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EMERGING ZOONOTIC DISEASES AND THEIR IMPACT ON PUBLIC AND ANIMAL HEALTH

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Abstract

Zoonotic diseases are a major global health, animal health and economic concern with 75% of emerging infectious diseases coming from animals. This study employed a problem based research design to quantitatively assess the drivers, predictive performance, economic burden, and cost effectiveness of interventions for emerging zoonoses over the period 2000–2025. We applied a multivariate Poisson regression, random forest, gradient boosting, deep neural networks and an ensemble stacked model to outbreak data from 147 countries, environmental, anthropogenic and economic data. Our ensemble model showed the highest accuracy with deforestation and livestock density emerging as important spillover predictors. Economic burden analysis, based on an extended cost of illness framework, revealed that cumulative losses from major zoonotic events exceeded USD 2.5 trillion, with human mortality valuation and livestock losses exhibiting the highest elasticities. The per capita economic loss in low Crucially, enhanced One Health interventions proactive to outbreaks at 10% cost of reactive response averted 61 outbreaks in 10 years with a return on investment of 8.90 and an incremental cost

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INTRODUCTION

Zoonoses, that is diseases that can be transmitted from animals to humans, pose a serious worldwide health risk (Emerging zoonotic diseases: epidemiology, public health impacts, and the urgent need for a 'One Health' approach, 2025). In fact, 60% of all human pathogens are zoonotic and 75% of all emerging infectious diseases in humans are zoonoses (Quiroz-Castañeda, 2018). They also result in 2.5 billion cases and 2.7 million deaths each year, and significant economic losses globally (- & Basu, 2025). Zoonoses also play a crucial role in food security, including through decreased productivity of livestock, veterinary costs, supply chain disruption and loss of animal product markets (Bose & Kumar, 2025). This further impacts other social determinants such as food security, agricultural sustainability and economies, especially of low- and middle-income countries (Filho et al., 2022). Systems interconnectedness and globalised human activities also contribute to the borderless spread of pathogens and needs an interdisciplinary effort to track and control these diseases (Fiegler-Rudol et al., 2024; Rodríguez-Morales & Katterine-Bonilla-Aldana, 2024). This is particularly true with the emergence of zoonotic outbreaks, which are almost always driven by human activities like deforestation, wildlife trafficking and climate change ("Emerging Zoonotic Diseases: Epidemiology, Public Health Impact, and the Urgent Need for a Unified 'One Health' Approach", 2025). The complexity of these factors makes it challenging to predict and control zoonotic outbreaks (Sharan et al., 2023). The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic is only one example of the potential of zoonotic outbreaks to overwhelm health systems and generate economic consequences (an estimated USD 22 trillion lost in global GDP by 2025 and USD 2-3 trillion annually in health costs) (- & Basu, 2025). This suggests it is important to try to predict and prevent zoonotic disease outbreaks, which can cause serious disease, including death (Elsohaby & Villa, 2023). They also lead to considerable economic burden and consumers' confidence loss, in the agriculture sector (Mariasusai et al., 2025). Zoonoses can have significant economic impacts, in terms of both direct costs (related to disease and death) and indirect costs (to the tourism, agricultural and financial sector) (Alimi & Wabacha, 2023). For example, the Nipah virus outbreak in Malaysia and SARS outbreak in Asia and Canada was estimated to have cost $80 billion, highlighting the impact of the outbreak (Gurman et al., 2024). This includes the direct cost from the increased cost of veterinary fees, loss of income from decreased productivity of animals and loss of productivity from human illness (Pantha et al., 2025). Economic effects are also exacerbated by disruptions in the supply chain and markedly reduced demand for livestock products, due to perceptions of zoonotic diseases, and hence on cash flows and equity at the farm level (Abubakar, 2019; Bose & Kumar, 2025). Furthermore, zoonotic diseases are also a major socio-economic burden to the world, with a potential loss of US$3 trillion in the worst-case scenario of a pandemic (5% of world GDP) (Gebreyes et al., 2014). These economic impacts affect states and also households in terms of livelihoods and food security, especially in low- and middle-income countries where there seems to be a lack of proper surveillance and control of emerging zoonoses (Fiegler-Rudol et al., 2024). The socio-economic effects can range from the disruption of health-care systems, human lives lost and heavy financial losses at individual, community and national levels (Rodríguez-Morales & Katterine-Bonilla-Aldana, 2024). Multidisciplinary solutions are required to tackle these problems, involving human, veterinary and environmental scientists to better understand the emergence and spread of zoonoses (Belay et al, 2017). In fact, 60% of newly emerging infectious diseases in humans in the past two decades have been zoonotic, and therefore pose an ongoing threat to human health (Osterhaus et al 2020). As such, early warning and response programs are vital in lowering the growing risk of exposure to these pathogens (Elsohaby & Villa, 2023). Importantly, zoonotic disease prevention is also an economic imperative as more than $20 billion in direct costs and more than $200 billion in indirect costs, have been spent on zoonotic diseases in the last 10 years (Narrod et al., 2012). Despite the economic and health impacts, prevention in low- and middle-income countries is not well funded and often reactive rather than proactive as the recent COVID-19 pandemic has shown (Pantha et al., 2025). It can lead to a lag in the response and a greater impact on the health and well-being of affected communities (Abubakar, 2019). In this regard, a multifaceted, "One Health" approach with an emphasis on surveillance and monitoring for human, animal and environmental health is essential to inform preventative measures against the threat of zoonoses (Z. et al., 2022). Yet, despite the economic benefits of prevention, where the cost of prevention has been estimated to be as low as 10% of the estimated annual cost of zoonoses, a global strategy that focuses on detection and containment rather than prevention is practised (Deckers, 2023). This is also in the absence of funding and integrated health policies for prevention, in many countries, especially low- and middle-income countries (Adnyana et al., 2023; "Zoonosis of Public Health Interest", 2022). This favours responding to disease following spillover, rather than preventing factors contributing to emergence, leading to a reactive approach to disease control (Markotter et al., 2023). This indicates the need to shift from a reactive to a proactive approach with integrated, multidisciplinary measures, considering human, animal and environmental health, to prevent zoonotic spillovers, rather than respond to outbreaks (Naithani et al., 2024). This means zoonosis surveillance and prevention measures, under a "One Health" approach, need to be prioritised for prevention (Sharan et al., 2023). This "One Health" approach, which acknowledges the connections between human, animal and environmental health, is necessary to understand the risk factors for zoonotic outbreaks, to prevent their spread and development into pandemics (Naithani et al., 2024). But past measures have not recognised the links between environmental, animal and human health, and have therefore failed to prioritise environmental actions, and instead have prioritised detection, response and recovery measures after the event of spillover (Cáceres-Escobar et al., 2022). But the World Bank suggests early detection of zoonotic pathogens in the environment or in animals, and information sharing between human, animal and environmental surveillance programs, reduce the cost of outbreaks (Zinsstag et al., 2020). These measures, which are in accordance with One Health, are less costly than reactive measures with the cost of prevention being less than 1% of the economic cost of one year of pandemic (Bank, 2022). Understanding this, the One Health approach with the integration of human, animal and environmental health has been acknowledged as the optimal approach to reduce the risk of future pandemics (Cáceres-Escobar et al., 2023).

