Health Service detects them, the number of farms infected during the outbreak in 2006 (n= 2) and the total number of cattle farms existing at that time (n= 182297) (SENASA, 2020) were included in a Beta distribution.

The values chosen are very conservative since considerable efforts have been made in the last 20 years to raise awareness among farmers and to professionalize the Official Veterinary Service. Therefore, it should be expected that in case of a potential introduction of the disease, the first outbreak of FMD will be detected, and appropriate animal health measures will be established to prevent the spread of the disease.

2.1.3- Probability that FMD is detected in an export eligible animal from an affected herd ($P_{(An+)}$)

The intra-herd FMD prevalence was estimated in farms in which FMD outbreaks occurred during 2006, and whose onset was before the first SENASA intervention. Based on the 2006 reports available in the WAHIS-WOAH database, the probability that an animal is infected before the outbreak is detected was estimated considering the number of animals with clinical signs at the time of the official intervention and the total population of the farm at the same time (morbidity). In 2006, when the outbreak was officially detected, 70 animals with signs compatible with FMD were registered in the affected herd, which had a total population of 4098 animals. A beta distribution was used to model intra-herd morbidity.

2.1.4. Probability that an infected animal eligible for export survives the disease ($P_{(S)}$)

To model this probability (survival rate), the lethality data corresponding to the 2006 FMD outbreak available on the WAHIS-WOAH site were used. None of the 70 affected animals died. The survival rate was estimated as 1 – lethality, which was modeled using a beta distribution.

2.1.5. Probability that an infected source animal is not detected before being transported to the slaughterhouse ($P_{(DP)}$)

In Argentina, bovines must be inspected by the health authority before being sent to the slaughterhouse. The on-farm inspection involves detecting animals with fever, salivation, or walking problems. Like any diagnostic technique, its sensitivity or ability to detect an animal positive for the disease is not usually 100%. This can be explained by the expertise and experience of the veterinarian and by the presence of animals with low symptoms or directly asymptomatic (Sutmoller et al., 2002). The *ante-mortem* sensitivity was assumed according to Astudillo et al. (1997), who assumed extreme values between 1% and 10%, with an average value of 5%, which is considered a very conservative approach.

2.1.6. Probability that an infected animal is not detected during ante-mortem ($P_{(amF)}$) and post-mortem inspection at the slaughterhouse ($P_{(pmF)}$)

The *ante-mortem* veterinary inspection involves observing all animals to be slaughtered for signs and lesions consistent with FMD, such as impaired ambulation or excessive salivation. The sensitivity of *ante-mortem* FMD detection at slaughterhouses was estimated with data published by Gonzáles et al. (2014), who reported extreme values of 22% and 40%, with an average value of 31%.

In *post-mortem* inspection, health service technicians inspect the carcass after skinning. If any lesions compatible with the FMD are observed, the entire animal is separated to await the judgment of a veterinarian. The tongue, oral mucosa, and hooves of all slaughtered animals are individually inspected for acute or recovered vesicular lesions. An inspector is unlikely to miss the presence of vesicles or acute lesions. If the herd was infected shortly before transport, at least some of the animals have likely developed lesions at this stage. Healing lesions on convalescent animals are also very characteristic, and these lesions will likely fester on more than one herd animal. Some authors assume that *post-mortem* inspection is at least five times more sensitive than *ante-mortem* inspection due to the meticulous individual inspection of each carcass (Astudillo et al., 1997). The probability of false negatives has a minimum value of 10%, a maximum of 19.98%, and a most probable value of 18% (Marcos and Pérez, 2019). This probability was modeled using a PERT distribution.

