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Illicit animal trade and infectious diseases

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ABSTRACT

Can evasionary practices in the commercial trade of live animals spread infectious animal diseases? We analyze the link between discrepancies in the traded value of live animals that are reported by partner countries – a proxy measure which has been used in the trade literature to uncover evidence on smuggling across items like antiques, cultural property, or natural resources – and infectious animal diseases. The results imply that a 1% increase in illicit live animal trade is associated with a 0.3% to 0.5% rise in infection cases in animals, which is driven by evasionary practices like species mis-classification and under-pricing. Crucially, we demonstrate that robust border inspections effectively curb these risks, offering a practical tool to combat the spread of animal diseases through illicit live animal trade.

1. Introduction

Globalization has accelerated the trans-border movement of live animals. The number of globally traded livestock doubled, from one to two billion specimen, between 2007 and 2017 (FAO data). According to veterinarians and epidemiologists, transporting live animals worldwide spreads disease-causing pathogens leading to costly outbreaks (Gómez & Aguirre, 2008; Fèvre et al., 2006; Beltran-Alcrudo et al., 2019). Communicable livestock diseases were estimated to have cost the global economy over US$ 80 billion since the mid-nineties (Karesh et al., 2005). Infectious diseases like Avian Flu, Rinderpest, Ebola and Chytridiomycosis have caused significant reductions in animal populations worldwide, and therefore threaten animal biodiversity (Engdawork, 2019). Further, there is a risk of infecting humans who come in contact with sick animals.[1] Due to the Covid-19 pandemic, the biosecurity risk from trade-related movement of live animals has emerged as a key concern for the international community.[2]

This paper studies illicit trade of live animals as a potential vector for spreading infectious animal diseases. Although both licit and illicit trade of live animals can transmit diseases, illicit trade carries a higher risk of spreading infections (Beltran-Alcrudo et al., 2019). This is because legal imports undergo standardized testing and quarantine procedures before entering the domestic market (Rappole & Hubálek, 2006). Illicit imports, on the other hand, can circumvent testing or quarantine protocols and are hence more likely to introduce pathogens in the local environment.

Anecdotal evidence suggests a potential link between illicit animal trade and infectious animal diseases. For instance, most cases of Brucellosis in sheep and cattle in Saudi Arabia are reportedly due to unscreened imports from Africa (Fèvre et al., 2006). Similarly, illicit wildlife trade is reportedly responsible for spreading pathogens like Avian influenza, Newcastle disease, or retroviral infections that can jump species barriers to infect wildlife, domestic animals, and human beings (Gómez & Aguirre, 2008). The illicit nature of such trade flows however implies that we do not have a credible estimate of the impact on local animal health, and whether policy measures can limit the spread of infectious diseases due to the illicit trading of live animals.

Using data on approximately ninety-five thousand disease outbreaks worldwide, we estimate the impact of illicit trade on the reported number of infected animals in the importing country. Through the description of animals affected in each outbreak, we match information on the number of infected animals to trade data on six four-digit product categories of live animals in the Harmonized System (HS) classification of traded products. Since illicit trade is not directly observable, we apply a proxy measure which is referred to as 'missing

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[1] In a list of 1,415 pathogens that can affect humans, about 60% are zoonotic, i.e. they are transmitted from animal species to humans (Karesh et al., 2005). International Livestock Research Institute (ILRI) (2012) estimated that some 56 zoonoses were together responsible for around 2.5 billion cases of human illness and 2.7 million human deaths a year.

[2] The 2021 *World Trade Report* (World Trade Organization (WTO), 2021), which reviewed the link between trade and natural or human-made disasters including Covid-19, acknowledged the potential role of livestock trade in transmitting diseases.

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imports' in the tariff evasion literature (Fisman & Wei, 2004). Missing imports estimates have been used previously to uncover evidence of smuggling of antiques, cultural property, and natural resources (Fisman & Wei, 2009; Vézina, 2015; Rotunno & Vézina, 2017). We compute missing imports through discrepancies in the value of live animal exports that are reported by all exporting countries to an importing country and the value of live animal imports reported by the importing country from all exporting countries. The dataset used for analysis covers about 130 countries and the six HS categories of live animals, over the period from 2004 to 2019.

The empirical analysis proceeds in several steps. We begin by making the case that missing imports are a suitable proxy for illicit trade in live animals, using two complementary approaches. We show that missing imports in live animals are positively correlated to import tariffs, which is highlighted as evidence for illicit trade in the tariff evasion literature (Fisman & Wei, 2004; Javorcik & Narciso, 2008; Rotunno & Vézina, 2012; Beverelli & Ticku, 2022). We further document a positive association between missing imports across all live animal categories and the number of illegally imported live wildlife specimen that are confiscated by customs agencies. Assuming that a proportion of illicit imports are seized by customs authorities, missing imports seem to capture illicit trade in live animals.

We next examine the relationship between missing imports and infections in related animal species. We document a positive association between missing imports and the number of infected animals in regression analysis that controls for unobserved importer-product and year characteristics, as well as accounts for importer-specific time trends that capture gradually evolving institutional change or the diffusion of disease-related knowledge. The association is also robust to controlling for local stock of animals in each HS4 product category, and country-level measures of economic development, economic geography, and customs quality. Our estimates imply that a 1% increase in missing imports is associated with a 0.3% to 0.5% increase in the number of infected animals among species that are included in a given HS4 product category.

The main challenge for causally interpreting these estimates stems from potentially omitted variables that vary within an importer-product over time. A key concern is that policy measures that restrict animal trade might be jointly correlated with illicit trade and infection cases. For example, import tariffs can affect disease outbreaks by curtailing the legal trade of live animals. However, there is also evidence that tariffs are positively correlated with missing imports (Fisman & Wei, 2004; Javorcik & Narciso, 2008; Rotunno & Vézina, 2012). Omitting import tariffs can lead to under-estimate the true effect of missing imports on infection cases. Similarly, measures to prevent the entry of infected animals into the country, through quarantine or certification requirements, or through border precautions, can also incentivize illicit trade of live animals. Another concern is that an importing country may systematically test its local animal stock for infections in product categories where it experiences higher evasion, which can bias our estimate upwards due to a detection effect. We collect data on different policy measures through which a country can restrict the trade of animal species or screen its animal stock for infections in a given product category, and show that the association between missing imports and infection cases is robust to controlling for the confounding policy variables.

A second source of endogeneity could be due to reverse causality, but the direction of bias is unclear. On the one hand, a surge in animal infections could reduce demand for import of associated animal products, which in turn would reduce the benefit of illicit trade (Yang, 2008; Javorcik & Narciso, 2017). The reverse causality would lead to under-estimate the true effect of missing imports on infection cases. On the other hand, prohibitive tariffs or import bans in response to infection surges might incentivize illicit trade (Vézina, 2015). The reverse causality due to a policy change would bias the effect of missing imports on infection cases upwards. We present additional evidence to alleviate concern of an upward bias in our estimate due to policy responses to infection surges. First, we show that our results are not sensitive to excluding observations where an import ban or prohibitive tariffs were likely introduced in response to an animal disease outbreak. Second, we perform a temporal placebo test where we show that current infection cases are not related to missing imports in the future. Third, we exploit an exogenous shock, the creation of the Golden Triangle Special Economic Zone (GT SEZ) at the international borders of Laos, Myanmar, and Thailand ('GT countries') in 2007, which facilitated the illegal trafficking of wild animals in its aftermath. We use a difference-in-differences setting to show that countries with a higher pre-treatment exposure to missing imports in wildlife from GT countries also recorded a higher number of animal infections in the short-term following the creation of the SEZ. The evidence is consistent with a causal effect of missing imports on infection cases.

A third concern is whether missing imports eventually are a good proxy for evasion by importers. Discrepancies in mirror trade statistics might arise due to differences in reporting across importers and exporters. For instance, exports are recorded as free on board (FOB) while imports include the cost of insurance and freight (CIF), and the recording convention may create discrepancies. Moreover, there is a concern that the discrepancies might arise specifically due to inaccurate reporting by exporters (Al Wazzan et al., 2023). We address the potential noise in our proxy measure in two ways. We show that the positive association between missing imports and infection cases is only observed in the sub-sample where imports are systematically under-reported compared to their mirror exports. This suggests we are not capturing a spurious correlation arising due to how exports and imports are respectively recorded.[3] We then apply a fixed-effects methodology used recently in the literature on firm-level trade, where we estimate the fraction of discrepancies that can be attributed to importers, after controlling for unobserved exporter characteristics that might contribute to overall discrepancies (Almunia et al., 2024). We show that the alternative measure of missing imports, which is independent of exporters' incentives to mis-report, is significantly related to the prevalence of infections in the importing country.

We then turn to the mechanisms and ask which evasionary practices in commercial live animal trade can explain the relationship between missing imports and infection cases. Practices such as mis-classification of species and mis-declaration of consignment value are identified in the criminology literature as some of the methods through which live animal species are trafficked (Wyatt et al., 2018). Incidentally, the tariff evasion literature has developed proxies to measure evasion through mis-classification across product categories or through the under-reporting of consignment value (Fisman & Wei, 2004; Javorcik & Narciso, 2008; Rotunno & Vézina, 2012). We find that missing imports are associated with higher infection cases in live animal categories that are likely to be mis-classified to evade taxes. We also find evidence that missing imports are associated with higher infection cases in live animal categories where evasion can take place through under-reporting of unit prices. We next assess policy interventions that can moderate the effect of missing imports on infection cases. We find that border inspections that are performed to prevent the introduction of animal diseases are effective in limiting the spread of infectious animal diseases through illicit live animal trade.