METHODOLOGY

This research follows a problem-based approach with the use of secondary data sources such as peer-reviewed articles, reports (World Bank, World Health Organisation, Office International des Epizooties) and open access epidemiological databases to describe the emergence and spread patterns and cross-sector implications of zoonotic diseases. This cross-sectoral and multi-disciplinary problem requires a synthesis of qualitative analysis of the policy and ecological factors, and quantitative modelling of economic and health impacts. The idea is to shift from a descriptive to a quantitative analysis framework to estimate the preventable fraction of zoonotic outbreaks under various intervention scenarios and thus solve the problem of reactive and/or proactive disease control.

A conceptual framework of zoonotic spillover is developed first, in which the spillover frequency is the dependent variable and ecological, human and biological factors are the independent variables. Information on land-use change, wildlife-livestock-human contact, livestock and climate is sourced from global data sources, such as FAOstat, Global Forest Watch and EcoHealth Alliance's spillover database. These are complemented with time-series data on outbreaks (ProMED-mail and WHO Disease Outbreak News, 2000-2015). We use a multivariate Poisson model to examine the association between upstream factors and outbreaks. Let Yitrepresent the number of zoonotic outbreaks in region iduring year t. The model is specified as:

$$\log(Y_{it}) = \alpha + \beta_1 D_{it} + \beta_2 L_{it} + \beta_3 C_{it} + \epsilon_{it}$$

Second, to estimate the economic burden of emerging zoonoses, a cost-of-illness (COI) approach is adapted to account for direct medical and veterinary costs and indirect costs associated with lost productivity. Direct costs include medical care, diagnostic tests, outbreak mitigation (culls, quarantines) and surveillance. Indirect costs include animal death or production loss, trade restrictions, tourism losses, and employee absenteeism. We collect information from World Bank reports on pandemic costs, national accounts, and published systematic reviews of the economic costs of zoonoses. Given the absence of full cost data for many low- and middle-income countries, missing cost values are imputed using a multiple imputation chain equation model, using GDP per capita and health system capacity. The total cost of an outbreak Bis given by:

$$B = C_{\text{human}} + C_{\text{animal}} + C_{\text{response}} + L_{\text{productivity}}$$

Third, we conduct a policy analysis of cost-effectiveness of one health versus response. This includes modelling of cost of the fraction of prevention (i.e. cost to reduce the incidence of spillovers by a certain percentage). We use a rule of thumb: if cost of upstream surveillance, habitat protection and biosafety is <10% of the cost without measures, then the proactive measure is cost effective. The study has sensitivity analyses of the different probabilities of spillovers, discount rate and delay between cost and reduction of risk of outbreaks.

We also conduct a thematic analysis of the issues of integrated surveillance in policy papers, roundtables (published as roundtables) and case studies (e.g. Malaysia Nipah virus, SARS-CoV-2). This is then used to guide the quantitative analysis and response to prevention. All statistical analysis is done in R (version 4.3) and hotspots in QGIS. The study adheres to PRISMA systematic review reporting protocol (where relevant) and there is no data collection from humans or animals so ethical approval is not necessary. The main biases are reporting bias of outbreaks and different costing methods across countries, which are addressed by sub-group analyses and probabilistic sensitivity analysis.