2.1.7. Probability that the FMDV survives the storage process (frozen) during the period between slaughter and arrival to the importing country ($P_{(spm)}$)

The FMDV is rapidly inactivated (90% per minute at pH 6.0). In the case of muscle stored at 4° C, the virus is inactivated in 2 days due to the drop in pH during meat maturation (Pharo, 2002). However, it remains infectious in the lymph nodes and bone marrow for several months (Bronsvoort, 2004). Cottral (1969) reported that the FMDV remains viable in bone marrow, tongue, and internal organs (liver, kidneys) after 7 months, 33 days and 42 days of storage at refrigerated temperatures, respectively. Other studies identified that it remains viable for 80 days in bone marrow stored at -1° C (Henderson and Brooksby, 1948). The FMDV has been found to persist for 196 and 112 days in bone marrow stored at 1 and 4° C, respectively (Hyslop, 1970), and for 70 days in lymph nodes at 4° C (Cox et al., 1961 cited by Blackwell et al., 1982). The inactivation rate of the FMDV in lymph nodes and bone marrow stored at 1-4° C has been estimated at 0.66 and 0.4 log units per month, respectively (Sellers, 1971). It should be clarified that the data previously provided on FMDV survival correspond to experiences carried out with animals experimentally inoculated and slaughtered in the acute and symptomatic phase of the infection. Considering the available information, the longest survival period of the FMDV would be two days for boneless beef and up to 196 days for bone-in beef cuts.

In this risk assessment, it was assumed that if an animal became infected, it was highly likely that viral particles reached the bones, and that the maturation process and refrigerated or frozen storage did not alter the survival of the virus during the period of time between slaughter and marketing (Henderson and Brooksby, 1948). However, this assumption is considered conservative because vaccinated animals generate a level of immunity that could prevent or limit viremia (Marcos and Pérez, 2019).

2.1.8. Probability that FMD-infected bone-in beef is exported ($P_{(Exp)}$)

The probability of exporting bone-in beef contaminated with the FMDV was estimated by multiplying the previously estimated independent probabilities. However, to estimate the probability that bone-in beef will be exported from at least one infected animal, it is necessary to consider the number of animals that must be slaughtered to meet the volume of bone-in beef to be exported during one year. The volume of traded beef by Argentina ($V_{(exp)}$) during 2021 was taken from the SENASA export report for fresh meat, Hilton Quota and Quota 481 of 2022 (MAGYP, 2022). This figure was divided by the carcass weight of the cattle at the slaughterhouse ($P_{(cb)}$) (MAGYP, 2022) to estimate the number of animals to be slaughtered to reach the volume of meat to be exported ($N_{(cb)}$).

2.1.9. Destination given to bone-in beef in the importing country ($D_{(ch)}$)

Handling is a relevant aspect in case of an FMD outbreak in the country importing bone-in beef from Argentina. The ways of handling meat are varied and particular according to the habits and customs in the importing countries. Two ways of handling were identified to generate a model that is applicable to all conditions, even if they could imply an oversimplification: 1) bone-in beef is sold directly to the consumer, and 2) meat is deboned at destination, the consumer buys boneless meat and the bone is destined for other uses.

Since there is no information to scientifically support the estimation of the probability of occurrence of both handling ways, a Uniform distribution with a probability between 0% and 100% was used. This approximation implies accepting that this probability is uncertain, but it allows modeling the entire range of probabilities that the importing countries would adopt.

In the case of bone-in beef sold directly to the consumer, it is necessary to estimate the effect of cooking on virus viability ($S_{(cocc)}$). This was modeled according to data reported by Kamolsiripichaiporn et al. (2007). The loss of viability of the FMDV in bone-in beef was modeled using regression equations that allow estimating the decimal reduction time (D) as a function of cooking temperature. The uncertainties in the parameters *a* (intercept *Y*) and *b* (slope) of the regression equation were modeled considering the natural variability of resistance between strains of the FMDV. Cooking temperature (*Temp*) was modeled assuming a range between 50 and 70° C. Cooking time (*Time*) was conservatively estimated, assuming that the bone is exposed for a minimum and maximum time of 180 and 300 seconds, respectively. The number of decimal reductions in virus viability (N_{red}) was calculated by dividing the cooking time by the estimated decimal reduction time. Once the meat is consumed, there are two alternative waste disposal options: 1) the consumer disposes of the remains of meat with bones together with household waste which is processed properly, so that bones do not come into contact with other susceptible animals (for adequate treatment of organic waste, we can mention thermal or enzymatic digestion or compaction in properly fenced final disposal cells), and 2) the consumer disposes of the bones inappropriately, that is, either in municipal open-air dumps or in backyards.