This paper contributes to the literature on trade and health. Early empirical literature had postulated that income gains from globalization and international trade would raise global health standards (Dollar, 2001; Owen & Wu, 2007).[4] However, human history is replete with

[3] The discrepancy due only to reporting differences should imply that imports are systematically larger than exports since they also include the cost of insurance and freight.

[4] Contrary to this view, recent evidence points to the harmful link between food imports and obesity (Giuntella et al., 2020). Recent studies also highlight the adverse effects of trade liberalization on health through the income and labor market channels (Colantone et al., 2019; Adda & Fawaz, 2020).

examples of international commerce enabling the spread of communicable diseases (Harrison, 2012; Boerner & Severgnini, 2014). A few papers recently have studied the link between contemporary trade practices and communicable diseases through the lens of human mobility. For instance, Oster (2012) finds that exports facilitated the incidence of HIV in Africa. She interprets the result to suggest that higher exports increase the movement of people in the logistics sector, which facilitates transmission of disease through sexual activity. Similarly, Lin et al. (2022) interpret the link between China's WTO accession and the subsequent spread of severe acute respiratory syndromes (SARS) to suggest that mobility driven by trade expansion spreads diseases. Ticku and Beverelli (2023) use an exogenous surge in demand for imported livestock in Islamic countries during Eid-al-Adha to show that livestock trade is significantly related to the spread of infectious animal diseases in importing countries. Antràs et al. (2023) provide a generalized framework to study the link between globalization and pandemics, where trade-related human mobility affects the spread of diseases across countries. In contrast to these studies, we provide evidence that illicit practices used in trading of live animals can be directly responsible for spreading infectious diseases. Closer to this research, Borsky et al. (2020) focus on international wildlife trade and find that stringency of trade agreements decreases the number of animals traded and therefore the potential of spreading zoonotic diseases. Our analysis however shows that measures restricting international trade of animals might not be effective in curtailing disease transmission if illicit trade practices are rampant.

There is also qualitative research outside economics that studies the role of licit and illicit trade channels in spreading infectious animal diseases (Karesh et al., 2005; Fèvre et al., 2006; Chomel et al., 2007; Pavlin et al., 2009; Smith et al., 2012; Beltran-Alcrudo et al., 2019). We only know of one study that quantifies the impact of infectious diseases introduced in the European Union via channels such as legal trade of animals and meat, illegal trade, pets, human travel, and windborne vectors (Simons et al., 2019). The authors use unpublished statistics of seizures from the United Kingdom's border agency to proxy illegal imports into the European Union. Seizures data might however not capture illegal imports well because they are endogenous to the quality of customs enforcement. In contrast, our empirical analysis employs a proxy of illicit trade that has been used in the economics literature to proxy smuggling across various items, and captures more precisely the link between illicit trade of animals and diseases outbreak worldwide.

Our work also complements the development literature that identifies how livestock contributes to household welfare (Collishaw et al., 2023). Livestock serves as a critical asset for households, helping to prevent poverty traps (Lybbert et al., 2004; Santos & Barrett, 2011; Diwakar & Shepherd, 2022); and insulating against unexpected income shocks (Deaton, 1991; Acosta et al., 2021). Further, livestock products are a vital source of food security and nutrition (Murphy & Allen, 2003), which are essential for child development (Headey et al., 2018). Our work identifies a novel trade-related mechanism that leads to livestock mortality, which has significant implications for household welfare.

2. Background: infection risk from illicit trade in live animals

Illicit trade in live animals typically occurs in the form of tax evasion in large commercial imports, import of illegal wildlife, and informal import for personal use (Beltran-Alcrudo et al., 2019). The first category involves commercial enterprises that engage in tax avoidance by entering the country through under-staffed port locations, or through deliberate falsification of cargo shipments. The falsification can occur through mis-classification of species to a similar variety with lower tariff, or by declaring lower values or lesser volumes. Mis-classification across species can circumvent border control measures which are introduced in anticipation of a specific infectious disease. For instance, a consignment of 'domestic chicken' that is mis-labeled as 'other live birds' may escape testing and quarantine protocols to avoid introducing a disease that affects poultry. Significant variation in tariff rates across similar looking live animals can also incentivize bundling of different species that can enable the spread of pathogens (Wyatt et al., 2018). Moreover, the falsification of consignment details can occur by declaring lower values or lesser volumes, which can reduce the possibility of inspection by customs officials (Wyatt & Cao, 2015). This should especially be the case if customs officials systematically inspect consignments of a higher value to maximize tariff revenue.[5]

The second category of illicit animal trade involves smuggling of illegal wildlife, such as of endangered animal species whose trade may be prohibited, but is highly lucrative due to their value as exotic pets or their utility in traditional medicine (Van Uhm, 2016). Common practices that involve smuggling of illegal wildlife include mis-labeling illegal wildlife as legally traded, declaring 'wild caught animals' as 'captive-breds', and obtaining certificates from corrupt officials (Van Uhm, 2016). There are also instances where a legal shipment of live animals is mixed with protected illegal species to avoid detection (Wyatt, 2013), which can enable transmission of pathogens across species.[6] The close contact with unscreened imported wildlife can pass on pathogens to native wildlife, domestic animals, and humans (Karesh et al., 2005).

Third, there are small-scale operations where animals are imported into the country through concealment in passenger luggage (Beltran-Alcrudo et al., 2019).[7] Such methods can particularly expose humans to zoonotic diseases.

The qualitative evidence presented in this section highlights the relationship between illicit trade in live animals and the spread of infectious animal diseases. The various forms of illicit imports discussed above can lead to disease outbreaks in destination countries, through eluding monitoring protocols, transmitting pathogens amongst different varieties of animal specimen, as well as through creating a close proximity between infected animals and human beings. The empirical methodology that we discuss next focuses on the evasionary practices in commercial trade of live animals, and their association with the spread of infectious animal diseases.

3. Empirical strategy

We construct a dataset that covers about 130 countries and the six live animal categories at the heading (four-digit) level of the Harmonized System (HS) classification: 0101 (horses, asses, mules and hinnies); 0102 (bovine animals); 0103 (swine); 0104 (sheep and goats); 0105 (poultry, fowls of the species Gallus domesticus, ducks, geese, turkeys and guinea fowls); and 0106 (live animals not elsewhere classified). We focus on the period from 2004 to 2019, for which data on animal diseases are available. This section discusses the empirical strategy to estimate the link between illicit import of live animals and

[5] Even in a country with advanced customs administration like the United States, only 25% of wildlife shipments that are declared at the border are inspected (Williams & Grante, 2009). Customs officials are likely to inspect more valuable consignments to ascertain their true value, in order to maximize import tariff revenues. Under-staffing of trained officials is an issue. The US Fish and Wildlife Service (FWS) is in charge of monitoring or detecting illicit trade in endangered species, invasive species, or regulated wildlife. In 2006 the FWS had posted a mere 112 wildlife officials at 38 ports of entry across country. In that year about 185,000 shipments were declared across US ports (Williams & Grante, 2009).

[6] The mixing of a legal consignment of animals with an illegally imported monkey, which eventually brought a deadly virus into the United States, is the premise of a Hollywood blockbuster movie, 'Outbreak'.

[7] The first recorded case of Highly Pathogenic Avian Influenza (HPAI) in the European Union was in a live eagle from Thailand, transported in a hand luggage, and seized at Brussels International Airport in October 2004 (Borm et al., 2005).

the spread of infectious animal diseases in the destination country. The following section describes the variables' construction and the data sources.

3.1. Baseline specification

The empirical specification to estimate the impact of illicit import of live animals on the spread of infectious animal diseases takes the following form:

$$Infections_{jkt} = \exp\left(\beta mi_{jkt} + \boldsymbol{\gamma}'\mathbf{z}_{jkt} + \lambda_{jk} + \mu_t\right) + \epsilon_{jkt} \quad (1)$$

where the dependent variable, $Infections_{jkt}$ is defined as the total number of infection cases specific to live animals in HS heading k during year t across all locations within each importing country j.

We use a count data model since the dependent variable is the count of animals infected. Specifically, we estimate the model using a Poisson pseudo-maximum-likelihood estimator (PPML), which is identical to a fixed effects Poisson model, but can also deal with clustered standard errors. Disease outbreaks, in fact, can exhibit both serial and spatial auto-correlation. Therefore, we cluster standard errors at country-level and year-level to permit valid inference if errors are auto-correlated within country, as well as within years across countries (Cameron et al., 2011).[8] Another advantage of the PPML estimator is that it provides a natural way to deal with zeroes in the dependent variable (Santos Silva & Tenreyro, 2006).[9]

The main explanatory variable, mi_{jkt} (missing imports), measures illicit trade in live animals, which is not directly observable. We follow the literature on tariff evasion and proxy missing imports through discrepancies in mirror trade statistics for live animals that are reported by partner countries.[10] We compute the discrepancies as the difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category k in year t (X_{jkt}) and the log value of imports (augmented by one) reported by importer j from all countries (M_{jkt}):[11]

$$mi_{jkt} \equiv \ln\left(1 + X_{jkt}\right) - \ln\left(1 + M_{jkt}\right) \quad (2)$$

The discrepancies in mirror trade statistics are a noisy measure that could arise due to factors other than smuggling, potentially giving rise to a measurement bias. We detail the sources of noise in Section 5.3. In Section 5.1 we present a battery of evidence suggesting that missing imports are indeed a suitable proxy for illicit trade in live animals, while in Section 5.3 we show that results are robust to alternative ways of estimating missing imports to alleviate issues of mis-measurement.