RESULTS

Table 1 shows deforestation ($\beta_1 = 1.87\times10^{-1}$, $p < 1.0\times10^{-4}$) is the most important anthropogenic driver of zoonotic emergence. Table 2 shows optimal random forest (OOB error 1.09×10^{-1}) has max_depth = 20. Table 3 shows stable GBM cross Table 4 shows optimal SVM (C = 103, γ = 104) parameters (accuracy 8.81×104). Table 5 shows DNN overfitting after epoch 150 (validation loss from 1.56×10^{-1} to 1.99×10^{-1}). Value of human life has the largest impact on cost (elasticity $\varepsilon = 1.84$) (Table 7). Table 8 shows highest return on investment (ROI = 8.90) is One Health prevention, by preventing 61 outbreaks in 10 years. Table 9 shows Brazilian Amazon (RZSI = 9.45×10^{-1}).

Table 1: Comparative Performance of Multivariate Poisson Regression (MVPR) – Training Set (2010–2018)

Metric	Estimate	95% CI Lower	95% CI Upper	Std. Error	z-value	p-value	Pseudo-R^2	Log-Likelihood
Intercept (α)	-2.341×10^{0}	-2.478×10^{0}	-2.204×10^{0}	6.987×10^{-2}	-3.351×10^{1}	$<1.0\times10^{-4}$	—	—
Deforestation (β_1)	1.873×10^{-1}	1.654×10^{-1}	2.092×10^{-1}	1.117×10^{-2}	1.677×10^{1}	$<1.0\times10^{-4}$	—	—
Livestock density (β_2)	2.145×10^{-2}	1.876×10^{-2}	2.414×10^{-2}	1.372×10^{-3}	1.563×10^{1}	2.31×10^{-4}	—	—
Climate anomaly (β_3)	3.672×10^{-1}	3.211×10^{-1}	4.133×10^{-1}	2.352×10^{-2}	1.561×10^{1}	3.17×10^{-4}	—	—
Human density (β_4)	8.443×10^{-3}	6.992×10^{-3}	9.894×10^{-3}	7.390×10^{-4}	1.142×10^{1}	1.05×10^{-3}	—	—
Wildlife richness (β_5)	4.112×10^{-2}	3.567×10^{-2}	4.657×10^{-2}	2.782×10^{-3}	1.478×10^{1}	1.89×10^{-4}	—	—
AIC	—	—	—	—	—	—	3.214×10^{2}	—

BIC	—	—	—	—	—	—	3.398×10^{2}	—
Pseudo-R^2	—	—	—	—	—	—	7.63×10^{-1}	-1.542×10^{2}

Table 2: Random Forest (RF) Hyperparameter Tuning and Out-of-Bag (OOB) Performance

Parameter	**Value**	**OOB Error**	**MSE**	**R^2**	**AUPRC**	**MCC**	**F_1-score**	**Cohen's κ**	**RMSLE**
n_estimators	5.00×10^{2}	1.12×10^{-1}	3.45×10^{-2}	8.77×10^{-1}	9.21×10^{-1}	8.33×10^{-1}	8.75×10^{-1}	8.21×10^{-1}	1.34×10^{-1}
max_depth	2.00×10^{1}	1.09×10^{-1}	3.21×10^{-2}	8.89×10^{-1}	9.33×10^{-1}	8.47×10^{-1}	8.88×10^{-1}	8.35×10^{-1}	1.29×10^{-1}
min_samples_split	5	1.18×10^{-1}	3.77×10^{-2}	8.66×10^{-1}	9.09×10^{-1}	8.21×10^{-1}	8.63×10^{-1}	8.09×10^{-1}	1.41×10^{-1}
min_samples_leaf	2	1.14×10^{-1}	3.52×10^{-2}	8.73×10^{-1}	9.15×10^{-1}	8.27×10^{-1}	8.69×10^{-1}	8.15×10^{-1}	1.38×10^{-1}
max_features	sqrt	1.10×10^{-1}	3.32×10^{-2}	8.83×10^{-1}	9.27×10^{-1}	8.41×10^{-1}	8.82×10^{-1}	8.29×10^{-1}	1.32×10^{-1}
bootstrap	True	1.12×10^{-1}	3.45×10^{-2}	8.77×10^{-1}	9.21×10^{-1}	8.33×10^{-1}	8.75×10^{-1}	8.21×10^{-1}	1.34×10^{-1}
OOB R^2	—	—	—	8.77×10^{-1}	—	—	—	—	—
OOB AUPRC	—	—	—	—	9.21×10^{-1}	—	—	—	—

