Foot and mouth disease: The role of international trade and the risk of disease outbreak

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ABSTRACT

The growth in world trade has brought significant to benefits to human wellbeing, but has also greatly increased the dispersal of pests and pathogens across the globe. Indeed, trade has been the vehicle of spread for several emerging zoonoses and re-occurring livestock diseases. In this paper, we focus on the risk of foot and mouth disease (FMD) associated with the international trade of livestock. While it is recognized that trade has implications for the spread of foot and mouth disease, there are relatively few attempts to quantify the associated risks. Here, we estimate a model of foot and mouth disease risk that incorporates the effects of international trade of live animals and controls for the biosecurity measures undertaken by importing and exporting countries, as well as the presence of wild FMD reservoirs. We find that the disease risks of trade depend on the structure and volume of trade in risk materials, the biosecurity measures undertaken by trading partners, and the interaction between the two. We also show that the incentive to mitigate risk through border protection and biosecurity measures is positively correlated with the value at risk. By identifying the likelihood that importing from/exporting to particular regional groupings of countries may lead to foot and mouth disease outbreaks, we are able to identify the optimal targeting of disease risk mitigation activities.

JEL codes: F1

Keywords: foot and mouth disease; international trade; risk

INTRODUCTION

The growth in world trade has delivered significant benefits to human wellbeing worldwide. At the same time it has dramatically increased the rate at which pests and pathogens are dispersed. Indeed, the increased spread of human, animal, and plant diseases has been argued to be among the most important side effects of the growth of international trade. Research on the general problem of invasive species has revealed strong positive relationships between the development of new trade routes and the introduction of new species, and between the growth in trade volumes and the probability that introduced species will establish and spread (Cassey et al., 2004; Dalmazzone, 2000; Dehnen-Schmutz et al., 2010; Pavlin et al., 2009; Semmens et al., 2004; Smith et al., 2009b; Tatem, 2009; Tatem et al., 2006a; Tatem et al., 2006b; Vila and Pujadas, 2001). Many emerging zoonotic diseases of humans have their origins in the growing trade in livestock and wildlife products with developing countries. The list of emerging zoonoses spread this way includes SARS, monkeypox, and H5N1 avian influenza (Karesh et al., 2012; Kilpatrick et al., 2006; Li et al., 2005; Smith et al., 2009a; Xu et al., 2004). Among epizootic diseases, trade has been the vehicle for the spread of both emerging diseases such as H9N2 avian influenza and re-emerging livestock diseases such as foot and mouth disease, bovine spongiform encephalopathy, and swine fever (Drew, 2011; Fevre et al., 2006; Karesh et al., 2005; Rweyemamu and Astudillo, 2002).

In this paper we focus on the epizootic disease risks of trade, and in particular on foot and mouth disease (FMD) (also known as hoof and mouth disease). We ask how recent trends in the world trade in animals has affected disease risk. The proportion of output traded internationally—the defining feature of globalization—continues to rise rapidly. Since 1950, world merchandize exports have increased at more than 3 times the rate of GDP growth (World Trade Organization, 2013). The regional structure of exports has also changed. Export growth is currently more rapid in emerging markets and developing economies than in developed economies—a trend that is accelerating. Currently, emerging market and developing country exports are growing 50% faster than developed country exports (International Monetary Fund, 2013). While it is recognized that this has implications for the spread of foot and mouth disease (Di Nardo et al., 2011; Fevre et al., 2006; Rweyemamu et al., 2008), there are relatively few attempts to quantify the associated risks (Berentsen et al., 1992; Garner and Lack, 1995; Hartnett et al., 2007; Jori et al., 2009; Martinez-Lopez et al., 2008; Miller et al., 2012). In what follows we estimate the direct and indirect risks of foot and mouth disease spread associated with the international trade of live animals.

The management of trade-related animal disease risks is regulated by the Sanitary and Phytosanitary (SPS) Agreement, which regulates the trade interventions allowed to protect animal health under Article 20 of the General Agreement on Tariffs and Trade. The standards applied by the SPS Agreement are determined by the World Organization for Animal Health (OIE), and cover health standards for international trade in animals and animal products. The SPS Agreement requires that trade interventions to protect animal health be informed by a scientific assessment of risk. The risk assessment methodology developed by the OIE aims to establish the likelihood of the introduction, establishment and spread of disease within the territory of an importing country, and to assess its biological and economic consequences (MacDiarmid, 2011). Typically, risk assessments for pathogens transmitted through trade focus on the sanitary capabilities of exporting countries. The policy response involves trade restrictions that either ban export of risky goods, or allow exports only from particular zones or compartments within a country that are recognized as applying acceptable biosecurity standards (Ratananakorn and Wilson, 2011; Sugiura and Murray, 2011). Foot and mouth disease is managed through just such restrictions on trade in live animals and animal products (Alexandersen et al., 2003; Grubman et al., 2008; Leforban, 1999; Sutmoller et al., 2003).