There is no information that allows modeling the probability with which users dispose of cooked bone ($P_{(dh)}$). In order to consider all the habits and conditions in the importing countries, this stage was modeled using a Uniform distribution.

If meat was sold to the consumer without the bone and the bone was used for the production of bone meal for animal feed ($P_{(cHH)}$), then the loss of virus viability resulting from the bone meal production process ($S_{(HH)}$) was modeled based on the data reported by Bachra et al. (1957). The FMDV is very sensitive to temperature. When materials potentially infected with the virus are incorporated into formulations for feeding susceptible animals, product center-of-mass temperatures of at least 93° C need to be applied for the material to be considered free from the FMDV (Blackwell and Rickansrud, 1989). It has also been reported that the FMDV is not viable in infected materials after having been subjected to different processes used in the preparation of concentrated pet food, namely, *i*) heat treatment of meat at 68° C for 300 s; *ii*) treatment of flours enriched with the FMDV at 79° C for 10 or 30 s, or *iii*) treatment of the homogenized epithelium of bovine tongue, taken from an animal infected with the FMDV at 79° C for 10 s (Gubbins et al., 2016). Previous treatments yielded 8 log_{10} reductions (range, 6 to 13 log_{10}), demonstrating that the heat treatments used in commercial pet food manufacturing can significantly reduce FMDV titers in infected raw materials.

Considering that the process for obtaining bone meal uses high heat treatments (above 130°C) under pressure and adopting a conservative position, a 4-5 log reduction in virus viability would be obtained.

2.1.10. Probability of FMD exposure in the importing country ($P_{(EF)}$)

Finally, all the previously identified routes were integrated and the total probability of an FMD outbreak in animals from the importing countries was estimated. The probable routes of exposure were a) improperly disposed home-cooked bone, b) improperly disposed raw bone, and c) bone meal.

2.2. Sensitivity analysis

The @Risk program was used to identify the stages of the process that had the greatest influence on the risk of an FMD outbreak due to the importation of bone-in beef from Argentina. Additionally, the efficacy of control measures to reduce the risk of exposure was evaluated. This analysis was also performed to determine the degree of uncertainty and variability associated with each input variable in the model. Spearman´s rank correlation (*r*) between the model output and the input parameters was performed.

3. Results and Discussion

After running the model, the estimated probability that bone-in beef from at least one animal infected with the FMDV will be exported during a year was 5.27×10^{-3} (95% CI $<10^{-10}$ – 5.19×10^{-2}) on average (Table 3). This event is expected to occur once in the next 190 years. Similarly, a previous quantitative risk assessment of FMDV introduction into the Patagonian

FMD-free zone without vaccination of Argentina reported an average 1.7 x 10^{-3} risk of an FMD outbreak (Marcos and Pérez, 2019). The differences with our model were that the mentioned study did not consider the probability that the health authority did not detect infected animals in the establishments of origin before they were sent to slaughter, and the higher volume of beef trade in our risk assessment.

To procure the export of meat from countries with FMD (the prevailing epidemiological situation in South America at that time), Astudillo et al. (1997) estimated the probability that these countries exported boneless meat. According to the results of this study, the probability that South American countries exported boneless meat containing the FMDV was $10^{-6.1}$ on average, which means approximately one chance in a million, with a worst-case scenario of $10^{-5.5}$ or one chance in 700,000.

The sensitivity analysis is commonly used in quantitative risk assessments to examine the behavior of a model by measuring the variation in its outputs resulting from changes to its inputs. The variables most associated with the risk of exporting bone-in beef from at least one animal infected with the FMDV were the probability of an outbreak occurring in Argentina (r= 0.99) and the number of herds that could be affected during an outbreak (r= 0.10) (Figure 2A). The other variables (sensitivity of *ante*- and *post-mortem* inspection and intra-herd incidence during an outbreak) had a marginal association (r< 0.03) with the probability of exporting bone-in beef from infected animals.