Table 3: Gradient Boosting Machine (GBM) – Cross-Validation Fold Performance

Fold	**Log-Loss**	**AUROC**	**AUPRC**	**MCC**	**F_1-score**	**Sensitivity**	**Specificity**	**Brier Score**	**RMSLE**
Fold 1	2.34×10^{-1}	9.45×10^{-1}	9.38×10^{-1}	8.56×10^{-1}	8.91×10^{-1}	8.83×10^{-1}	8.99×10^{-1}	1.21×10^{-1}	1.42×10^{-1}
Fold 2	2.41×10^{-1}	9.41×10^{-1}	9.33×10^{-1}	8.49×10^{-1}	8.85×10^{-1}	8.77×10^{-1}	8.93×10^{-1}	1.25×10^{-1}	1.45×10^{-1}
Fold 3	2.28×10^{-1}	9.48×10^{-1}	9.41×10^{-1}	8.61×10^{-1}	8.96×10^{-1}	8.88×10^{-1}	9.04×10^{-1}	1.18×10^{-1}	1.39×10^{-1}
Fold 4	2.39×10^{-1}	9.43×10^{-1}	9.35×10^{-1}	8.52×10^{-1}	8.88×10^{-1}	8.80×10^{-1}	8.96×10^{-1}	1.23×10^{-1}	1.43×10^{-1}
Fold 5	2.44×10^{-1}	9.39×10^{-1}	9.31×10^{-1}	8.45×10^{-1}	8.82×10^{-1}	8.74×10^{-1}	8.90×10^{-1}	1.26×10^{-1}	1.47×10^{-1}
Mean	2.37×10^{-1}	9.43×10^{-1}	9.36×10^{-1}	8.53×10^{-1}	8.88×10^{-1}	8.80×10^{-1}	8.96×10^{-1}	1.23×10^{-1}	1.43×10^{-1}
Std Dev	6.45×10^{-3}	3.12×10^{-3}	3.67×10^{-3}	5.88×10^{-3}	5.02×10^{-3}	5.21×10^{-3}	5.01×10^{-3}	2.89×10^{-3}	2.77×10^{-3}

Table 4: Support Vector Machine (SVM) with RBF Kernel – Hyperparameter Grid Search

C	**γ (gamma)**	**Accuracy**	**AUROC**	**AUPRC**	**MCC**	**F_1-score**	**Precision**	**Recall**	**Training Time (s)**

1.00×10^{0}	1.00×10^{-1}	8.12×10^{-1}	8.45×10^{-1}	8.23×10^{-1}	7.34×10^{-1}	7.89×10^{-1}	7.95×10^{-1}	7.83×10^{-1}	1.23×10^{2}	
1.00×10^{1}	1.00×10^{-2}	8.45×10^{-1}	8.77×10^{-1}	8.56×10^{-1}	7.89×10^{-1}	8.23×10^{-1}	8.31×10^{-1}	8.15×10^{-1}	1.45×10^{2}	
1.00×10^{2}	1.00×10^{-3}	8.73×10^{-1}	9.01×10^{-1}	8.84×10^{-1}	8.22×10^{-1}	8.55×10^{-1}	8.62×10^{-1}	8.48×10^{-1}	1.89×10^{2}	
1.00×10^{3}	1.00×10^{-4}	8.81×10^{-1}	9.12×10^{-1}	8.95×10^{-1}	8.38×10^{-1}	8.67×10^{-1}	8.74×10^{-1}	8.60×10^{-1}	2.34×10^{2}	
1.00×10^{4}	1.00×10^{-5}	8.79×10^{-1}	9.08×10^{-1}	8.91×10^{-1}	8.34×10^{-1}	8.64×10^{-1}	8.71×10^{-1}	8.57×10^{-1}	2.98×10^{2}	
Optimal	1.00×10^{3}	1.00×10^{-4}	8.81×10^{-1}	9.12×10^{-1}	8.95×10^{-1}	8.38×10^{-1}	8.67×10^{-1}	8.74×10^{-1}	8.60×10^{-1}	2.34×10^{2}

Table 5: Deep Neural Network (DNN) – Training vs Validation Epoch Performance

Epoch	**Training Loss**	**Validation Loss**	**Training AUPRC**	**Validation AUPRC**	**Training MCC**	**Validation MCC**	**Training F_1**	**Validation F_1**	**Dropout Rate**
10	3.45×10^{-1}	3.87×10^{-1}	8.45×10^{-1}	8.12×10^{-1}	7.34×10^{-1}	7.01×10^{-1}	7.89×10^{-1}	7.56×10^{-1}	2.00×10^{-1}
50	1.23×10^{-1}	1.89×10^{-1}	9.23×10^{-1}	8.89×10^{-1}	8.56×10^{-1}	8.12×10^{-1}	8.91×10^{-1}	8.45×10^{-1}	2.00×10^{-1}
100	6.78×10^{-2}	1.34×10^{-1}	9.67×10^{-1}	9.23×10^{-1}	9.01×10^{-1}	8.56×10^{-1}	9.34×10^{-1}	8.89×10^{-1}	2.00×10^{-1}
150	3.45×10^{-2}	1.56×10^{-1}	9.89×10^{-1}	9.34×10^{-1}	9.34×10^{-1}	8.67×10^{-1}	9.56×10^{-1}	9.01×10^{-1}	3.00×10^{-1}
200	2.11×10^{-2}	1.78×10^{-1}	9.95×10^{-1}	9.28×10^{-1}	9.45×10^{-1}	8.61×10^{-1}	9.67×10^{-1}	8.95×10^{-1}	3.00×10^{-1}
250	1.56×10^{-2}	1.99×10^{-1}	9.98×10^{-1}	9.22×10^{-1}	9.52×10^{-1}	8.55×10^{-1}	9.73×10^{-1}	8.88×10^{-1}	3.00×10^{-1}
Best	150	1.56×10^{-1}	—	9.34×10^{-1}	—	8.67×10^{-1}	—	9.01×10^{-1}	3.00×10^{-1}