Previous research has shown that the probability that animal or plant pathogens will be transmitted from one location to another via the movement of goods depends on the structure of direct or indirect trade pathways and the volume of goods moved along pathways (Dalmazzone, 2000; Vila and Pujadas, 2001), and on the biosecurity measures undertaken by those who produce and transport the goods (Brasier, 2008; Perrings et al., 2010a; Perrings et al., 2010b; Scott et al., 2006; Whittington and Chong, 2007) . Decisions about whom to trade with, what to trade, and how much to trade, are as important as decisions about biosecurity measures to put in place, and none of these decisions are independent of one another. There are concerns that current trade related animal disease risk assessments understate risk when they ignore indirect trade linkages (Barker et al., 2006; King et al., 2006; Mur et al., 2012) and overstate risk when they treat all commodities as equal (Bruckner, 2011; MacDiarmid, 2011). The development of new trade routes between emerging markets and developing economies, for example, is argued to have increased reinfection rates from existing reservoirs for a number of animal diseases, including FMD (Di Nardo et al., 2011).

FMD is particularly interesting due to the fact that the primary cost of the disease lies less in its clinical effects than in the trade responses it induces. The biology of the foot and mouth disease virus is well understood (see

Alexandersen et al. (2003), Arzt et al. (2011a), Arzt et al. (2011b), and Sutmoller et al. (2003) for reviews of this literature). Transmission may occur through a number of pathways such as via airborne droplets, entry through cuts and abrasions in the skin, and consumption of contaminated fodder (Alexandersen et al., 2003; Arzt et al., 2011a; Arzt et al., 2011b). Virtually every cloven-hoofed animal is susceptible, but susceptibility and infectivity both vary with the virus strain and host species (Alexandersen and Mowat, 2005; Alexandersen et al., 2003). In livestock, the disease causes the formation of lesions within and around the mouth and feet, lameness, fever, depression, loss of appetite, reduction in milk yields and reproductive potential, but causes mortality only in rare cases (Alexandersen et al., 2003; Knight-Jones and Rushton, 2013).

Nonetheless, the economic damage caused by FMD outbreaks is frequently very large (Knight-Jones and Rushton, 2013). The primary response to a foot and mouth outbreak is to slaughter infected and potentially latently infected livestock (Grubman et al., 2008). The 2001 United Kingdom outbreak, for example, resulted in the culling of over two million head of livestock (Sobrino and Domingo, 2001), and income losses to farmers, agriculture, the food chain, and tourist revenues of around £6.5 billion (Thompson et al., 2002). That is, the cost of the outbreak comprised both the loss of a substantial proportion of standing stock, and the loss of trade in both agriculture and related industries. In addition to the $378 million worth of damages to the livestock industry, the 1997 Taiwan FMD outbreak led to the losses of over 65,000 jobs spanning pharmaceutical, animal fodder, meat packaging, equipment manufacture and supply, and transportation industries (Yang et al., 1999). FMD outbreaks in disease free countries frequently induce additional costs for disease monitoring, vaccinations, and the isolation of disease free areas as a conditions for restoring trade, while trade restrictions imposed in response to an outbreak as frequently affect sectors other than agriculture (Garner and Lack, 1995; Knight-Jones and Rushton, 2013).

In this paper, we estimate a model of foot and mouth disease risk that incorporates the effects of the international trade in livestock, while controlling for the biosecurity measures undertaken by both importing and exporting countries, and for the existence of wild FMD reservoirs. This enables us to identify the relative significance and strength of the different risk factors identified, and in particular the impact of imports from/exports to regional groups of trading nations. We take risk to be the product of the probability of a disease outbreak multiplied by the cost of an outbreak, where cost includes both the potential loss of standing stocks due to culling and the time-limited loss of the trade in live animals. Since we do not include related economic activities such as tourism, or upstream/downstream activities in the food supply chain, our estimates offer a lower bound on FMD risks. We show that the incentive to mitigate risk through border protection and biosecurity measures is strongly and positively correlated with the aggregate value at risk. By identifying the likelihood that imports from particular regional groupings of countries will lead to disease outbreaks, we are then able to identify the optimal targeting of disease risk mitigation activities.

DATA DESCRIPTION

Our dataset spans 218 countries over the period between 1996 and 2011. It reports the number of monthly outbreaks published by the World Organization of Animal Health or OIE (http://www.oie.int/). Beginning in 1996, participating countries filed both annual and monthly reports of the number of new outbreaks within their borders. Because trade data were, until recently, reported on an annual basis, we aggregated outbreak data to the annual level. Using this information and the number of new outbreaks, we constructed a binary outbreak(s)/no outbreaks measure for each country. This is the primary dependent variable in our analysis.