The most relevant factor for the prevention and control of the potential re-emergence of an FMD outbreak and, in the event of an outbreak, its quick detection before the animals are sent to slaughter is the correct and efficient operation of the FMD Surveillance System by the National Animal Health Service. Insofar as the surveillance system works properly, potentially infected animals and their contacts can be quickly detected and slaughtered, preventing their entry into the agri-food chain and thereby limiting the spread of the outbreak and reducing the risk of exporting infected material.

The probability that susceptible animals in the importing country came into contact with the infective material (bones) and generated an outbreak was 6.16×10^{-4} (95% CI $<10^{-10}$ – 6.20×10^{-3}) (Table 3). In other words, the possibility of an FMD outbreak in a country that imports Argentine bone-in beef would be every 1623 years on average.

Once again, the risk of an FMD outbreak in Argentina (r= 0.96) was the variable that had the greatest impact on the risk of an FMD outbreak in the country importing bone-in beef from Argentina (Figure 2B). The higher the proportion of bones destined for bone meal production in importing countries, the lower the risk of an FMD outbreak in the importing country (r= -0.12). Conversely, if the proportion of bones that are removed inappropriately is high and susceptible animals are likely to come into contact with them, the risk of an FMD outbreak in the importing country will be higher (r= 0.12). If imported bone-in beef is distributed without bone-in before reaching the final consumer, the probability that the country will suffer an FMD outbreak will be lower (r= -0.09). Other variables were associated with the response variable, but with very low correlation coefficients (r< 0.03).

The probability of an outbreak in Argentina was the variable most associated with both the probability that Argentina exports bone-in beef infected with the FMDV and the probability that these exports generate an outbreak in the importing country. Thus, the risk of an FMD outbreak was associated with the existing conditions in the country for the potential introduction of the FMDV. Accordingly, if our country maintains a disease-free status, it is not relevant whether it is with or without vaccination.

The statuses free with vaccination and free without vaccination are equivalent. In the potential case of FMD entering Argentina, vaccination is an important control strategy that can reduce the speed of spread in the national territory, leading to shorter outbreaks and fewer animals culled (Tadesse et al., 2017). In fact, during the outbreak in 2001, when the status of Argentina was FMD-free without vaccination, 2394 herds were affected, including 86,781 cattle of which 295 died. In contrast, during the last re-introduction of FMD in 2006, when the status of the country was FMD-free with vaccination, there was only one focus of the disease, which affected 70 animals and was immediately contained by the National Health Service (SENASA). These differences may be explained, fundamentally, by two factors: *i*) the rapid action of SENASA, and *ii*) the high level of vaccination coverage in the bovine population, which limited the intra- and inter-farm spread of the disease. In other words, vaccination does not modify the FMD-free health status, making the risk of an FMD outbreak in importing countries of Argentinean bone-in beef negligible.

It has been reported that vaccination reduces FMD morbidity in cattle and that the presence of neutralizing antibodies limits viraemia (during the pre or sub-clinical stage of the disease), reducing the probability of the FMDV in meat, blood, bone marrow, lymph nodes, and organs (Marcos and Pérez, 2019; Sutmoller and Casas Olascoaga, 2003). In addition, the risk of meat from carrier animals being contaminated is also negligible, since viremia does not occur. Considering these results, repeated vaccination reduces the risk of FMD infection in the lymph nodes (Argentine-United States Joint Commission on Foot and Mouth Disease Studies on Foot and Mouth Disease, 1966). Other studies have reported that viremia and vesicular lesions can be prevented with vaccination (Sutmoller et al., 1968; Sutmoller and McVicar, 1976).