The vector $\mathbf{z}_{jkt}$ in Eq. (1) includes control variables that vary along all dimensions of the data (policy measures to contain the spread of infections and the stock of animals) or within country over time (income, economic geography, and other institutional characteristics). The model also includes importer-product fixed effects (λ_{jk}) and year fixed effects (μ_t).

The coefficient of interest in Eq. (1) is β, which measures the elasticity of infection cases to missing imports.

[8] In a robustness exercise discussed in Appendix Section G, we cluster standard errors at the country level for inference if errors are only auto-correlated within country.

[9] In the baseline regression of column (1) of Table 2, out of 6,021 observations, the dependent variable has 4,351 zeros and 1,670 positive integers.

[10] Morgenstern (1950) and Bhagwati (1974) were the first to suggest that discrepancies in mirror trade statistics could be due to illicit transactions in international trade. Recent evidence shows that imports are systematically under-reported compared to their mirror exports at higher import tariffs, which provides evidence for evasionary practices in commercial trade (Fisman & Wei, 2004; Javorcik & Narciso, 2008; Beverelli & Ticku, 2022).

[11] In a robustness exercise discussed in Appendix Section G, we show that adding a small constant (or zero), rather than one, to the value of exports and imports before taking logs does not affect the results.

4. Data

This section describes the main variables and their sources.

4.1. Dependent variable

We obtain data on animal diseases from FAO's EMPRES Global Animal Disease Information System (EMPRES-i). The database contains daily information on the outbreak of thirty-two animal diseases, which is obtained from the World Organization for Animal Health (OIE) and the national health agencies.[12] The data comprise of approximately ninety-five thousand disease outbreaks that occurred worldwide during the period from 2004 to 2019. The database records the number of animals of a species infected by a specific disease outbreak, and its consequences in terms of animal fatalities as well as the human response in the form of slaughtering infected animals. The analysis focuses on recorded infection cases since both animal deaths and subsequent human actions are likely to be determined by country-specific institutional characteristics.

Out of the thirty-one diseases with confirmed cases in EMPRES-i, the OIE classifies fifteen diseases as affecting a single class of species, fourteen diseases as affecting multiple species, and two as 'other diseases' (see Appendix Table A-1). While it is straightforward to match diseases that affect a single species to an HS4 live animal category, it is complicated to match diseases that affect multiple species. To overcome this challenge and precisely assign diseases to an animal category k (four-digit HS heading), we use descriptions of the species affected by each outbreak that are available in the raw data. The matching strategy is discussed in Appendix Section A.

All infection cases specific to live animals in HS heading k during year t are summed within each country j, which yields a dependent variable, $Infections_{jkt}$, which varies by importing country, HS heading, and year. The infection cases are aggregated at the jkt dimension to ensure consistency with trade data.[13] The dependent variable is set to zero if no cases were reported in any location of country j in HS heading k and year t.[14]

4.2. Other variables

To construct missing imports (see Eq. (2)), we source trade data from UN COMTRADE, which are available annually in thousand US dollars at the country level for the entire sample period.

We further collect data for several control variables that vary across the importer-product-year (jkt) and importer-year (jt) dimensions. Among variables that vary across the jkt dimension, we include four policy measures that can be associated with a disease outbreak. Our first measure is the Most-Favored-Nation (MFN) tariff imposed by importing country j on product k in year t. We obtain tariff information from UNCTAD TRAINS and WTO IDB.[15] The next three measures are,

[12] Out of the thirty-two diseases in EMPRES-i, one disease (Rinderpest) is only observed in unconfirmed cases. We exclude all unconfirmed cases from the dataset to reduce measurement error. This leads to the exclusion of Rinderpest from the sample.

[13] Trade data are reported by a country each year for an HS product category. While trade data are available at a finer level than a four-digit product classification, it was only feasible to match animal diseases to the four-digit live animal categories.

[14] In Appendix Table A-7, we present a sensitivity check relaxing the assumption that the dependent variable is set to zero if no infection cases were reported, i.e., without replacing missing values with zeros.

[15] We refer to WTO IDB if data is missing in UNCTAD TRAINS. There are gaps in coverage across countries, sectors and years. We do not attempt to fill these gaps, except in the rare cases in which, within each jk combination, two identical tariffs rates in years $t-1$ and $t+1$ respectively precede and follow a missing value in year t. In such cases, we replace the missing value with the value reported in $t-1$ and $t+1$.

respectively, the number of precautions at the border, the number of screening measures, and the number of surveillance measures that were issued by importer j on HS heading k in year t.[16] Border precautions are applied at the border posts to prevent the introduction of a disease into the country and can range from quarantine, certification of health status in the exporting country, details on the zone or herd of origin of the imported animal, or testing of animals before loading the consignment. Screening measures are diagnostic tests carried out systematically either within the framework of a control programme for the disease, or for qualifying herds/flocks as free from the disease. Surveillance measures continuously investigate a given population to detect the occurrence of disease for control purposes, and may involve testing a part of the population. Besides policy measures, we also collect data on the stock of animals in importer j in product category k in year t. The data are obtained from FAOSTAT.

The control variables which vary at the jt dimension include GDP per capita in current US$ (in logs), sourced from IMF's World Economic Outlook (WEO) data, April 2021 edition; the quality of port infrastructure, sourced from the World Economic Forum's Global Competitiveness Report; remoteness;[17] control of corruption, from the World Bank's World Governance Indicators; an OECD membership dummy; and trade openness, i.e. the ratio of trade to GDP, sourced from the Quality of Governance Institute.

In some estimations we exclude observations with emergency SPS measures to address the issue of reverse causality. To this end, we construct the variable 'Emergency import ban', a binary variable equal to one if the importing country j imposed an emergency SPS measure to stop importing product k in year t from any partner country. The variable is constructed from textual analysis of WTO Integrated Trade Intelligence Portal (I-TIP) data.[18]

Appendix Table A-4 describes all variables used in the empirical analysis, while Appendix Table A-5 presents the in-sample summary statistics.

5. Results

5.1. Missing imports as a proxy for illicit live animals trade

We begin by making the case that missing imports are a suitable proxy for illicit trade in live animals. Fig. 1 graphically illustrates the relationship between missing imports and import tariffs in raw data. The right-skew in the distribution of missing imports at high tariff rates suggests that imports are systematically under-reported in comparison to exports when tariffs are high, suggesting tariff-motivated evasion in the commercial trade of live animals. Appendix Figure A-2 shows a similar right-skew in missing imports at higher tariffs across live animal product categories.

We next use two empirical tests to assess whether missing imports are a suitable proxy for illicit trade. We use the intuition from the tariff evasion literature, which concludes that a positive association between missing imports and import tariffs captures evasionary behavior.[19] Further, we hypothesize that illicit imports are positively correlated with the number of confiscated live animal specimen at customs. Our hypothesis is in line with studies of other illicit behaviors, such as illegal migration (Friebel et al., 2024), that use apprehensions to proxy illegal activity. We expect to find a positive association between missing imports and the number of confiscated specimen.

Columns (1)–(2) of Table 1 estimate the effect of MFN tariffs on missing imports by OLS, respectively excluding or including additional controls (border precautions, screening measures, and surveillance measures). These specifications control for importer, HS4 product, and year fixed effects. We find a positive association between MFN tariff and missing imports. The effect is statistically significant at 5% level. The point estimate implies that a one percentage-point increase in tariff rate is associated with a 0.12% increase in missing imports.[20] The estimated tariff semi-elasticity of missing imports in live animals is comparable to but slightly smaller in magnitude than tariff semi-elasticities estimated in recent studies covering a large set of countries and an exhaustive list of product categories.[21]

In columns (4)–(5) of Table 1 we estimate the relationship between missing imports and the number of confiscated animal specimen using a PPML specification, where we control for importer and year fixed effects.[22] The coefficient is positive and statistically significant at 5% level. We find that missing imports (in number of units) are positively correlated with the number of animals that are confiscated by the customs. The point estimate of column (3) implies that a 1% increase in missing imports is associated with a 0.46% increase in the number of confiscated animal specimen.

Taken together, the evidence presented in this section justifies using missing imports as a proxy for illicit imports of live animals.

5.2. Missing imports and infection cases

Column (1) of Table 2 reports the association between missing imports and infection cases, after controlling for importer-product and year fixed effects. The effect is positive and statistically significant at 1% level. The point estimate implies that a 1% increase in missing imports is associated with a 0.4% increase in the number of infection cases.