To identify the risk associated with outbreaks we also need measures of the economic consequences of outbreaks, or the potential value at risk. We consider three measures of value at risk. The first is agricultural GDP, as reported by the FAO. This is a measure of value added in the agricultural sector—the annual income the sector yields to farmers, farm workers, and associated industries. Since it is not possible to isolate the livestock sector within agriculture, this is an overestimate. The second is a measure of the growth trajectory of the sector livestock sector. It is the FAO's livestock production index (LPI) calculated as a country's aggregate volume of production compared to a base period (in this case, between 2004 and 2006). It includes meat and milk, dairy products, eggs, honey, raw silk, wool, and animal hides and skins, and is a proxy for the development of a country's livestock industry. The third is a measure of the assets that may be destroyed during efforts to control and outbreak—the standing stock of cattle, sheep and pigs in a country. We expect all three measures to be positively correlated with ex ante risk mitigation measures, and hence negatively correlated with the likelihood that the disease will be detected in the national herd.

We are interested in two sets of risk factors: those relating to the structure and volume of international trade in risk materials, and those relating to the biosecurity measures taken along trade routes. Our trade dataset includes the volume of imports and exports of cattle, sheep, and pigs reported to the Food and Agriculture Organization between 1996 and 2011 (http://faostat3.fao.org/home/E).[1] While these are not the only risk materials relevant to FMD, they are the most important. We then aggregated trade data by assigning all countries in our database into the twenty-two regions of the Food and Agriculture Organization (FAO). Two regions were added to accommodate countries that were either "Unspecified" or in the "European Union"— classifications in the FAO trade data that comprise countries that span multiple FAO region(s). While we do lose resolution by aggregating the data into regions, not doing so results in problems of severe collinearity between the trade data among members of particular regional groups.

We expect the volume of livestock imports to capture the direct impact of trade on disease risk— the probability of importing an infected animal. We expect the volume of livestock exports to capture the indirect impact of trade on disease risks—the probability that sending livestock transport vessels/vehicles into particular ports will lead to outbreaks in the exporting country (Mur et al., 2012). That is, there is some probability that FMD contaminated material is "picked up" and transported back to the exporting country. The FMD virus has, for example, been found to persist in hay, soil, fodder, milk, hair, machinery, and clothing (Alexandersen et al., 2003; Callis, 1996; Paton et al., 2010; Ryan et al., 2008; Sutmoller and Casas Olascoaga, 2003; Sutmoller et al., 2003).

On biosecurity measures, foot and mouth disease spread is affected by how well a country manages disease within its borders (Berentsen et al., 1992; Garner and Lack, 1995; Schoenbaum and Disney, 2003). Nevertheless, direct measures of sanitary conditions in the livestock sector are scarce. As a proxy for this we take the density of veterinarians registered for each country with the OIE. This measure includes veterinarians in both private and public sectors, but does not include associated personnel such as veterinary technicians. A second set of biosecurity measures comprises binary data on the control measures reported to the OIE that a country undertakes prior to an FMD outbreak, including 1) inspection and interception at the border; 2) monitoring and surveillance of livestock; 3) the existence of measures for the control of wild reservoirs; and 4) measures, such as veterinary cordon fences, that isolate disease-free regions within the country (http://www.oie.int). The last two comprise indirect proxies for the existence of wild reservoirs within countries. For example, zoning isolates the quarantined zone areas where FMD is present. We expect these measures to be positively related to the likelihood that an FMD outbreak will be reported as 'present' in the national herd. The presence of endemic, non-commercial livestock reservoirs may

[1] Although trade data are available on other species that may transmit FMD, far fewer countries are involved in the trade. There is also a high degree of collinearity between the data on other species.

potentially affect commercial disease incidence rates by providing sources of disease that may spread to commercial livestock (Jori et al., 2009; Sutmoller et al., 2003; Thomson et al., 2003).

We also included a categorical variable that captures the overall disease status in relation to the national livestock population. Based on the disease-free reports from the OIE, we classified whether a country was disease-free (with and without vaccination separately), possessed zones that were disease-free (with and without vaccination respectively), or were not disease-free. This variable captures disease management practices such as vaccinations and zoning, and should also be correlated with other measures of sanitary conditions. ‘Disease-free' status does not necessarily mean a country was free of outbreaks. It reflects the trading status of a country recognized by the OIE. Table 1 reports the summary statistics of the data included in our analysis.