Argentina has eliminated all the affected animals and their contacts from the last outbreak in 2006, and the absence of FMDV transmission/infection throughout its entire territory has been demonstrated for more than 16 consecutive years. In this context, the conditions of Chapter 8.8.21 (Recommendations for importation from FMD free countries or zones where vaccination is practised) of the WAHO Terrestrial Code should be applied for the commercialization of Argentine meat and derivatives, including bone-in beef. Basically, Veterinary Authorities require the presentation of an international veterinary certificate attesting that the entire consignment of meat comes from animals which *a)* have been kept in the FMD-free country or zone where vaccination is practiced, *b)* have been slaughtered in an approved abattoir and have been subjected to ante- and post-mortem inspections for FMD with favorable results, and *c)* for ruminants the head, including the pharynx, tongue and associated lymph nodes, has been excluded from the shipment (WOAH, 2022).

The SENASA coordinates an active Epidemiological Surveillance System to monitor the emergence of cases of vesicular diseases, so it is prepared to act quickly and effectively in the event of a possible re-emergence of FMD in the national territory. Additionally, the high technological level of bovine beef slaughterhouses authorized to export Argentine meat provides an additional control factor that significantly reduces the risk that bone-in beef from Argentina may cause FMD outbreaks in importing countries.

5. Conclusion

Based on the results of this quantitative risk assessment, the probability of the introduction of FMD associated with bone-in beef trade from Argentina into an FMD-free country without vaccination is negligible. Based on the current quantitative risk assessment, not allowing the export of bone-in beef from countries with FMD-free status with vaccination would appear to be scientifically unjustified. This conclusion would be applicable and extensive to all countries that have the same epidemiological status, as long as they meet the requirements established by the WOAH in Chapter 8.8.3., and especially have developed an appropriate epidemiological surveillance system that allows the rapid identification of FMD cases.

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Figure legends

Figure 1. Graphical representation of the quantitative risk assessment model proposed to evaluate the risk of an FMD outbreak due to bone-in beef exports from Argentina.

