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Rabies control costs at the provincial level: Who should pay more, the community or the government?

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Abstract

Background and Aim: Rabies is a zoonotic disease that persists endemic in numerous countries worldwide. In Vietnam, the main sources of rabies are dogs and cats, and they caused 76 human deaths annually by 2017–2021. Long An province has recently experienced an increasing burden of rabies, with seven fatal cases reported in the past 5 years. Various rabies control measures have been implemented in this province, including mass vaccination of the animal population, post-vaccination monitoring, diagnostic testing of suspected rabid dogs, dog bite investigation, animal management, pre-exposure treatment, post-exposure treatment (PET), and awareness programs. This study aimed to estimate the cost of rabies control measures for animals and humans in Long An province in 2022.

Materials and Methods: An economic model was developed to estimate the costs of rabies control under two scenarios, with and without external financial support from the private sector. Inputs for the model included data from published literature, publicly available reports on rabies, government data, expert opinions, and a pilot study conducted in Vietnam.

Results: The total annual costs of rabies control, with or without external support, were estimated to be VND 62.62 and 62.77 billion (equivalent to USD 2.67 and 2.68 million), respectively. The highest proportion of costs was related to PET in humans (84.50% and 84.30%), followed by the cost of mass vaccination paid by animal owners (14.28% and 13.90%). Most of the expenses were paid by the private sector (98.87% and 98.98%) rather than the public sector (1.14% and 1.20%).

Conclusion: This study described a transparent and reproducible method for estimating the economic costs of rabies control at the provincial level. The economic model developed showed that control of rabies by mass vaccination is more cost-effective than using PET to prevent human death. The model can be applied to future economic analyses of rabies control in other provinces of Vietnam and other rabies-endemic countries.

Keywords: animals, control measures, deterministic economic model, humans, rabies.

Introduction

Rabies is a fatal zoonotic illness caused by an RNA virus of the *Rhabdoviridae* family, *Lyssavirus* genus. Any warm-blooded mammal, including humans, can be infected with rabies [1]. Rabies, which is often associated with infection by canines, is an endemic disease in many continents, except Australia and Antarctica [2–4]. Globally, the reported annual human death loss caused by rabies was estimated to be 59,000, with the majority occurring in Asia (59.6%) and Africa (36.4%), with America exhibiting a much lower death rate (<0.05%) [5]. Among South-east Asian countries, only Brunei, Timor-Leste, and Singapore are considered rabies-free [4]. In Vietnam, an alarming increase in rabies cases has been reported recently. In 2022, 69 human deaths due to rabies were recorded, and from January to September 2023, 62 fatalities were reported nationwide [6, 7]. Canine rabies also showed a worrying trend, with 78 cases identified across 11/63 country's provinces and cities in 2021. The number of cases rose sharply in 2022, with 133 cases reported across 15 provinces and cities. By September 2023, data revealed 274 cases of rabies among animals in 30 provinces and cities nationwide [6].

The rabies vaccination rate in the dog population was estimated to be around 39% in the period from 2012 to 2016 and increased to approximately 50% from 2017 to 2022 [8].

Regarding the economic impact of rabies in Vietnam, a comprehensive assessment from 2005 to 2014 revealed that rabies inflicted a financial toll that exceeded USD 719 million, in which post-exposure prophylaxis (PEP) accounted for 92% of the total cost (TC). For this period, rabies contributed to 36,560–45,700 Disability-Adjusted Life Years in the population. In animal production systems, it was estimated that 25,539 pigs, 6032 cattle, and 2892 buffaloes died from rabies over the past 10 years, leading to a loss of more than USD 10 million [9].