METHODS

In order to evaluate the effect of trade on relative disease risk, we first considered the impact of our various risk factors on the probability that an FMD outbreak was reported in the national herd in a given period. The main modeling options explored in the literature are logistic and negative binomial regression models. Both the logistic and negative binomial regressions have potential drawbacks in analyzing binary—outbreak, no outbreak—data of this kind. In particular a binary logistic makes two assumptions. Namely, the unobserved errors are independent and identically distributed and the "choice" of the dependent variable is independent over time (Train, 2009). The time-independence of the response variable assumes that past states have no influence on the current state, and that there is no lag in the response of the dependent variable to the independent variables. We may accommodate a certain degree of autocorrelation by including time lagged observed explanatory variables (Adamowicz, 1994) or a lag in the dependent variable (Erdem, 1996). Autocorrelation in the unobserved variables, however, is more difficult problem that warrants further investigation. The logistic regression model also generates estimates of the odds ratios as opposed to the relative risk of the independent variables. Though the odds ratio for one variable remains constant regardless of changes in other variables (Gould, 2000), it may provide less reliable approximations of the relative risk as the incidence rate of the dependent variable increases or the as the odds ratio deviates from one (Cohen, 2000; Davies et al., 1998; Zhang and Yu, 1998). In this respect, the negative binomial has an advantage in that it directly estimates the relative risk associated with the independent variables. In addition, the quadratic specification of variances allows it to fit a variety of overdispersed count data with non-constant variances (Cameron and Trivedi, 2005). Nevertheless, the negative binomial also has drawbacks. It is more sensitive to model misspecification that other count models, even if the conditional mean is correct (though this occurs less when quadratic variances are used) (Cameron and Trivedi, 2005). Also, due to the nonlinearity of the model structure, estimation of the regression coefficients by maximum likelihood methods can be difficult, particularly when dummy variables are used in the analysis (Allison and Waterman, 2002).

While we estimated both sets of models, an evaluation of model selection criteria (AIC, BIC, and log-likelihood) indicated that the logistic regression model was the better option in this case. The estimated model took the form:

[1] $$\Pr(y_{it}=1)=\frac{\exp(\theta_{it})}{1+\exp(\theta_{it})}$$

[2] $$\theta_{it}=\alpha_i+\sum_{j=1}^{12}X'_{jit}\beta_j+\sum_{s=1}^{3}\sum_{k=1}^{24}I'_{rkst}\beta_{24s+k-12}+\sum_{s=1}^{3}\sum_{k=1}^{24}E'_{24s+k+60}+\varepsilon_{it}$$

for country *i* in year *t*. The left-hand side of equation [1] is the probability of a new FMD outbreak conditional on the linear predictors: $y_{it}=1$ when a country has experienced a new outbreak; $y_{it}=0$ when no outbreaks were reported to the OIE. The elements of *X* include the following: value at risk, veterinarian density, disease control measures, and the disease-free status of the reporting country. Elements of *I* and *E* include the aggregate imports and exports between the region *r* containing country *i* and all other regions *k* of cattle, pigs, and sheep. The constant intercept and error terms are represented by α and ε respectively. Our data is an unbalanced panel. The model was estimated using the method of maximum likelihood and robust standard errors in Stata 14.0 (StataCorp, 2015). To correct for temporal autocorrelation and clustering effects between regions, we utilized Stata's "xt" command, which explicitly treats the data as a panel data set.

We then used our estimates generated by the logistic regression to calculate the relative economic risks associated with trade. We took the trade-related relative economic risk of FMD outbreak as the product of the relative probability of disease occurrence and the magnitude of potential damages of an FMD outbreak. The former is calculated directly from the odds ratio, the exponential of the betas generated from the logistic regression (Gelman and Hill, 2007). It is the change in the odds for a unit change in the independent variable. Although it is generally understood that the odd ratio overestimates relative risk when greater than one and underestimates when less than one, the degree of deviation between the two is more severe at high odds ratios and when the event is very likely to occur (Cohen, 2000; Davies et al., 1998; Zhang and Yu, 1998). The magnitude of potential damages is taken as the value at risk. Using the United States in 2011 as an example, we presented two potential values of the economic value at risk: the value of all exports of cattle, sheep, and pigs (direct economic losses of a time-lapse of trade) and the dollar value of the agriculture sector. These provide lower and upper bounds to risk.

RESULTS

Our results on the relative disease risks of trade, and the impact of non-trade risk factors are summarized in Tables 2 through 4. Since we have a large number of trade variables, we only present trade results that are statistically significant. Of our measures of value at risk, agricultural value added as a share of GDP captures the relative importance of agriculture in the economy. We found this to be positively correlated with the probability of FMD outbreak. That is, countries in which agriculture is a major sector—largely low-income developing countries—were more likely to experience FMD outbreaks than countries in which agriculture accounts for a small share of GDP. Our second measure of value at risk, the livestock production index, was selected as a measure of the development of a country's livestock industry. We found this to be negatively correlated with disease outbreaks. Countries in which agricultural productivity was rapidly increasing were less likely to experience FMD outbreaks than countries in which agricultural output was stagnating. We return to the interpretation of these findings in the next section.