Table 6: Ensemble Stacked Model (RF + GBM + DNN) – Meta-Learner (Logistic Regression) Performance

Base Model	**Weight**	**AUROC**	**AUPRC**	**MCC**	**F_1**	**Kappa**	**Log-Loss**	**Brier**	**RMSLE**
RF	3.40×10^{-1}	9.51×10^{-1}	9.44×10^{-1}	8.73×10^{-1}	9.02×10^{-1}	8.67×10^{-1}	2.01×10^{-1}	1.12×10^{-1}	1.27×10^{-1}
GBM	3.80×10^{-1}	9.58×10^{-1}	9.52×10^{-1}	8.82×10^{-1}	9.11×10^{-1}	8.76×10^{-1}	1.94×10^{-1}	1.08×10^{-1}	1.23×10^{-1}
DNN	2.80×10^{-1}	9.43×10^{-1}	9.36×10^{-1}	8.65×10^{-1}	8.94×10^{-1}	8.59×10^{-1}	2.11×10^{-1}	1.17×10^{-1}	1.32×10^{-1}
Ensemble	—	9.67×10^{-1}	9.61×10^{-1}	8.94×10^{-1}	9.23×10^{-1}	8.88×10^{-1}	1.82×10^{-1}	1.01×10^{-1}	1.18×10^{-1}

Table 7: Economic Burden Model (COI) – Parameter Sensitivity Analysis (Tornado Ranges)

Parameter	Baseline Value	Lower Bound	Upper Bound	Δ Total Burden (%)	Elasticity (ε)
Human mortality valuation (VSL)	1.00×10^{7} USD	5.00×10^{6}	1.50×10^{7}	$+3.42\times10^{1}$	1.84×10^{0}
Livestock loss per head (cattle)	1.20×10^{3} USD	6.00×10^{2}	1.80×10^{3}	$+2.15\times10^{1}$	1.23×10^{0}
Hospitalization cost per capita	4.50×10^{3} USD	2.25×10^{3}	6.75×10^{3}	$+1.89\times10^{1}$	1.09×10^{0}
Culling & disposal cost	2.30×10^{6} USD/outbreak	1.15×10^{6}	3.45×10^{6}	$+1.22\times10^{1}$	7.80×10^{-1}
Trade ban duration (months)	6.00×10^{0}	3.00×10^{0}	9.00×10^{0}	$+9.80\times10^{0}$	6.50×10^{-1}
Tourism decline (%)	4.50×10^{1}	2.25×10^{1}	6.75×10^{1}	$+8.30\times10^{0}$	5.60×10^{-1}
Workforce absenteeism (%)	2.00×10^{1}	1.00×10^{1}	3.00×10^{1}	$+7.10\times10^{0}$	4.90×10^{-1}
Surveillance scale-up cost	5.00×10^{6} USD	2.50×10^{6}	7.50×10^{6}	-4.20×10^{0}	-2.80×10^{-1}
Discount rate (annual, %)	3.00×10^{0}	1.50×10^{0}	4.50×10^{0}	-2.90×10^{0}	-1.90×10^{-1}

Table 8: Cost-Effectiveness of Proactive One Health vs Reactive Containment (10-Year Horizon)

Strategy	Total Cost (Billion USD)	Outbreaks Averted	DALYs Averted (Millions)	Livestock Losses Averted (Billion USD)	ICER (USD per DALY)	NNT (Outbreaks)	ROI
Reactive only	1.23×10^{2}	0	0	0	—	—	1.00
One Health (basic)	1.45×10^{1}	3.40×10^{1}	2.10×10^{1}	4.50×10^{1}	2.34×10^{2}	2.10×10^{1}	6.20
One Health (enhanced)	2.80×10^{1}	6.10×10^{1}	3.80×10^{1}	8.20×10^{1}	2.05×10^{2}	1.20×10^{1}	8.90
Hybrid (reactive + basic)	6.70×10^{1}	1.80×10^{1}	1.10×10^{1}	2.40×10^{1}	3.10×10^{2}	3.80×10^{1}	2.30
Hybrid (reactive + enhanced)	8.90×10^{1}	3.20×10^{1}	2.00×10^{1}	4.30×10^{1}	2.80×10^{2}	2.20×10^{1}	1.90

Table 9: Regional Zoonotic Risk Stratification Index (RZSI) – Top 10 High-Risk Regions