Next, we control for several variables that might jointly determine illicit imports and the spread of diseases. Policy measures that aim to limit the introduction of animal diseases by restricting trade of live

[16] The data on border precautions, screening, and surveillance measures are obtained from the OIE. The raw data contain information both on the type of disease and on the species affected (Birds; Buffaloes; Camelidae; Cats; Cattle; Cervidae; Dogs; Equidae; Goats; Rabbits; Rabbits/hares; Sheep; Sheep/goats; Swine). The matching with HS headings is straightforward.

[17] This is computed, for country j in year t, as the weighted sum of bilateral distances between j and each foreign country i, with weights given by i's share of world GDP in year t. Data on bilateral distances are from CEPII's *GeoDist* (Mayer & Zignago, 2011), while GDP data are from IMF WEO.

[18] The WTO SPS Agreement does not require WTO members to notify every SPS measure. The general notification obligations of Annex B of the agreement apply only when an international standard, guideline or recommendation does not exist, or the content of a proposed SPS regulation is not substantially the same as the content of an international standard, guideline or recommendation (in the case of animal health and zoonoses, the standards, guidelines and recommendations of reference are those developed by the OIE), and if the regulation may have a significant effect on trade of other Members. The data on import bans we collect through WTO I-TIP, therefore, do not necessarily cover all emergency SPS measures imposed by WTO members. Other non-tariff measures (NTMs) available across countries on World Bank World Integrated Trade Solution (WITS) cannot be used in this study because they are recorded only as of 2012 (2010 for the European Union).

[19] Importers have a higher incentive to under-report import value relative to the true value, which is proxied through exports, at higher import tariffs. Hence the gap between exports and imports should widen with an increase in import tariffs.

[20] Appendix Figure A-3 shows that the estimated tariff semi-elasticity is robust to excluding live animal product categories individually.

[21] Beverelli and Ticku (2022) estimate a tariff semi-elasticity of 0.2 to 0.3% in a sample that includes over 120 countries and around 5000 HS6 product categories during the years 2012, 2015 and 2017. Bussy (2023) estimates a tariff semi-elasticity of 0.16% in a sample that spans 197 countries and around 5000 HS6 product categories during the years 1988–2017.

[22] We calculate missing imports in unit quantities rather than in values as the confiscation variable is measured in number of units instead of consignment value. The data on confiscated specimen are obtained from the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) Trade Database. The additional controls of column (4) are averages across HS4 products within importer-year.

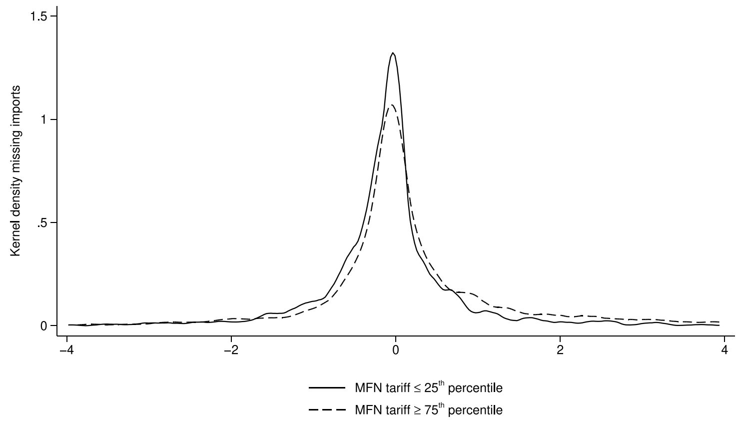

Fig. 1. Import tariffs and illicit trade in live animals. *Notes:* For exposition clarity, the Kernel densities of missing imports are shown for values of missing imports between the 1st and the 98th percentile (respectively, −4 and 4). Missing imports is the difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category (HS heading) k in year t, and the log value of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. MFN tariff is the Most-Favored-Nation tariff imposed by importing country j on live animal category k in year t, sourced from UNCTAD TRAINS and (in case of missing information) from WTO IDB.

animals might be correlated with infection cases and illicit trade. For instance, import tariffs can reduce disease incidence through curtailing licit trade of live animals. The positive relationship between import tariffs and missing imports is also well established in the tariff evasion literature (Fisman & Wei, 2004; Javorcik & Narciso, 2008; Rotunno & Vézina, 2012). Omitting import tariffs can therefore lead to underestimating the true effect of missing imports on infections. Similarly, countries might implement behind-the-border measures such as screening (i.e. testing) and surveillance (i.e. continuous investigation), in anticipation of or in response to evasionary practices at the border, for example when border controls are ineffective at curbing such trade, or even encourage it. Enhanced screening or surveillance is also likely to be correlated with the reported infection cases through restricting legal trade or through improved detection. Import demand can also be correlated with the local animal stock, which in turn might determine the number of infection cases. Country characteristics such as the level of economic development, trade openness, and the quality of port infrastructure are also potential confounders, as they could be correlated with missing imports and with the number of infection cases. Poor quality of port infrastructure, in particular, might incentivize evasion by raising trade costs, as well as increase infections among imported livestock through poor handling or by increasing the time of clearance. Furthermore, a country's remoteness to international trade can also simultaneously impact illicit trade and the introduction of infectious animal diseases.[23]

In column (2) of Table 2 we control for five measures, which vary along all the three dimensions of the data (jkt), as well as six country-level measures to address the omitted variable bias. The jkt measures include the MFN tariff rate, border precautions, screening measures, surveillance measures, and the stock of animals in an HS4 category that is available in a country in a given year. The country-level controls include GDP per capita, the quality of port infrastructure, the country's remoteness to international trade, the control of corruption, an OECD membership indicator, as well as a measure of trade openness. The coefficient of interest β is robust to the inclusion of these confounding variables, and the magnitude is higher than the estimate in column (1).

In columns (3) and (4) of Table 2 we additionally include country-specific linear time trends to control for gradually evolving country-specific omitted variables such as trade liberalization or diffusion of disease-related knowledge.[24] The magnitude is only slightly reduced to 0.27–0.5. Finally, in columns (5) and (6) we use a saturated model, where we control for omitted factors related to short-term changes within importing country and within product category by including importer-product, importer-period and product-period fixed effects, where period corresponds to the years 2004–2006, 2007–2009, 2010–2012, 2013–2015 and 2016–2019 respectively.[25] The point estimates are robust to estimating a more demanding specification. Overall, Table 2 highlights a robust positive association between our measure of illicit imports and infection cases in the destination country.

Before discussing the causal interpretation of our findings, we perform two key checks on our baseline estimations. First, we assess if there is significant product-level heterogeneity in the association between missing imports and animal infections. Appendix Figure A-4 shows that the association between missing imports and infection cases is the strongest in live animal product categories 0101 (horses, asses, mules and hinnies), 0105 (poultry), and 0106 (live animals not elsewhere classified). Second, we check if the baseline results are sensitive to alternative model and data specifications. Appendix Table A-7 shows that our results are robust to alternative model and data specifications.

5.3. Identification issues

Omitted variable bias. The inclusion of several controls and fixed effects addresses the concern that omitted time-varying factors within an importer and within a product might be driving our results. To further bolster our results, we conduct a placebo test where we randomly assign

[23] A country's remoteness can be related to missing imports in two ways: in remote countries it might just be costlier to evade using alternative entry routes, and trading in live animals is likely to experience high iceberg costs. Both can explain the discrepancies in mirror trade statistics. Remoteness is also likely linked to infection cases, although the sign of the relationship is ambiguous ex ante. On the one hand, remote countries can be protected from the introduction of virulent pathogens. On the other hand, local animal species might be more susceptible to the introduction of new pathogens. For a discussion of the ambiguous links between a country's exposure to international mobility and expected harm from epidemics, see Clemens and Ginn (2020).

[24] In a robustness exercise we also included sector-specific linear time trends alongside country-specific linear time trends. The results, available in the replication package, are similar to those in columns (3)–(4) of Table 2.

[25] The inclusion of a more conservative specification with importer-product, importer-year and product-year fixed effects leads to an asymptotic bias in the coefficient of interest, which arises from estimating many parameters in PPML-FE with three-way fixed effects. The issue is discussed in detail in Online Appendix Section E.

Table 1
Missing imports as a proxy for illicit trade.