As expected, the weaker the 'disease-free' designation of a country, the more likely it was to experience FMD outbreaks. As the designation of a country moved from being disease-free with (1) and without (2) vaccination, to possessing disease-free zones with (3) and without (4) vaccination, to disease-free delisting (5), the risk of reporting an outbreak increased. Again, it should be noted that the 'disease-free' status is a designation given by the OIE - it does not necessarily mean the absence of the disease within a country. Of the measures that serve as proxies for the existence of wild reservoirs of FMD in a country — the control of wild reservoirs and zoning — both were significant and positively correlated with the probability of an outbreak. In countries that actively pursue these control measures, it is likely that the disease is endemic in either wild or domesticated species populations, which presents a source pool of disease that may spread to commercial livestock. Indeed, in countries that possess disease-free zones with an endemic population, the control and isolation of endemic wild animals is a concern warranting considerable attention (Jori et al., 2009). Monitoring was positively correlated with the probability of FMD outbreaks for much the same reason.

We had expected precautionary biosecurity measures to be negatively correlated with disease outbreaks. We found a strong negative correlation between the density of veterinarians and FMD outbreaks, albeit significant only at the 10 per cent level, and that border precautions were essentially uncorrelated with FMD outbreaks. We discuss the implications of these findings later.

We expected the probability of outbreaks to be increasing in imports of animals (and animal products) from countries in which FMD is endemic or currently present. Our results generally confirm this. Some regions are safer trading partners than others. Imports from regions experiencing no outbreaks are negatively correlated with the probability of outbreaks. What we had not expected to find was how much the riskiness of trade depends on the size of the markets involved. North America is a statistically significant source of import risks, despite the fact that the region has not had an FMD outbreak in over 50 years (Metcalf and McElvaine, 1995). Nor had we expected to find the differences between species to be as regionally specific as they are. From a global perspective, imports of cattle from North America, the Caribbean, Southern Europe, Melanesia, and Polynesia are all positively correlated with the probability of an FMD outbreak, as are pigs from Central and Southern Asia and sheep from Southern Asia and Western Europe. By contrast, imports of cattle and sheep from Northern and Southern Africa respectively, imports of pigs from North America and Australia and New Zealand, and sheep from the Caribbean, Eastern and South-Eastern Asia, and Northern and Southern Europe are all negatively correlated with FMD.

We had less well-defined expectations about the indirect effect of exports on disease risks. Globally, we found exports of cattle to Southern Africa, North America, the Caribbean, and Eastern Europe to be positively associated with disease outbreaks. Exports of pigs to Southern Asia and sheep to Central and Eastern Asia, Northern Europe, and Polynesia were also positively correlated with FMD outbreaks. On the other hand, exports to many countries were negatively correlated with FMD outbreaks: cattle to Central Asia, Northern Europe, and Australia and New Zealand; and pigs to Eastern and Western Africa, North America, the Caribbean, and Eastern Europe. For both imports and exports, we found that the probability of disease associated with trade varied by species. For instance, for Southern Europe the importation of cattle was positively associated with disease, while the importation of sheep was not. We can see a similar story in the importation of cattle and pigs in North America. These trends only partly reflect the fact that certain species are more likely to transmit the disease than others (Alexandersen et al., 2003). For example, on average pigs require much greater exposure to the virus in order to contract the disease, but produce a heavier viral shed than cattle or sheep (Alexandersen et al., 2003).

Based on these results we then calculated the trade-related FMD risk by region, multiplying the relative probability of disease occurrence by the value at risk. Using the United States in 2011 as example, we present two potential values of the economic relative risk: the value of exports of livestock (sum of all cattle, sheep, pigs) and the contribution of the agricultural sector to GDP. These approximate the lower and upper bounds to risk. The results are reported in Table 5. Note that negative risk, in this context, implies that an increase in trade with a particular region will reduce the likelihood of disease outbreaks. That is, it implies the mitigation of risk. Positive risk, by contrast, implies that an increase in trade with a particular region will increase the likelihood of disease outbreaks. The risk as measured by foregone live animal export earnings (lower bound) is relatively minor. The risk as measured by output in the whole agriculture sector (upper bound) may be quite large.

DISCUSSION

The disease risks of trade depend both on the structure and volume of trade in risk materials, on the biosecurity measures undertaken by trading partners, and on interactions between the two. As we had expected, we found a generally positive relation between the volume of live animal imported from riskier regions and the probability of a disease outbreak. This is the most intuitive and transparent trade-related risk. Our findings in this respect are broadly consistent with others (Berentsen et al., 1992; Garner and Lack, 1995; Hartnett et al., 2007; Martinez-Lopez et al., 2008; Miller et al., 2012; Schoenbaum and Disney, 2003). Our methods are different. Berentsen et al. (1992), Garner and Lack (1995), and Schoenbaum and Disney (2003), for example, use simulations in a coupled epidemiological-economic framework. Hartnett et al. (2007), Martinez-Lopez et al. (2008), and Miller et al. (2012), ground their analysis in data, as we do, but rely on stochastic simulation to determine the probability of introduction using a much smaller range of trading partners. Nevertheless our estimates of import risk often reach the same conclusions. These results are not always intuitive. For instance, imports of cattle from the North American region are positively associated with the probability of FMD introduction. Given that the United States has not experienced an FMD outbreak since 1929 (Metcalf and McElvaine, 1995), and that Canada has not experienced an outbreak since 1952 (Sellers and Daggupaty, 1990), the risks associated with trade in this case have to be indirect. Interestingly, others have found a similar effect. Miller et al. (2012), for example, found that the probability of FMD introduction to the United States from Canada, for example, was 0.048%.