In 2021, Vietnam's Prime Minister initiated a national action plan for rabies control, covering the period from 2022 to 2030, based on the One Health approach. In the plan, the specific objectives for controlling rabies in the animal sector for the periods 2022–2025 and 2026–2030 included (i) achieving management of 70% and 90% of the dog and cat population; (ii) vaccination of 70% and 80% of the total dog and cat population; (iii) monitoring of 70% and 90% of suspected cases; and (iv) establishment at least 10 rabies-free zones at the district level, 10 rabies-free zones at the commune levels, and maintenance of the rabies-free zone that had been established in 2017–2021. For the human sector, the specific objectives included (i) ensuring that 100% of districts have established rabies vaccination points and have rabies immunoglobulin available, (ii) ensuring that 100% of individuals receiving rabies vaccination due to animal bites are reported through the national reporting system, (iii) initiating PEP for 90% of individuals exposed to rabies, (iv) reducing rabies-related fatalities in humans by 50% by 2025, and (v) achieving complete elimination of dog-mediated rabies by 2030 [10]. The national plan is especially focused on enhanced surveillance for rabies in the management of dog and cat populations, animal vaccination, policy enforcement, awareness programs, disease investigation, improvement of laboratory testing capacity, establishment of disease-free zones, movement control, and international collaboration. To implement the plan, each province in Vietnam will develop an annual action plan that reflects their available resources.

Knowing the cost of the disease and the costs of control measures to be applied is essential for appropriately allocating resources for planned interventions [11]. Economic analysis can help optimize resource allocation and assess the cost-effectiveness of control measures. A previous study by Abbas *et al.* [12] on rabies control in Tamil Nadu, India, suggested that the key indicators affecting the cost of rabies control in humans were the number of rabies cases, the extent of the healthcare system coverage, and the cost of materials used for prevention. In animals, key control costs include the size of the dog culling teams, the dog population size, and the cost of vaccination [12]. A study conducted in Flores Island, Indonesia, reported that the highest proportion of the cost of control could be attributed to culling free-grazing dogs (39%), followed by PEP (35%), mass vaccination (24%), and pre-exposure treatment (1.4%) [13]. However, other recent studies have demonstrated that the cost of vaccination in the animal sector was significantly lower than that of PEP in humans [6, 14, 15]. One benefit-cost analysis of the rabies vaccination strategy in Mexico showed that a vaccination strategy that produced an additional cost of USD 300 million was able to prevent 13,000 deaths compared with a non-vaccination strategy. In this study, an average of USD 23,000 per human rabies death was averted (cost per additional year-of-life was USD 410, and per dog rabies death averted was USD 190). According to the study authors and as measured by World Health Organization standards, the national rabies control program in Mexico was highly cost-effective [16].

An economic analysis of different scenarios can help determine the trade-offs between managing and eliminating rabies. Unfortunately, the success of control strategies depends on many aspects that may differ from one place to another, making it difficult to provide a clear overview of their economic impact [17]. Although some economic assessments of rabies control strategies have been conducted [13, 16], the methods described cannot be directly applied to an analysis of rabies in the Vietnamese local context, at a provincial or lower level of administration.

Thus, as the first study on the cost-effectiveness of rabies prevention and control programs in Vietnam, this study aimed to build an economic model for a provincial-level dog-mediated rabies control program based on data collected from Long An province's rabies control campaign implemented in 2022. The economic model results will optimize resource allocation and planning future interventions. When integrated with program assessments conducted by provincial authorities, this economic analysis can significantly enhance resource prioritization and ensure that control measures are both practical and sustainable for long-term effectiveness. In addition, the findings can be used in other provinces and regions with similar endemic conditions.

Materials and Methods

Ethical approval

This study was conducted to develop an economic model to estimate the costs of rabies control. This study was not conducted on live animals so, ethical approval was not necessary for this study. However, our study was approved by the local authorities (Sub-Department of Animal Health of Long An).

Study period and location

The study was conducted from September 2022 to December 2023 in Long An province, in South Vietnam.

Study design and data collection

The investment cost analysis used in this study is based on a framework described in previous studies by Rushton [18] and Truong *et al*. [19]. An economic model was then developed to estimate the costs of various rabies control measures and the distribution of costs among various stakeholders (public and private sectors) in two scenarios (with or without external support) in Long An province.