Dependent variable	Missing imports		Confiscated (qty.)	
	(1)	(2)	(3)	(4)
MFN tariff	0.001**	0.001**		
	(0.001)	(0.001)		
Border precautions		0.000		−0.051
		(0.003)		(0.116)
Screening measures		−0.005		−0.222
		(0.005)		(0.157)
Surveillance measures		−0.003		0.174
		(0.005)		(0.116)
Missing imports (qty)			0.457**	0.380*
			(0.212)	(0.215)
Model	OLS	OLS	PPML	PPML
R-squared	0.200	0.200		
Importer FE	Yes	Yes	Yes	Yes
Product FE	Yes	Yes	No	No
Year FE	Yes	Yes	Yes	Yes
No. of importers	146	146	68	68
Years included	2004–2019	2004–2019	2004–2019	2004–2019
Observations	9159	9159	985	985

Notes: *p < 0.10, **p < 0.05,***p < 0.01. Dependent variable in columns (1)–(2): difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category (HS heading) k in year t, and the log value of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. Dependent variable in columns (3)–(4): number of imported units of live wildlife specimen confiscated by the customs authority in importing country j in year t, sourced from the CITES Trade Database. MFN tariff is the most favored nation tariff imposed by importing country j on live animal category k in year t, sourced from UNCTAD TRAINS and (in case of missing information) from WTO IDB. Missing imports (qty) is the difference between the log quantity of exports (augmented by one) reported by all exporting countries to importing country j, averaged across all live animal HS headings (0101, 0102, 0103, 0104, 0105, and 0106), in year t, and the log quantity of imports (augmented by one) reported by importing country j from all countries, averaged across all live animal HS headings (0101, 0102, 0103, 0104, 0105, and 0106), in year t, sourced from UN COMTRADE. Border precautions is the number of precautions at the border issued by importing country j on diseases affecting live animal category k in year t, averaged within jt across k, sourced from the OIE-WAHIS database. Screening measures is the number of diagnostic tests conducted by importing country j on diseases affecting live animal category k in year t, averaged within jt across k, sourced from the OIE-WAHIS database. Surveillance measures is the number of continuous investigation measures implemented by importing country j on diseases affecting live animal category k in year t, averaged within jt across k, sourced from the OIE-WAHIS database. Standard errors clustered at the importer and year level in parentheses. Products (HS headings) included in columns (1)–(2): 0101, 0102, 0103, 0104, 0105, and 0106.

missing imports across product categories within the same importer-year, and estimate a specification that corresponds to column (1) of Table 2 after excluding observations where the random assignment matches the correct assignment. As shown in Appendix Figure A-6, the effect of missing imports across incorrectly assigned product categories converges to zero. The close to zero effect of missing imports across incorrectly assigned product categories, even when the importer-year dimension is held constant, suggests that omitted time-varying country-level variables are unlikely to drive the relationship between missing imports and infection cases.

It is also plausible that our results are driven by omitted exporter side characteristics. If one or more exporting countries are experiencing a disease outbreak, it might incentivize their traders to under-report exports, to circumvent border precautions imposed by the importer. This would imply a negative correlation between infections in the exporting countries and missing imports.[26] Countries whose trading partners are experiencing a disease outbreak, in turn, might be more likely to import infected animals and therefore report a higher number of infected animals. Omitting the exporter side outbreaks might thus lead us to under-estimate the true effect of missing imports on animal infections. To alleviate this concern, we conduct a robustness check where we use bilateral trade data to control for exposure to infections in partner countries, measured by the trade-weighted average of infections across all countries exporting live animals to j in year t.[27] Appendix Table A-8 shows that the results are robust to adding this control.[28]

Reverse causality. Another challenge for causal identification is potential reverse causality, specifically if infection cases affect illicit trade. The direction of the bias due to reverse causality is however unclear. On one hand, more infections could reduce illicit trade. This is because animal disease outbreaks may result in a decline in import demand for related species.[29] According to the theory of tariff evasion, the benefit from mis-representing consignment value is a positive function of the size of imports (Yang, 2008). Disease prevalence is therefore likely to reduce missing imports in associated animal specimen through its negative impact on import demand. This reverse causality feedback would lead to under-estimate the elasticity of infection cases to missing imports, implying that our estimates are a lower bound of the true effect.

On the other hand, a disease outbreak could result in a policy response that restricts the legal inflow of imports, such as through prohibitive taxes or import bans. There is evidence that trade restrictions can incentivize illicit trade in associated goods (Vézina, 2015). The potential reverse causality through this mechanism would bias our estimates upwards. To address this concern, we present sub-sample analyses where we alternatively exclude all observations where country j imposed an emergency Sanitary and Phytosanitary (SPS) measure, or all observations where j imposed prohibitive tariffs, on live animal product k in year t in response to a disease outbreak. These are plausibly the cases where missing imports are most likely to respond to a policy change due to more infections. Excluding these observations should therefore alleviate concerns of an upward bias in our β estimate due to potential reverse causality. Table 3 presents estimates from sub-sample analyses where we exclude all observations with SPS emergency ban (panel (a)), or with prohibitive tariff (panel (b)).[30] The results shown in each column can be compared to the corresponding column in Table 2. The association between missing imports and infections is robust even after excluding observations where the upward bias due to reverse causality is most plausible.

[26] Missing imports are measured as the difference between exports reported by partner countries and imports reported by the importing country. The under-reporting of exports, by construction, would result in smaller values of missing imports.

[27] The trade weights are computed for the beginning of the sample (year 2004) from FAO's Detailed Trade Matrix.

[28] We also check whether missing imports underestimate illicit trade for countries that share boundaries with their exporters, if some trade flows bypass customs. We do not find evidence that missing imports are systematically underestimated when countries have a higher share of border exporters. Further, we assess whether there is any differential impact of missing imports on infectious diseases between countries which are proximate to their exporters and more geographically isolated countries. We control for the interaction between missing imports and the share of border exporters. While missing imports remain positive and statistically significant, their interaction with the share of border exporters is statistically not different from zero. The results are available in the replication package.

[29] Appendix Figure A-1 provides the example of the Netherlands. Cattle imports fell sharply in 2001–2002 due to the emergence of the mad cow disease (BSE) and the Foot and Mouth Disease (FMD) (Achterbosch & Döpfer, 2006), and it took another couple of years for imports to return to the pre-outbreak levels.

[30] Prohibitive tariffs are defined as tariffs above the 95th percentile of the distribution of MFN tariffs within each country. Results are unaffected if the 99th percentile is used instead of the 95th percentile of the distribution of MFN tariffs within each country to define prohibitive tariffs.

Table 2
Baseline estimations.

	(1)	(2)	(3)	(4)	(5)	(6)
Missing imports	0.395***	0.564***	0.266*	0.508***	0.381*	0.518**
	(0.135)	(0.170)	(0.147)	(0.171)	(0.203)	(0.218)
MFN tariff		0.236***		0.218***		0.078**
		(0.069)		(0.083)		(0.035)
Border precautions		−0.138*		0.002		−0.111
		(0.081)		(0.058)		(0.146)
Screening measures		0.156		0.027		0.315*
		(0.144)		(0.089)		(0.164)
Surveillance measures		−0.073		−0.112		0.009
		(0.116)		(0.121)		(0.172)
Live animal stock		−0.854		0.078		−1.195
		(0.908)		(1.968)		(2.652)
GDP per capita		−1.012		1.003		3.145**
		(1.248)		(2.275)		(1.285)
Quality of port infrastructure		0.477		0.496		2.205**
		(0.714)		(1.320)		(1.063)
Remoteness		0.002		0.003		0.004**
		(0.001)		(0.002)		(0.002)
Control of corruption		2.809**		4.929**		3.019
		(1.142)		(2.029)		(2.296)
OECD membership		4.001**		6.606**		−6.138***
		(2.016)		(2.685)		(0.587)
Trade openness		−0.014		−0.017		0.038
		(0.015)		(0.027)		(0.042)
Importer-product FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	No	No
Importer-specific time trend	No	No	Yes	Yes	No	No
Importer-period FE	No	No	No	No	Yes	Yes
Product-period FE	No	No	No	No	Yes	Yes
No. of importers	136	116	136	116	135	113
Years included	2004–2019	2006–2018	2004–2019	2006–2018	2004–2019	2006–2018
Observations	6021	4031	6021	4031	5045	3386

Notes: *p < 0.10, **p < 0.05,***p < 0.01. PPML regressions. Dependent variable: number of observed animal infection cases by importing country j, live animal category (HS heading) k and year t ($Infections_{jkt}$), sourced from FAO's EMPRES Global Animal Disease Information System (EMPRES-i). Missing imports is the difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category k in year t, and the log value of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. MFN tariff is the Most-Favored-Nation tariff imposed by importing country j on live animal category k in year t, sourced from UNCTAD TRAINS and (in case of missing information) from WTO IDB. Border precautions is the number of precautions at the border issued by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. Screening measures is the number of diagnostic tests conducted by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. Surveillance measures is the number of continuous investigation measures implemented by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. GDP per capita is the log of country j's GDP per capita in year t, sourced from IMF's World Economic Outlook (WEO). Quality of port infrastructure is country j's quality of port infrastructure in year t, sourced from the World Economic Forum's Global Competitiveness Report. Live animal stock is the log of one plus the stock of live animals in importing country j in live animal category k in year t, sourced from FAOSTAT. Remoteness is the weighted sum of bilateral distances between importing country j and exporting country i (sourced from CEPII's *GeoDist* database — see Mayer & Zignago, 2011), with weights given by i's share of world GDP in year t (sourced from IMF WEO): $Remoteness_{jt} \equiv \sum_i \left(GDP_{it}/\sum_i GDP_{it}\right) Dist_{ij}$. Control of corruption, varying by country (j) and year (t), sourced from the World Bank's World Governance Indicators. OECD membership is a dummy equal to one if country j is member of the OECD in year t. Trade openness is the ratio of trade to GDP of country j in year t, sourced from the Quality of Governance Institute. Standard errors clustered at the importer and year level in parentheses. Products (HS headings) included: 0101, 0102, 0103, 0104, 0105, and 0106. Periods in columns (5)–(6): 2004–2006, 2007–2009, 2010–2012, 2013–2015, 2016–2019.