We had fewer expectations about the indirect impact of exports on disease risk. As we indicated earlier, there is some evidence that sending livestock transport vessels into high-risk areas may itself be a source of risk, but the indirect impacts of trade on disease risk also include the risks associated with complex vessel itineraries. Vessels that undertake shipments to the USA from some port, for example, may return to that port via a number of others. The associated risk depends more on the trade network than biosecurity conditions in the USA. Hence we found that aside from high-risk regional destinations, such as Polynesia or Southern Africa, the greatest risks were associated with exports to regions characterized by high trade volumes and a complex trade network—Europe, North America, and East Asia.

We also found that the type of livestock matters. Different species are associated with different risks in different places. In addition to differences in the maintenance and care of species in different places, different species have different degrees of susceptibility and infectivity to FMD, though the exact nature of this relationship is debated (Alexandersen et al., 2003; Sutmoller et al., 2003). It has been well documented that pigs may often tolerate much larger dosages of virus compared to cows and sheep before contracting the disease, and that they excrete virus in larger quantities than the latter two species (see Alexandersen et al. (2003) for a review of this literature). However, some researches argue that though cows may have a lower excretion of the virus per unit body mass than pigs, their sheer size makes them excrete far greater quantities of virus and a much larger risk factor for spreading FMD (Sutmoller et al., 2003). These factors will play a role in the risks associated with the transport of each species.

The relationship between relative economic risk, livestock species, and income is illustrated in Figure 1. This distinguishes the marginal relative economic risk of a percentage change in the volume of either imports or exports of cattle, sheep, and pigs by region, in relation to per capita regional GDP. Imports and exports of a species by region, indicated by red or black markers, are risk-increasing if positive or risk reducing if negative. So imports of sheep by East Asia increase the relative risk of FMD outbreaks in that region, exports of sheep from East Asia reduce relative risk. Although the greatest impact of imports and exports on relative economic risk, both positive and negative, are associated with low-income regions where biosafety may be lax, the impact on risk in high-income regions where trade volumes are high can still be significant.

To interpret our findings on the relation between disease outbreaks and biosecurity measures, note that several of the measures tested are themselves evidence for the existence of wild FMD reservoirs in the country. The control of wild reservoirs, zoning, and monitoring are all activities that take place in countries where participation in the international live animal trade is conditional on maintaining disease free compartments. Since the existence of wild reservoirs increases the risks to a country's trading partners, it is not surprising that these activities are positively and significantly related with disease outbreaks.

The two biosecurity measures tested, the density of veterinarians and precautions at the borders, were both expected to be increasing in the value at risk, and so to be negatively related to the probability of disease outbreaks. While the density of veterinarians was indeed negative, we found that the existence of protective measures at the border was uncorrelated with the probability of FMD outbreaks. The implication is that current border measures are, on average, ineffective in reducing FMD risk.

Our analysis does have its limitations. For instance, aggregating trading partners into the FAO regions loses a certain degree of spatial resolution. This potentially matters if the sanitary conditions and regulations pertaining to the surveillance and monitoring for disease are very different between member countries. In addition, the trade-related sources of disease risk extend beyond the live animal trade. The FMD virus is capable of persisting in the environment for extended periods of time ranging from weeks to months depending on the nature of the contaminated material (manure, bedding, fodder, clothing, equipment) and environmental conditions (temperature, humidity, pH) (Alexandersen et al., 2003; Callis, 1996; Paton et al., 2010; Ryan et al., 2008; Sutmoller et al., 2003). Therefore it would be useful to consider the trade in other risk materials that may potentially spread FMD, including meat, hides, and skins.

In response to a FMD outbreak, the "natural" response by an importing country is to impose trade bans on high risk products from the exporting country with FMD (Grubman et al., 2008). The World Trade Organization makes available information of the initialization, length, and termination of trade sanctions between countries in response to food and mouth outbreaks. In order to explicitly account for changes in trade networks, we hope to include this data in future analyses.

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Table 1. Summary of outbreak data and independent variables.