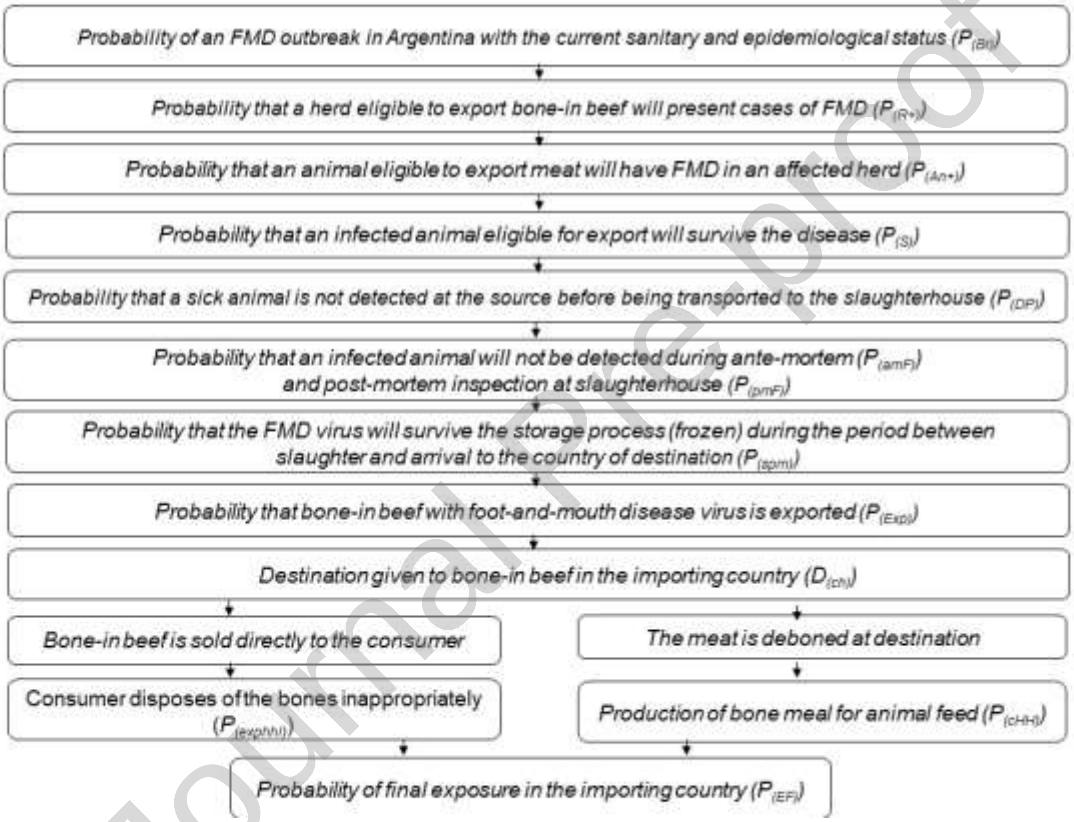

Figure 2. Sensitivity analysis of the probability of A) exporting bone-in beef from at least one animal infected with the FMDV and B) FMD outbreak due to the importation of bone-in beef from Argentina.

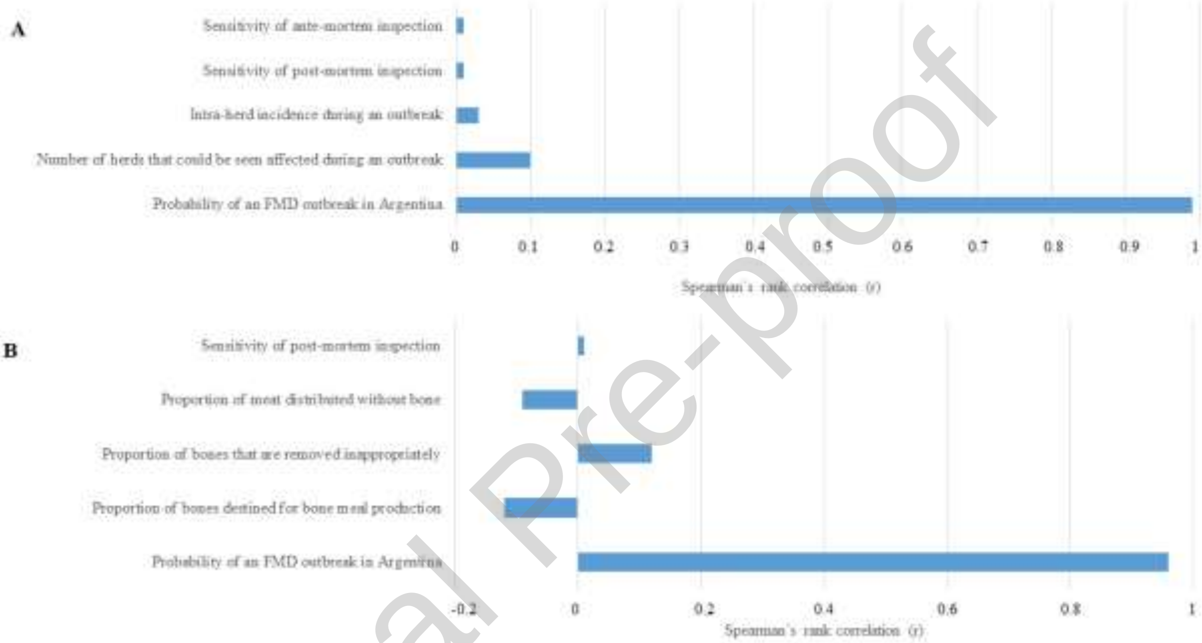

Table 1: Recommendations for importation of fresh meat or meat products of FMD susceptible animals from countries or zones with different FMD status

FMD status of the exporting country or zone	Recommendations Veterinary Authorities should require the presentation of an international veterinary certificate attesting that the entire consignment of meat comes from animals which:
FMD-free country or zone where vaccination is not practiced[1]	- have been kept in a FMD-free country or zone where vaccination is not practised or FMD- free compartment. - have been slaughtered in an approved slaughterhouse and have been subjected to ante and post-mortem inspections with favourable results.
FMD-free country or zone where	- have been kept in the FMD-free country or zone where vaccination is practiced.