We also address the issue of reverse causality more generally by performing a temporal placebo test similar to Oster (2012), where we show that current infection cases are not related to future missing imports. We use a specification that regresses the number of new infection cases in year t on missing imports in year t, along with missing imports in year $t+1$ to year $t+3$. Appendix Figure A-5 shows the effect of contemporaneous and future missing imports on infection cases. We find that the contemporaneous effect of missing imports continues to be statistically significant and it is conspicuously larger in magnitude than the lead effects, which are not precisely estimated.

Measurement issues. The measurement of illicit trade is ridden with potential error. A discrepancy in the values of mirror trade statistics can arise as exports are recorded in free on board (FOB) terms, while imports are calculated including the cost of insurance and freight (CIF). If discrepancies in mirror trade statistics simply reflect differences in how exports and imports are reported, their association with infection

Table 3
Estimations in subsamples.

	(1)	(2)	(3)	(4)
	(a) Excluding emergency import bans			
Missing imports	0.368*** (0.132)	0.624*** (0.152)	0.299** (0.152)	0.601*** (0.143)
Importer-product FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Importer-specific time trend	No	No	Yes	Yes
Additional controls	No	Yes	No	Yes
Years included	2004–2019	2006–2018	2004–2019	2006–2018
No. of importers	135	116	135	116
Observations	5679	3840	5679	3840
	(b) Excluding prohibitive tariffs			
Missing imports	0.404*** (0.139)	0.564*** (0.170)	0.265* (0.161)	0.508*** (0.171)
Importer-product FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Importer-specific time trend	No	No	Yes	Yes
Additional controls	No	Yes	No	Yes
No. of importers	130	116	130	116
Years included	2004–2019	2006–2019	2004–2019	2006–2019
Observations	5473	4031	5473	4031

Notes: $^{*}p < 0.10$, $^{**}p < 0.05$,$^{***}p < 0.01$. PPML regressions. Dependent variable: number of observed animal infection cases by importing country j, live animal category (HS heading) k and year t ($Infections_{jkt}$), sourced from FAO's EMPRES Global Animal Disease Information System (EMPRES-i). Missing imports is the difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category k in year t, and the log value of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. Additional controls of columns (2) and (4): MFN tariff, Border precautions, Screening measures, Surveillance measures, Live animal stock, GDP per capita, Quality of port infrastructure, Remoteness, Control of corruption, OECD membership, and Trade openness. Standard errors clustered at the importer and year level in parentheses. Products (HS headings) included: 0101, 0102, 0103, 0104, 0105, and 0106.

cases might be spurious. It is reasonable to think that some systematic components of such discrepancy are absorbed by fixed effects, and therefore are not correlated with the errors. For instance, freight and insurance cost may systematically differ across animal categories. Such systematic differences are accounted for by importer-product fixed effects.[31] To investigate whether the positive association between missing imports depends on the way data are reported, in Appendix Table A-9 we provide analysis by sub-sample of missing imports. We show that the positive association between missing imports and infection cases is only found in the sub-sample where exports are larger than imports, i.e., if imports are systematically under-reported, and not in the sub-sample where exports are smaller than imports, which is likely to occur because imports are inclusive of insurance and freight costs. These results suggest that we are not merely capturing a spurious correlation between discrepancies in mirror trade statistics and infection cases in live animals arising from how exports and imports are recorded.

Discrepancies in the value of mirror trade statistics could also arise due to incorrect reporting by the exporters. To address this concern, in the spirit of Almunia et al. (2024), we use a measure of missing imports which isolates the importer's contribution to discrepancies, after controlling for the unobserved characteristics of its partner countries that might contribute to their mis-reporting of export values. Specifically, we construct a measure of missing imports that is based on bilateral trade data and recovers the importer's contribution to discrepancies after controlling for the unobserved characteristics of its partner countries. As detailed in Appendix Section I, we proxy missing imports as the vector of importer-product-time fixed effects in two alternative models in which bilateral missing imports are the dependent variable. In a first model, following the logic of Almunia et al. (2024), we control for exporter (i) fixed effects — thereby assuming that exporter characteristics that potentially affect mis-reporting do not vary over time or across products. In a second model, we control for bilateral distance (a proxy for transport costs) between countries, and exporter-product-year (ikt) fixed effects, thereby assuming that exporter characteristics that affect mis-reporting could vary across time and products.[32] The results of the estimation of Eq. (1) which uses the importer-product-time fixed effects from these alternative models as missing imports are shown in Appendix Table A-10. The estimated elasticity of infections to missing imports remains positive, and the magnitude is quantitatively larger than the elasticities in the baseline model of Table 2. Even though the sample size is reduced by more than 50% because missing imports could be estimated only for 85 importers in the first model, and 78 importers in the second model (versus 136 in Table 2), this effect is statistically significant.

More generally, one may wonder whether missing imports are a good proxy for illicit trade in live animals. In defense of our approach, there is evidence that discrepancies in mirror trade statistics capture illicit trade in a diverse set of items, such as antiques, timber and mineral products (Fisman & Wei, 2009; Vézina, 2015). Moreover, in Section 5.1, we have provided empirical tests that justify that missing imports are a suitable proxy for illicit trade in live animals.

To further corroborate a causal interpretation of the relationship between missing imports and infection cases, in the next subsection we provide case-study evidence exploiting an exogenous event that facilitated the illegal trafficking of wild animals in its aftermath, and we assess its contribution to the spread of infectious animal diseases worldwide.

5.3.1. Case study: Golden Triangle Special Economic Zone, illicit wildlife trade, and infection cases

In 2007, the Golden Triangle Special Economic Zone (GT SEZ) was created on a 3000 acre land that the Laos government leased for ninety-nine years to a casino tycoon-owned Chinese firm (Diana, 2017). The SEZ is located at the international borders of Laos, Myanmar, and Thailand, in a region that has historically been known for trafficking of narcotics, humans, and wildlife (Environmental Investigation Agency (EIA), 2015).[33] Since its creation, the lack of transparency and legal ambiguities in the SEZ have bolstered various illicit activities including the illegal trade of wildlife (Organisation for Economic Co-operation and Development (OECD), 2019), putting the GT SEZ under the spotlight as a major illegal wildlife trade hub.[34]

[31] Country-specific time trends, included in some estimations, further account for the systematic variation in missing imports within country, for instance due to gradual reforms affecting the logistics sector. Arguably, average distance shipped between exporter and importer is likely a key driver of the cost of insurance and freight (CIF), which is not captured by fixed effects. The inclusion of remoteness partly addresses this issue, because remoteness is a GDP-weighted average of bilateral distances.

[32] This approach not only addresses issues related to inaccurate reporting by exporters, but also and more generally issues related to any exporters' characteristics that might be correlated with missing imports.

[33] The issue of illicit trade in Special Economic Zones is a general one, which recently attracted attention even in the G20. In a communique dated 22 September 2020, the G20 Trade and Investment Ministerial Meeting guarded "against the risk of illicit trade" in SEZs. In particular, France noted that "counterfeiting, money laundering, drug smuggling or even illicit practices benefiting to terrorist groups might indeed take advantage of different legislations, legal loopholes or unseen practices taking place in SEZs", and the United States "noted concern that SEZs may attract the interest of criminal actors who want to take advantage of the relaxed oversight and softened customs controls to manufacture and distribute illicit goods". See http://www.g20.utoronto.ca/2020/G20SS_Communique_TIMM_EN.pdf.

[34] The animal species and their products traded in the SEZ include black bears, elephants, pangolins, rhinos, serows, tigers, and turtles (Environmental

Recently, environmental groups have led an effort to deter illegal wildlife trafficking from the GT SEZ. For instance, the Environmental Investigation Agency published a report in 2015 that described the SEZ as an "illegal wildlife supermarket" (Environmental Investigation Agency (EIA), 2015). The investigation spurred the Laotian authorities to conduct raids on four businesses selling illegal wildlife products inside the SEZ.[35] In 2018 the US Treasury imposed sanctions on the casino company that operates the SEZ, on accounts of drug, human, and wildlife trafficking, as well as for involvement in child prostitution.[36]

We hypothesize that the creation of the GT SEZ facilitated trafficking of wildlife into and out of Laos, Myanmar, and Thailand (henceforth 'GT countries'), at least in the first few years after the SEZ's inception, before attracting global civil society's scrutiny. Therefore, countries that were exposed to higher missing imports in wildlife from GT countries would also have experienced a short-term increase in infection cases following the creation of the SEZ.

Fig. 2 compares the evolution of infection cases in countries with a high exposure to missing imports in HS heading 0106, which contains wildlife, from GT countries to the evolution of infection cases in low exposure countries.[37] We consider all animal infection cases in HS chapter 01 since unscreened import of wildlife can transmit diseases to both native wildlife and domestic animals (Karesh et al., 2005). The infection cases in high exposure countries are similar to those in low exposure countries in years prior to the creation of the SEZ in 2007. From 2008 onward, high exposure countries experienced a significant increase in infection cases relative to the low exposure countries. The gap however tapers off after 2015, which is likely due to the increase in enforcement against illicit trafficking of wild animals from the SEZ.