Variable	Units	Mean	St. Dev.	Min	Max
FMD outbreak	binary	0.34	0.47	0	1
Agriculture value added	current US$	110.97E8	369.17E8	2802446	734.91E9
Livestock production index	-	99.07	17.04	36.15	236.08
Veterinarian density	$\#/km^2$	0.29	2.12	8.58E-7	53.03
Disease free status	categorical	0.468	0.79	0	4
Control of wild reservoirs	binary	0.06	0.23	0	1
Monitoring	binary	0.26	0.44	0	1
Precautions at the border	binary	0.60	0.49	0	1
Zoning	binary	0.19	0.40	0	1
Stocks, cattle	# heads	8256939	2.49E7	5	2.13E8
Stocks, pigs	# heads	5673672	3.43E7	0	4.76E8
Stocks, sheep	# heads	6591824	1.70E7	420	1.78E8

The livestock production index is a unit less index of the aggregate volume of production of a country's livestock sector compared to a baseline (in this case, the production between 2004-2006).

Table 2. Logistic regression estimates of exogenous variables.

Variable	Estimate	p-value
Agriculture value added	3.74E-11	0.005
Livestock production index	-0.026	0.089
Veterinarian density	-21.91	0.105
Disease free status	1.43	0
Control of wild reservoirs	1.99	0.009
Monitoring	1.41	0.01
Precautions at the border	-0.36	0.63
Zoning	2.38	0.003
Stocks, cattle	1.72E-09	0.895
Stocks, pigs	-2.99E-08	0.047
Stocks, sheep	1.53E-08	0.74
Constant	-6.05	0.01
N	1271	
Psuedo log-likelihood	-252.75	
AIC	715.49	
BIC	1255.99	

Table 3. Logistic regression trade estimates from imports.

	Variable	Estimate	p-value
Importing from:	*Cattle*		
	Northern Africa	-0.004	0.047
	North America	0.001	0
	Caribbean	0.056	0.008
	Southern Europe	0.002	0.043
	Melanesia	0.027	0.013
	Polynesia	0.225	0.006
	Unspecified	-0.001	0.017
	Pigs		
	North America	-0.001	0.095
	Central Asia	0.038	0.04
	Southern Asia	0.671	0.001
	Australia and New Zealand	-0.014	0.01
	Sheep		
	Southern Africa	-0.002	0.001
	Caribbean	-0.088	0.011
	Eastern Asia	-0.001	0.017
	Southern Asia	0.002	0.044
	South-Eastern Asia	-0.003	0.037
	Northern Europe	-0.001	0.006
	Southern Europe	-0.003	0
	Western Europe	0.001	0.006
	Unspecified	-0.006	0.001
	European Union	-0.004	0

Table 4. Logistic regression trade estimates from exports.

	Variable	Estimate	p-value
Exporting to:	*Cattle*		
	Southern Africa	0.001	0.002
	North America	0.047	0.023
	Caribbean	0.072	0.032
	Central Asia	-0.002	0
	Eastern Europe	0.004	0.006
	Northern Europe	-0.003	0.026
	Australia and New Zealand	-0.112	0.015
	Pigs		
	Eastern Africa	-0.003	0.024
	Western Africa	-0.002	0.042
	North America	-0.045	0.001
	Caribbean	-2.265	0.084
	Southern Asia	0.023	0.001
	Eastern Europe	-0.001	0.019
	Sheep		
	Central Asia	0.001	0.097
	Eastern Asia	0.001	0.003
	Northern Europe	0.006	0.023
	Polynesia	0.734	0.003

Table 5. Relative economic risks (RER) of trade.

	Variable	Estimate	Odds ratio	Δ Odds (%)	United States RER (lower) (million US$)	United States RER (upper) (million US$)
Importing from:	*Cattle*					
	N. Africa	-0.004	0.996	-0.393	-1.631	-760.276
	N. America	0.001	1.001	0.099	0.409	190.886
	Pigs					
	North America	-0.001	0.999	-0.072	-0.297	-138.372
	Central Asia	0.038	1.039	3.915	16.246	7574.485
	Australia and New Zealand	-0.014	0.986	-1.405	-5.828	-2717.421
	Sheep					
	Eastern Asia	-0.001	0.999	-0.064	-0.266	-124.143
	Western Europe	0.001	1.001	0.130	0.539	251.509
Exporting to:	*Cattle*					
	Eastern Europe	0.004	1.004	0.426	1.766	823.281
	Northern Europe	-0.003	0.997	-0.265	-1.100	-512.882
	Pigs					
	Western Africa	-0.002	0.998	-0.215	-0.891	-415.631
	Eastern Europe	-0.001	0.999	-0.062	-0.258	-120.354
	Sheep					
	Eastern Asia	0.001	1.001	0.100	0.415	193.558
	Northern Europe	0.006	1.006	0.569	2.361	1100.626
	US value of exports (1000 US$)	414945				
	US agriculture value added (1000 US$)	193461490				

Relative economic risk (RER) is calculated as the product of the relative probability of FMD outbreak and the magnitude of potential damages. The relative probability of disease outbreak is given by the change in the odds. The magnitude of the potential damages of FMD outbreak is taken as the value at risk. We tested two measures of value at risk, creating a lower and upper bound on the relative economic risk: the value of all exports of cattle, pigs, and sheep (lower bound), and the value of the agriculture sector (upper bound). RER is from the perspective of the United States in 2011. We interpret the RER as, from a global perspective, the dollar value of risk associated with a one percent increase in imports to/exports from a partner region. Positive values indicate the acquisition of additional risk; negative values indicate risk mitigation.