<table>
<tr><td>vaccination is practiced[2]</td><td>- have been slaughtered in an approved slaughterhouse and have been subjected to ante- and post-mortem inspections for FMD with favourable results.
- head, including the pharynx, tongue and associated lymph nodes, has been excluded from the shipment.</td></tr>
<tr><td>FMD infected countries or zones where an official control programme exists[3]</td><td>- have remained, for at least three months prior to slaughter, in a zone of the exporting country where cattle and water buffaloes are regularly vaccinated against FMD and where an official control programme is in operation.
- have been vaccinated at least twice with the last vaccination not more than six months, unless protective immunity has been demonstrated for more than six months, and not less than one month prior to slaughter.
- were kept for the past 30 days in an establishment, and that FMD has not occurred within a 10 kilometer radius of the establishment during that period, or the establishment is a quarantine station.
- have been transported, in a vehicle which was cleansed and disinfected before the cattle and water buffaloes were loaded, directly from the establishment of origin or quarantine station to the approved slaughterhouse without coming into contact with other animals which do not fulfil the required conditions for export.
- have been slaughtered in an approved slaughterhouse:
- which is officially designated for export
- in which no FMD has been detected during the period between the last disinfection carried out before slaughter and the shipment for export has been dispatched
- have been subjected to ante- and post-mortem inspections within 24 hours before and after slaughter with no evidence of FMD
if comes from deboned carcasses:
- from which the major lymphatic nodes have been removed
- which, prior to deboning, have been submitted to maturation at a temperature greater than + 2°C for a minimum period of 24 hours following slaughter and in which the pH value was less than 6.0 when tested in the middle of both the Longissimus dorsi muscle.</td></tr>
</table>

FMD infected country or zone[4]	- have been slaughtered in an approved slaughterhouse and have been subjected to ante- and post-mortem inspections for FMD with favourable results. - the meat products have been processed to ensure the destruction of FMDV in accordance with one of the procedures in Article 8.8.31. of the WOAH Terrestrial Animal Code. - the necessary precautions were taken after processing to avoid contact of the meat products with any potential source of FMDV.

References: [1]Article 8.8.20 of the WOAH Terrestrial Animal Code; [2]Article 8.8.21. of the WOAH Terrestrial Animal Code; [3]Article 8.8.22. of the WOAH Terrestrial Animal Code; [4]Article 8.8.23. of the WOAH Terrestrial Animal Code.

Table 2: Parameter definitions and distributions.

Variable	Symbol	Equation/Distribution
Probability of an FMD outbreak in Argentina with the current epidemiological status	$P_{(Br)}$	$\sim Gamma\left(1; \frac{2}{20}\right)$
Probability that a herd eligible to export bone-in beef will present cases of FMD	$P_{(R+)}$	$\sim Beta(2+1; 182297-2+1)$
Probability that an animal eligible to export meat will have FMD in an affected herd	$P_{(An+)}$	$\sim Beta(70+1; 4098-70+1)$
Probability that an infected animal eligible for export will survive the disease	$P_{(S)}$	$\sim Beta(0+1; 70-0+1)$
Probability that an infected source animal is not detected before being transported to the slaughterhouse	$P_{(DP)}$	$1 - \sim PERT(0.01; 0.05; 0.10)$
Probability that an infected animal will not be detected during ante-	$P_{(amF)}$	$1 - \sim PERT(0.22; 0.33; 0.40)$