The above discussion and the descriptive evidence from Fig. 2 motivate the following difference-in-differences (DD) specification with continuous treatment, where we estimate the effect of the SEZ on infection cases in importing countries, conditional on their pre-treatment exposure to missing imports in HS heading 0106 from GT countries:

$$Infections^{GT}_{jt} = \beta Exposure^{W}_{j} \times Post_t + \lambda_j + \mu_t + \omega_j t + \epsilon_{jt} \quad (3)$$

where $Infections^{GT}_{jt}$ is the count of infection cases in importer j in year t. $Exposure^{W}_{j}$ measures missing imports in HS heading 0106, which contains wildlife (therefore the W superscript), from GT countries in importer j in three years prior to the creation of the GT SEZ, 2004–06.[38] $Post_t$ is a dummy variable that equals one if $t \geq 2008$. The coefficient of interest β measures the increase in the number of infections following the creation of the SEZ, conditional on an importing country's prior exposure to missing imports from the GT countries.

The results from the DD specification are presented in Table 4. Columns (1), (3), and (5) report the results of estimations that include importer and year fixed effects. Columns (2), (4), and (6) report the results of estimations that include importer and year fixed effects, as well as country-specific linear time trends. The inclusion of country-specific linear time trends relaxes the common trend assumption and captures potential correlated trends between infection cases and illicit animal trade.

Table 4
Golden Triangle Special Economic Zone regressions.

Sample	2004–2010		2004–2013		2004–2019	
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure × post	0.615**	0.894*	0.913***	0.693*	1.025***	0.073
	(0.306)	(0.515)	(0.353)	(0.420)	(0.340)	(0.295)
Importer FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Importer-specific time trend	No	Yes	No	Yes	No	Yes
No. of importers	114	114	117	117	126	126
Observations	798	798	1170	1170	2016	2016

Notes: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. PPML regressions. Dependent variable: number of observed animal infections in live animals (HS 01) by importing country j and year t, ($Infections^{GT}_{jt}$), sourced from FAO's EMPRES Global Animal Disease Information System (EMPRES-i). Exposure is computed as missing imports in HS heading 0106 vis-à-vis 'Golden Triangle' (the sum of Laos, Myanmar, and Thailand), averaged in the pre-treatment period (2004–2006), by importing country j. Missing imports are the difference between the log value of exports (augmented by one) reported by Golden Triangle countries to importing country j in HS heading 0106 in year t, and the log value of imports (augmented by one) reported by importing country j from Golden Triangle countries in HS heading 0106 in year t, sourced from UN COMTRADE. Post is a dummy equal to one in the post-treatment period (from 2008 onward). Standard errors clustered at the importer level in parentheses.

In columns (1)–(2) we estimate the effect of GT SEZ over the period 2004–2010. This sample covers three years before and three years after the creation of the GT SEZ in 2007. The significant and positive coefficient on the interaction term suggests that countries with a higher prior exposure to missing imports in wildlife recorded a higher number of animal infections in the short-term following the creation of the SEZ. We obtain similar results in columns (4)–(6) when we extend the sample to the period until 2013. In columns (5)–(6) we consider the entire sample until 2019. In the full sample, the coefficient on the interaction term is greatly reduced, and the effect is statistically not different from zero when country-specific linear time trends are included.[39]

These results suggests that the creation of GT SEZ contributed significantly to the rise in infection cases in countries that were relatively more exposed to illicit imports in wildlife from Laos, Myanmar, and Thailand. However, this impact was relatively short-lived, perhaps due to the fact that illegal wildlife trade passing through the SEZ came under close scrutiny from civil society and national governments a few years after the SEZ was created.

Together, the results presented in this Section 5.3 support a causal interpretation, i.e., an increase in illicit imports in a given HS4 product category results in a higher number of infections in related animal species in the destination country.

6. Product vulnerabilities and policy interventions

6.1. Channels of illicit trade and infection cases

The tariff evasion literature identifies three channels through which evasion can occur. First, tariff evasion can occur through the misclassification of products, i.e., an importer could report a higher taxed product as a lower taxed variety (Fisman & Wei, 2004). Second, tariff

Investigation Agency (EIA), 2015; Gomez et al., 2016; World Wide Fund for Nature (WWF), 2017; Gomez & Shepherd, 2018; Organisation for Economic Co-operation and Development (OECD), 2019).

[35] A video is available at https://www.facebook.com/159023380915975/videos/485943378223972.

[36] "Treasury Sanctions the Zhao Wei Transnational Criminal Organization", US Department of the Treasury, 30 January 2018, available at https://home.treasury.gov/news/press-releases/sm0272.

[37] High exposure countries are those where average missing imports from the GT SEZ countries were in the top 50th percentile during the 'pre-treatment' period (2004–2006). Low exposure countries are those where missing imports from the GT SEZ countries were in the bottom 50th percentile during the same period.

[38] To construct $Exposure^{W}_{j}$, we treat the three GT SEZ countries, Laos, Myanmar, and Thailand, as a unique exporter i. We then compute missing imports in importer j in year $s \in [2004, 2005, 2006]$ in HS heading 0106 as $mi_{js} \equiv \ln(1 + X_{ejs}) - \ln(1 + M_{ejs})$. We finally compute the 2004–2006 average: $Exposure^{W}_{j} \equiv (1/3)\sum_s mi_{js}$. Note that there is no data availability before 2004 in the FAO's EMPRES-i database.

[39] We also estimated specifications that control for the number of border precautions by importing country j in year t affecting HS heading 0106. The results, available in the replication package, are similar to the ones reported in Table 4.

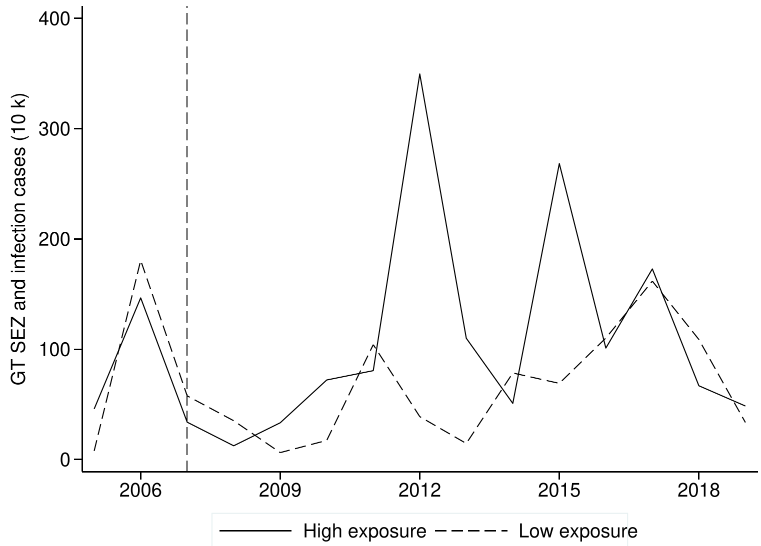

Fig. 2. Illicit trade from GT SEZ and infection cases. *Notes:* The vertical line represents 2007, the year when the Golden Triangle Special Economic Zone (GT SEZ) was created. High exposure countries are those where average missing imports from the GT SEZ countries were in the top 50th percentile during the 'pre-treatment' period (2004–2006). Low exposure countries are those where missing imports from the GT SEZ countries were in the bottom 50th percentile during the same period. For exposition clarity the trend in infection cases is depicted from 2005 onwards.

evasion can occur through the under-reporting of unit prices (Javorcik and Narciso, 2008; 2017). Finally, tariff evasion can occur through the under-declaration of product quantities (Rotunno & Vézina, 2012). Notably, the literature on corruption in animal trade (see Section 2) also identifies the mis-declaration of values and volumes or mis-classification of species as mechanisms of illicit trade in live animals (Wyatt et al., 2018). Theoretically, mis-assigning species type or under-reporting of quantities or prices can be a pathway for transmission of diseases to the extent they help to evade consignment checks.

Motivated by this literature, we investigate whether live animal product categories susceptible to mis-classification or under-reporting of prices drive the positive link between illicit trade and the spread of infectious animal diseases. It is important to note at the outset that we cannot estimate whether products susceptible to under-reporting of quantities show a stronger association between illicit trade and animal diseases. This is because the test proposed to identify this channel relies on variation in the way product quantities are recorded (Rotunno & Vézina, 2012).[40] In our dataset, the reporting on live animal product quantities is overwhelmingly consistent, with 93% of exports and 98% of imports measured in terms of the number of items. Constructing a product level binary variable to denote reporting units other than "number of items" is hence redundant.

To test whether illicit trade increases the spread of infectious diseases through mis-classification, we adopt two complementary approaches. In a first approach, we construct the dummy variable 'High MFN tariff w.r.t. HS 01', which equals one if the MFN tariff τ_{jkt} is larger than the average tariff on live animals (HS chapter 01) applied by importer j in year t, computed excluding HS heading k.[41] Intuitively, if this dummy variable is equal to one, a trader interested in minimizing tariff payment could mis-classify live animals across categories, declaring them as belonging to headings that are taxed less at the border. The 'High MFN tariff w.r.t. live animals' dummy variable is then interacted with missing imports. A positive coefficient on the interaction term would indicate that missing imports have a larger impact on the spread of infectious diseases in cases where traders have the incentive to mis-classify across live animal categories to evade import tariffs.