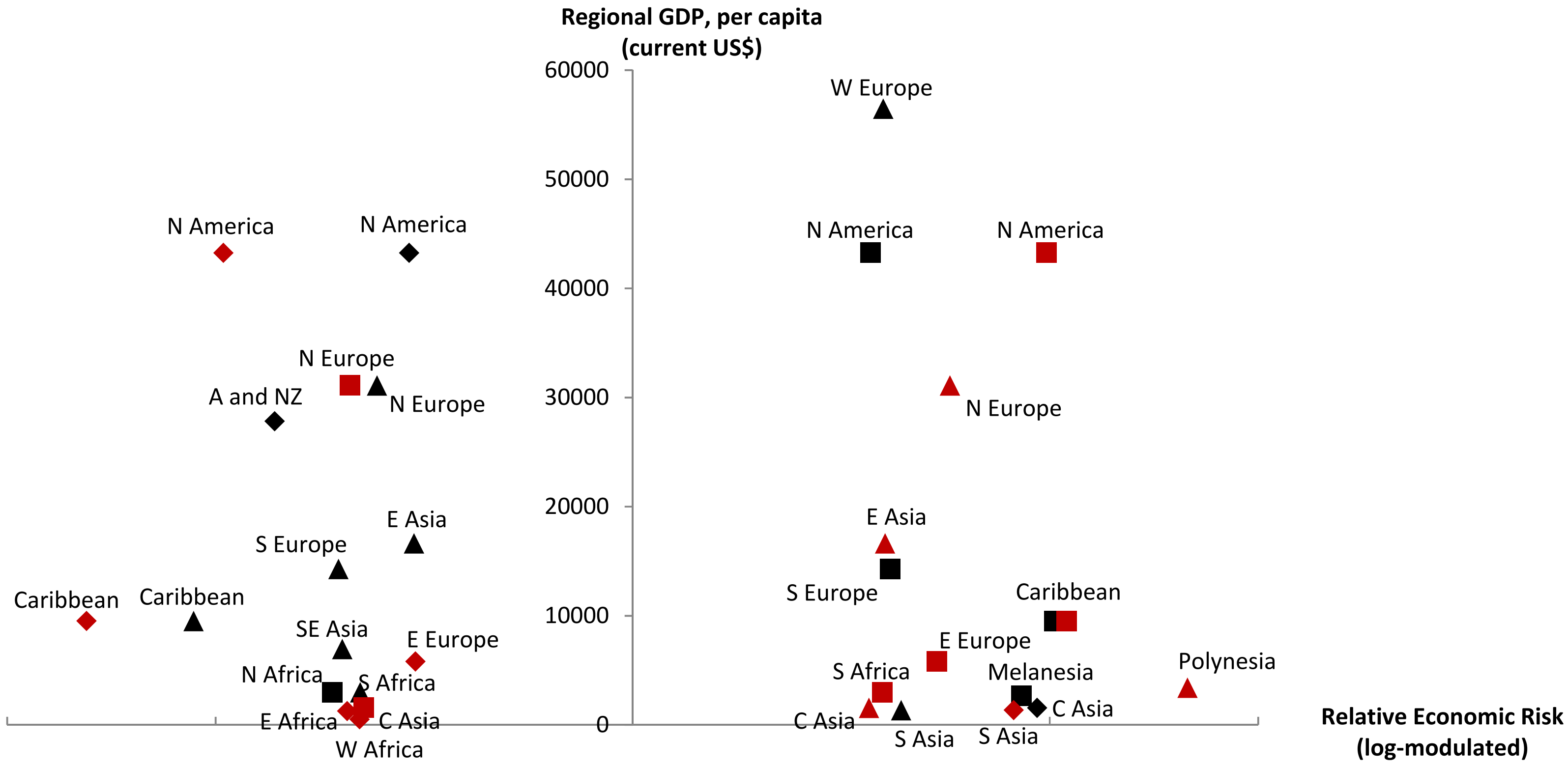

Figure 1. Regional GDP per capita versus relative economic risk. Regional GDP is the average GDP per capita of all nations within a region averaged over the study period (1996-2011). Relative economic risks have been log-modulated. Marker color indicates imports (black) or exports (red), while the species is given by the marker shape (square, cattle; diamond, pigs; triangle, sheep). Regions are labeled next to their corresponding marker.