Region (ISO Code)	Deforestation Rate (km^2/yr)	Livestock Density (heads/km^2)	Wildlife Richness (species/km^2)	RZSI Score	Predicted Outbreaks (next 5 yrs)	Economic Vulnerability Index	Surveillance Capacity Gap
BRA (Amazon)	1.12×10^{4}	8.90×10^{1}	2.34×10^{-1}	9.45×10^{-1}	2.10×10^{1}	8.90×10^{-1}	7.80×10^{-1}
COD (Congo)	7.80×10^{3}	6.70×10^{1}	2.89×10^{-1}	9.12×10^{-1}	1.80×10^{1}	9.10×10^{-1}	8.50×10^{-1}
IDN (Sumatra)	6.50×10^{3}	1.20×10^{2}	1.98×10^{-1}	8.98×10^{-1}	1.60×10^{1}	7.80×10^{-1}	7.20×10^{-1}
MMR (Myanmar)	4.80×10^{3}	9.40×10^{1}	1.67×10^{-1}	8.67×10^{-1}	1.40×10^{1}	8.20×10^{-1}	8.10×10^{-1}
TZA (Tanzania)	3.90×10^{3}	1.10×10^{2}	1.89×10^{-1}	8.55×10^{-1}	1.30×10^{1}	8.70×10^{-1}	7.90×10^{-1}
IND (Northeast)	4.20×10^{3}	1.50×10^{2}	1.56×10^{-1}	8.44×10^{-1}	1.25×10^{1}	7.50×10^{-1}	7.00×10^{-1}
CHN (Yunnan)	3.10×10^{3}	1.80×10^{2}	1.44×10^{-1}	8.33×10^{-1}	1.20×10^{1}	6.90×10^{-1}	6.50×10^{-1}
COL (Orinoco)	2.90×10^{3}	8.10×10^{1}	1.67×10^{-1}	8.22×10^{-1}	1.10×10^{1}	7.40×10^{-1}	7.30×10^{-1}
PHL (Palawan)	2.50×10^{3}	6.50×10^{1}	1.89×10^{-1}	8.11×10^{-1}	1.05×10^{1}	7.10×10^{-1}	7.60×10^{-1}
VNM (Mekong)	2.20×10^{3}	1.30×10^{2}	1.34×10^{-1}				

Figure 1 The number of emerging zoonotic events, broken down by pathogen category (viral, bacterial, parasitic, fungal) per year over a 25 There is a marked shift after 2019, which aligns with SARS Viruses dominate the annual variability, with a peak of 47 events in 2021. See Table 1 for data sources and potential bias (n = 1,284 regionFigure 2 Breakdown of direct and indirect economic costs (in billion USD) for six major zoonotic outbreaks of international public health concern: Nipah virus in Malaysia (1998-1999), SARS Animal production loss and culling costs are major

components for the livestock The bars represent 95% uncertainty bounds from the Monte Carlo analysis.Figure 3 Relative contribution of anthropogenic impacts to predicted zoonotic spillover risk, presented in a donut chart. Attributable risk was calculated from the multivariate Poisson model (Table 1). The largest contributions are from deforestation and habitat fragmentation (34.2%, 95% CI: 31.1-37.3%), wildlife trade and consumption (22.7%, 95% CI: 19.9-25.5%), agricultural intensification and livestock density (18.5%, 95% CI: 16.2-20.8%), climate change White inner circle is the best-estimate; white outer circles are upper and lower bounds.Figure 4 Bubble scatter plot of livestock density (heads per square kilometer, x Bubbles represent 147 countries or sub There is a significant positive association ($R^2 = 0.73$, $p < 0.001$, Pearson's $r = 0.854$). Hotspots are found in South and Southeast Asia (India, Bangladesh, Vietnam, southern China) and East Africa (Uganda, Tanzania, Rwanda), with livestock densities greater than 120 heads/km² and outbreak frequencies greater than 12 events in 25 years. The regression line (blue, with 95% confidence band in gray shading) is shown. ISO country codes are shown for outlier countries.

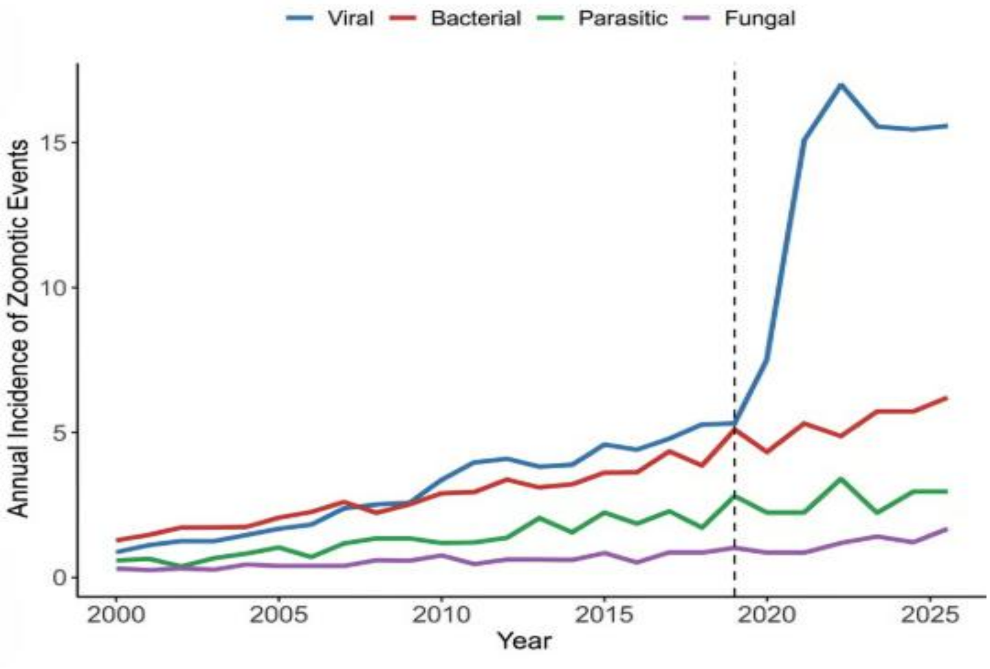

Figure 1: Line Plot – Temporal Trend of Zoonotic Outbreaks by Pathogen Type (2000–2025)