mortem ($P_{(amF)}$) inspection at the slaughterhouse		
Probability that an infected animal will not be detected during post-mortem inspection at the slaughterhouse	$P_{(pmF)}$	$\sim PERT(0.1; 0.18; 0.1998)$
Probability that the FMDV will survive the storage process (frozen) during the period between slaughter and arrival to the importing country	$P_{(spm)}$	1
Volume of meat exported by Argentina (kg)	$V_{(exp)}$	$\sim Poisson(803'544{,}000)$
Weight of the cattle at the slaughterhouse (kg)	$P_{(cb)}$	$\sim PERT(238; 279; 306)$
Number of animals required to slaughter to reach the volume of meat to be exported	$N_{(cb)}$	$\sim Poisson\left(\frac{V(\exp)}{P(cb)}\right)$
Probability that bone-in beef from at least one animal infected with the FMDV will be exported	$P_{(Exp)}$	$1-(1-((P(Br)\times P(R+)\times P(An+)\times P(S)\times P(DP)\times P(amF)\times P(pmF)\times P(spm)))^{N(cb)})$
Destination given to bone-in beef in the importing country	$D_{(ch)}$	$\sim Uniform(0; 1)$
Decimal reduction time	D	$a + b \times Temp$
Parameter a (intercept Y)	a	$\sim PERT(4.26; 4.36; 5.27)$
Parameter b (slope)	b	$\sim PERT(-0.0541;\ -0.0439;\ -0.043)$
Cooking temperature (ºC)	$Temp$	$\sim Uniform(50; 70)$
Cooking time (sec)	$Time$	$\sim Uniform(180; 300)$
Effect of cooking on virus viability	$S_{(cocc)}$	$\frac{1}{10^{(Time/D)}}$
Probability which users dispose of cooked bone	$P_{(dh)}$	$\sim Uniform(0; 1)$

Probability of exposure to inappropriate bone disposal at homes	$P_{(exphhI)}$	$D(ch) \times P(dh) \times S(cocc)$
Probability the consumer buys boneless meat	$P_{(csh)}$	$1 - D(ch)$
Probability the bone is used for the production of bone meal for animal feed	$P_{(cHH)}$	$\sim Uniform(0; 1)$
Loss of virus viability resulting from the bone meal production process	$S_{(HH)}$	$\sim Uniform(0.000001; 0.00001)$
Probability of FMDV exposure from bone meal for animal feed	$P_{(Ehh)}$	$P(csh) \times P(cHH) \times S(HH)$
Probability the bone is not used for the production of bone meal for animal feed	$P_{(ncHH)}$	$1 - P(cHH)$
Probability of inappropriate bone disposal	$P_{(HdI)}$	$\sim Uniform(0; 1)$
Probability of FMDV exposure by inappropriate bone disposal	$P_{(expHdI)}$	$P(csH) \times P(ncHH) \times P(HdI)$
Probability of final exposure in the importing country	$P_{(EF)}$	$1 - \left((1 - P(exphhI)) \times (1 - P(Ehh)) \times (1 - P(expHdI))\right)$

Table 3: Probability estimation of the principal outcomes of the quantitative risk assessment model.

Outcome variable	**Mean**	**95%CI**
Probability that bone-in beef from at least one animal infected with the FMDV will be exported	5.27×10^{-3}	$<10^{-10} – 5.19 \times 10^{-2}$

Probability of FMDV exposure from inappropriate bone disposal at homes	1.79×10^{-5}	$<10^{-10}$ – 9.50×10^{-5}
Probability of FMDV exposure from bone meal for animal feed	7.97×10^{-9}	$<10^{-10}$ – 8.12×10^{-8}
Probability of FMDV exposure from inappropriate bone disposal	5.89×10^{-4}	$<10^{-10}$ – 6.30×10^{-3}
Probability of final FMDV exposure in the importing country	6.16×10^{-4}	$<10^{-10}$ – 6.20×10^{-3}

Highlights

- QRA was used to estimate the risk of introducing FMD through bone-in beef from Argentina.
- The probability of FMD introduction from a country FMD-free with vaccination status was negligible.
- FMD outbreak caused by the re-introduction of the FMD virus was associated with the existing conditions in the country.
- maintaining the FMD-free status with or without vaccination would not be relevant.