A concern with the 'High MFN tariff w.r.t. HS 01' dummy is that mis-reporting across different HS headings may not be feasible, because the HS headings are quite distinct categories of animals: it is hardly feasible to declare a horse a cow. We propose a second approach to address this issue, which relies on a comparison between the MFN tariff on HS heading $k \in [0101, 0102, 0103, 0104, 0105]$ and the MFN tariff in HS heading 0106 (live animals not elsewhere classified). The idea is that it may be feasible to mis-report live animals in 0101, 0102, 0103, 0104, and 0105 as live animals under HS heading 0106. For instance, 'Guinea fowls', which are classified in HS category 0105, might be mis-classified as 'other live birds' in HS category 0106. The dummy 'High MFN tariff w.r.t. HS 0106' takes value one if the MFN tariff applied on HS heading $k \in [0101, 0102, 0103, 0104, 0105]$ is larger than the MFN tariff on HS heading 0106. This dummy is interacted with missing imports. A positive coefficient on the interaction between this dummy and missing imports would indicate that missing imports have a larger impact on infectious diseases in cases where mis-classification is incentivized. The results on the mis-classification channel are presented in columns (1) and (2) of Table 5. The coefficient on the interaction term is positive and statistically significant in both columns, suggesting a higher incentive to mis-classify imported animals when tariffs on similar animal categories are lower. The result provides empirical support to the hypothesis that evasion through mis-classification is responsible for higher infections.

Next we assess whether evasion of live animals through under-pricing results in higher infection cases. Differentiated products are those whose prices may range widely due to difference in product quality, and hence it may be difficult for customs officials to detect under-pricing of the consignment (Javorcik & Narciso, 2017). To test the under-reporting of unit prices channel, we interact missing imports

[40] The underlying intuition is that evasion is easier when a consignment is recorded in the number of items instead of kilos.

[41] For instance, the tariff imposed by the importing country on live swine (HS heading 0103) is compared to the average tariff on other HS headings in chapter 01 (0101, 0102, 0104, 0105, and 0106). If it is larger than this average, the dummy takes value one. Note that such dummy varies along all the three dimensions of the dataset.

Table 5
Mechanisms.

Mechanism	Mis-classification		Under-reporting
	(1)	(2)	(3)
Missing imports	0.157* (0.081)	0.324*** (0.093)	−0.657** (0.305)
High MFN tariff w.r.t. HS 01	1.531*** (0.581)		
High MFN tariff w.r.t. HS 01 × Missing imports	0.524*** (0.177)		
High MFN tariff w.r.t. HS 0106		1.424 (0.881)	
High MFN tariff w.r.t. HS 0106 × Missing imports		0.200* (0.119)	
Differentiated HS heading × Missing imports			1.136*** (0.351)
Importer-product FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
No. of importers	130	133	136
Years included	2004–2019	2004–2019	2004–2019
Observations	5473	4814	6021

Notes: *p < 0.10, **p < 0.05,***p < 0.01. PPML regressions. Dependent variable: number of observed animal infection cases by importing country j, live animal category (HS heading) k and year t ($Infections_{jkt}$), sourced from FAO's EMPRES Global Animal Disease Information System (EMPRES-i). Missing imports is the difference between the log value of exports (augmented by one) reported by all exporting countries to importing country j in live animal category k in year t, and the log value of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. High MFN tariff w.r.t. HS 01 (live animals) is a dummy equal to one if the MFN tariff applied by importing country j in live animal category k in year t is larger than the average tariff on live animals (HS chapter 01) applied by importer j in year t, computed excluding HS heading k. High MFN tariff w.r.t. HS 0106 is a dummy equal to one if the MFN tariff applied by importing country j in year t on HS heading $k \in [0101, 0102, 0103, 0104, 0105]$ is larger than the MFN tariff applied by importing country j in year t on HS heading 0106 (Animals; live, n.e.c. in chapter 01). Tariff data are sourced from UNCTAD TRAINS and (if data are missing in that database) WTO IDB. Differentiated HS heading is a dummy equal to one if live animal category k is differentiated, based on the Rauch (1999)'s (conservative) classification (see Appendix Section J for details). Standard errors clustered at the importer and year level in parentheses. Importer-HS heading (jk) and year (t) fixed effects included in all specifications. HS headings included: 0101, 0102, 0103, 0104, 0105, and 0106 in columns (1) and (3); 0101, 0102, 0103, 0104, and 0105 in column (2).

with the 'Differentiated HS heading dummy'. As detailed in Appendix Section J, we exploit the Rauch (1999)'s (conservative) classification and classify HS headings 0102, 0103, and 0104 as homogeneous, and HS headings 0101, 0105, and 0106 as differentiated.[42] Results presented in column (3) of Table 5 show that the effect of the interaction term is positive and statistically significant at 1% level. The result suggests that evasion through under-reporting of unit prices is also responsible for higher infection cases.

6.2. Policy interventions

The discussion in Section 2 highlights that the disease impact of illicit trade in the form of evasionary practices in commercial trade of live animals is likely to depend on the restrictiveness of border and behind-the-border policy interventions to regulate the spread of infectious animal diseases. In this section, we explore whether such measures moderate the effect of illicit trade on animal diseases.[43] We use the variation in the intensity of border controls, i.e. the number of measures applied by country j in year t at checkpoints open to international movement of animals, where import inspections are performed to prevent the introduction of diseases affecting live animal category k. We also use the variation in intensity of behind-the-border measures, screening and surveillance respectively, that countries impose in a year to prevent the spread of diseases affecting live animal category k. We interact the missing imports variable with HS4 live animal-product-specific policy measures imposed by importing country j in year t, measuring the intensity of border precautions, screenings, and surveillance measures.

We hypothesize that more intense border controls and behind-the-border screening or surveillance moderate the relationship between missing imports and infection cases. The results presented in column (1) of Table 6 show that intensive border precautions mitigate the effect of missing imports on animal infections. On the other hand, the interaction term involving behind-the-border measures in columns (2) and (3) are negative but statistically not different from zero. Overall, our results suggest that border inspections that are performed to prevent the introduction of animal diseases moderate the role of illicit live animal trade in spreading infectious animal diseases.

[42] The Rauch classification is at the four-digit level of aggregation of the SITC Rev. 2 classification. Standard crosswalks, available at http://wits.worldbank.org/product_concordance.html, are used to concord it to the HS 2007 classification.

[43] We thank an anonymous referee for suggesting we explore the relationship.

Table 6
Policies to limit animal diseases.

	(1)	(2)	(3)
Missing imports	0.501***	0.455***	0.483***
	(0.123)	(0.148)	(0.142)
Border precautions	−0.040		
	(0.076)		
Border precautions × Missing imports	−0.025***		
	(0.008)		
Screening measures		0.134	
		(0.126)	
Screening measures × Missing imports		−0.028	
		(0.039)	
Surveillance measures			−0.060
			(0.112)
Surveillance measures × Missing imports			−0.019
			(0.024)
Importer-product FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
No. of importers	136	136	136
Years included	2004–2019	2004–2019	2004–2019
Observations	6021	6021	6021

Notes: *p < 0.10, **p < 0.05,***p < 0.01. Missing imports is the difference between the log quantity of exports (augmented by one) reported by all exporting countries to importing country j in live animal category k in year t, and the log quantity of imports (augmented by one) reported by importing country j from all countries in live animal category k in year t, sourced from UN COMTRADE. Border precautions is the number of precautions at the border issued by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. Screening measures is the number of diagnostic tests conducted by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. Surveillance measures is the number of continuous investigation measures implemented by importing country j on diseases affecting live animal category k in year t, sourced from the OIE-WAHIS database. Standard errors clustered at the importer and year level in parentheses. Products (HS headings) included: 0101, 0102, 0103, 0104, 0105, and 0106.

7. Conclusions

Outbreaks of infectious diseases in animal populations, and their associated harm, have grown in recent years. This has coincided with an increase in the cross-border movement of live animals. To date there is limited evidence on the role of trade-related international movement of live animals in spreading disease-carrying pathogens. This paper estimates the impact of evasionary practices in the commercial trade of live animals on animal disease outbreaks.

Evidence across 130 countries over a sixteen year period shows that evasionary practices in commercial live animal trade are systematically linked to infectious diseases in associated animal species. The relationship is predicated on the characteristics of animal categories which make them susceptible to customs evasion. We find that the link between illicit trade and infection cases is specifically present in imported animal species which are likely to be mis-classified or whose unit price is likely under-reported for tax evasion. Crucially, we demonstrate that robust border inspections effectively curb these risks, offering a practical tool to combat the spread of animal diseases through illicit live animal trade. Besides border inspections, measures which reduce tax evasion practices might also indirectly moderate the cross-border transmission of animal diseases. Trade facilitation reform that reduces the incentive for customs evasion is an example of such a policy.

In this paper we do not quantify the economic consequences of animal disease outbreaks. Future research can estimate these economic consequences, and consider the mediating role of within-country characteristics such as the local economic structure. This should help identifying the economic impact of animal disease outbreaks in a more causal way. The link between animal disease outbreaks and human health through income shocks is another topic for future research.

CRediT authorship contribution statement

Cosimo Beverelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rohit Ticku:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.worlddev.2025.106969.

Data availability

A full replication package is included in the supplementary material.

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