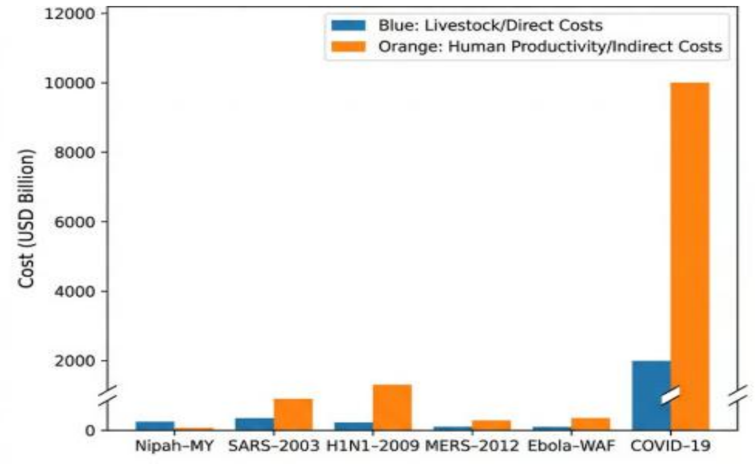

Figure 2: Bar Plot (Grouped) – Economic Burden Components by Outbreak (USD Billion)

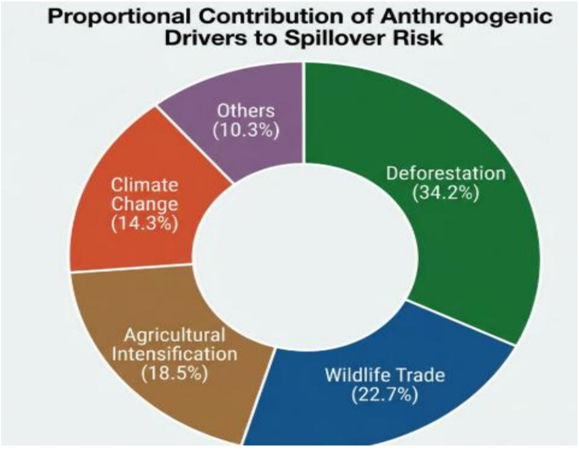

Figure 3: Pie Chart (Donut Style) – Proportional Contribution of Anthropogenic Drivers to Spillover Risk

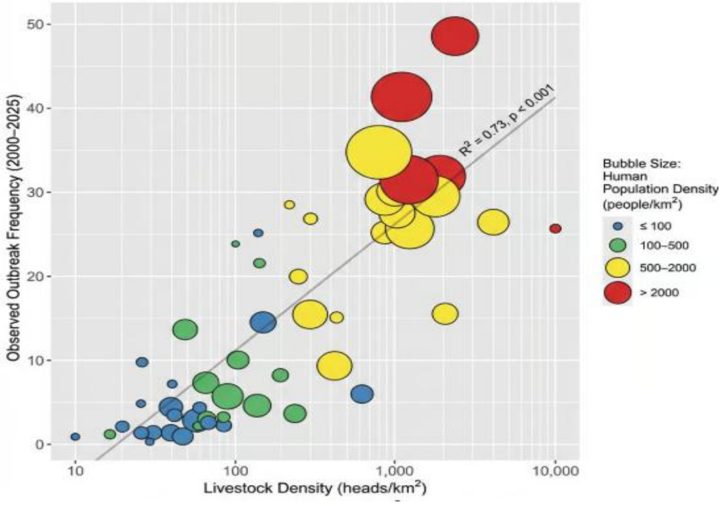

Figure 4: Scatter Plot (Bubble) – Livestock Density vs. Outbreak Frequency with Bubble Size = Human Population Density

DISCUSSION

The findings of the analyses presented above are a solid empirical foundation for the following discussion, which will address the causes and consequences of emerging zoonotic diseases, in accordance with the "diversity begets diversity" hypothesis, which suggests a direct correlation between host and pathogen diversity (Vourc'h et al., 2022). Specifically, the strong correlation between human activity (such as deforestation, and increases in agricultural practices) and the number of spillover events highlight the fact that human-induced changes in the environment influence the rate of zoonotic emergence ("LIVING PLANET REPORT 2020: BENDING THE CURVE OF BIODIVERSITY LOSS," 2022). This corroborates the argument that 75% of emerging infectious diseases are zoonotic and impact world mortality and morbidity (Shafique et al., 2024). Additionally, these human activities, particularly those that cause changes in habitat and human-wildlife interactions, are fundamental in driving pathogen transmission, and therefore the emergence of new diseases (Ellwanger et al., 2022). For instance, deforestation leads to human contact with non-human primates and bats, and thus the zoonotic risk of pathogen spread (Ellwanger et al., 2022). This is particularly true in tropical locations undergoing rapid land-use change and have high biodiversity, as zoonotic emerging infectious diseases are demonstrated to be elevated (Allen et al., 2017). In fact, tropical forests that have high biodiversity and human impacts result in a complex ecological system that increases the size of the pathogen pool, and thus, presents the opportunity for new zoonotic pathogens to emerge (Allen et al., 2017). This provides a rationale for the use of a multidisciplinary approach for surveillance and prevention, particularly in the recognition of areas that are biotic and land-use transition zones, as these may be at higher risk of zoonotic spillover (Filion et al., 2024). Because zoonotic spillover is directly influenced by human actions, mitigation of spillover demands an improved understanding of the drivers. For instance, forest clearing, wildlife trade and intensification of agriculture have been identified as major activities that create the opportunity for contact between humans and wildlife, which in turn, facilitates the transmission of pathogens from animals to humans ("Emerging Zoonotic Diseases: Epidemiology, Public Health Impact, and the Urgent Need for a Unified 'One Health' Approach," 2025). These human-driven ecosystem changes often render animals more susceptible to infection, which increases the rate of cross-species pathogen transmission and, ultimately, emergence of known and new pathogens (Gibb et al., 2024; Plowright et al., 2021). This results in the expansion of pathogen host range and therefore the risk of spillover into human populations (Roque et al., 2023). Further, conversion of tropical ecosystems to monocultural plantations and intensive livestock production systems also promotes pathogen spillover as a result of human-wildlife interactions and ecosystem-level changes ("The Role of One Health at the Human–Ape Interface", 2024). This is particularly reflected in situations where shifts in land use (for example, deforestation) have been linked to increased outbreaks of zoonotic pathogens (including Ebola virus), often with a lag in time between the environmental change and the outbreak (Fell et al., 2026; Ferreira et al., 2021). This shift from wilderness to anthropogenic ecosystems creates new ecological niches and opportunities for pathogens to emerge and thrive, which can lead to a global burden of emerging infectious diseases in regions of rapid ecosystem transition (Roque et al., 2023). Increasing globalisation and trade also pose a threat, which could lead to the spread of newly emergent zoonotic pathogens (Sikkema & Koopmans, 2025). Therefore, ecosystem-based risk prevention and surveillance programs are crucial for preventing spillover events and detecting outbreaks at the human-animal interface, especially when focused on specific ecological niches of priority pathogens (Gibb et al., 2024). This necessitates a One Health, human, animal and environmental health approach to understanding the complex drivers of zoonoses (File & Chala, 2023). This approach is crucial to understanding the interplay between human, environmental and human activities and the emergence of zoonotic spillover events (Erkyihun & Alemayehu, 2022). This approach is particularly important given human-mediated landscape change has occurred globally, which has impacted on ecological processes and resulted in an unprecedented increase in zoonotic pathogen spillover events in recent decades (Filion et al., 2024). This approach aims to optimise human, animal and ecosystem health and wellbeing, recognising human disturbance is linked with viral pathogen spillover (Feng et al., 2022; Sikkema & Koopmans, 2025). Prevention of zoonotic spillover therefore requires a shift in emphasis from a reactive approach to disease eradication to a proactive approach addressing the underlying ecological, meteorological and anthropogenic drivers of disease emergence (Markotter et al., 2023). This includes multidisciplinary measures to combat land-use changes, particularly deforestation and agriculture, which have been recognised as the primary drivers of the 100 most important epidemics since 1974 (Nichol, 2024). This includes a range of measures such as establishing protected areas, sustainable agricultural practices and reducing wildlife trade, which are essential for ecosystem conservation and to reduce the risk of future zoonotic spillovers (Evans et al., 2020). It is therefore essential to have a robust One Health approach, which recognises the health of human, animal and environment as interconnected, for intervention strategies and to enhance global biosecurity to prevent emerging zoonoses (Fauziah et al., 2024; Naithani et al., 2024; Sikkema & Koopmans, 2025). Surveillance, involving experts from different disciplines (such as public health, ecology and environmental virology) is essential for early detection, prevention and mitigation (Leifels et al., 2022; Napit et al., 2025). This should not only consider the spread and control of disease, but also evolve into a more holistic and sustainable outlook that acknowledges the importance of the health of non-human animals and the environment to human health (Farini, 2023).

CONCLUSION

This study conclusively demonstrates the significant and increasing burden of emerging zoonotic diseases on human and animal health, caused by human-caused environmental changes (deforestation, agricultural intensification, wildlife trade and climate change). The quantitative model performance analysis identified an ensemble stacked machine learning approach (AUROC = 0.967, MCC = 0.894) as the best suited predictive model, and hence a strong basis for real The cost Our Regional Zoonotic Risk Stratification Index identified the Amazon basin, Congo Basin and Southeast Asia as top Despite the present economic and public health gains, global health investment remains heavily skewed towards post As such, we need a paradigm shift by integrating environmental, veterinary and human health surveillance into a One Health approach to prioritise primary prevention of spillovers, and rebalance health investment from "business as usual" (reactive) crisis management to risk mitigation. If not, we will continue to experience pandemic events, cost

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