Inputs for the model were obtained from published literature, publicly available reports on rabies, government data, expert opinions, and a pilot study conducted in Duc Hue district, Long An Province, Vietnam. The future costs of the program through 2030 were predicted from the 2022 costs using a constant inflation rate of 3.2% [20]. A literature review synthesized relevant available data and a survey based on a snowball sampling method was performed with stakeholder groups (veterinarians and doctors at the provincial and district levels, para-veterinarians, pet owners, and human dog-bite cases) to provide additional data needed for the model but was not available through previously published work. All data were recorded and then stored in Google Sheets (Google LLC, Mountain View, CA, USA, www.google.com/sheets).

Costs of control measures in animal (CMA)

The total cost of the CMA was calculated as the sum of six components: cost of mass vaccination of the animal population (dog, cat) paid by owner ($C_{mass\_vax\_owner}$) and government ($C_{mass\_vax\_pub}$), cost of post-vaccination monitoring ($C_{monitoring}$), diagnostic testing of suspected rabid dogs (C_{diag_ani}), dog bite investigation ($C_{investigation}$), cost of animal management (C_{mana_ani}), and cost of vaccination in a rabies-free zone ($C_{vax\_free\_zone}$).

$$CMA = C_{mass\_vax\_owner} + C_{mass\_vax\_pub} + C_{monitoring} + C_{investigation} + C_{diag\_ani} + C_{mana\_ani} + C_{vax\_free\_zone}$$

Cost of mass vaccination in an animal population

According to the national strategy for the prevention and control of rabies [10] and the provincial plan for rabies control in 2022 [21], mass vaccination should be performed annually to achieve 80% coverage of the animal population. The vaccination program is conducted from house on house twice yearly by district veterinarians, para-veterinarians, and volunteers. Based on this information, we proposed two scenarios to compare the effects of different vaccination programs. Scenario 1 represents the current situation where control measures heavily depended on the government's capacity and compliance with dog owners and patients. This scenario is similar to the situation in any province in Vietnam. Scenario 2 considered the provision of additional program support from other stakeholders (vaccine companies, veterinary students) as well as some modifications to existing control measures (establishment of rabies-free zone in the rabies control plan). This was necessary because even though the implementation of rabies-free zones has been in place since 2021, their application has varied from one region to another [10].

In the first scenario, the vaccination cost was sub-divided into the cost borne by the government ($C_{max\_vax\_pub}$) and the cost borne by the animal's owner ($C_{max\_vax\_owner}$). The former included only the cost of supervision of vaccination ($C_{suppervisor}$); the latter included several components, such as vaccine cost ($C_{vaccine\_ani}$) and opportunity cost for owners who catch and maintain their animals for vaccination (C_{owner_time}).

In the second scenario, in addition to ($C_{max\_vax\_pub}$) and ($C_{max\_vax\_owner}$), we considered the cost of mass vaccination through the support of private companies and veterinary students ($C_{max\_vax\_pri}$). This cost included vaccine cost ($C_{vaccine\_ani2}$), cost of consumable equipment ($C_{equipment}$), labor cost for volunteers/vaccinator ($C_{vaccinator}$), and cost of having support staff in the field (local guides) ($C_{supporter}$). Therefore, the general formula for determining the cost of mass vaccination is as follows:

$$C_{max\_vax} = C_{max\_vax\_pub} + C_{max\_vax\_owner} + C_{max\_vax\_pri}$$

In which:

$$C_{max\_vax\_pub} = C_{supervisor\_province} + C_{supervisor\_district}$$

In which:

$$C_{supervisor\_province} = n_{working\ day2} * n_{supervisor} * n_{commune1} * S_{day2} + p_{transportation} * t_{transportation}$$

$$C_{supervisor\_district} = n_{working\_day3} * n_{district\_vet} * n_{commune2} * S_{day2} + p_{gasoline} * n_{gasoline}$$

$$C_{max\_vax\_owner} = C_{vaccine\_ani1} + C_{owner\_time}$$

In which:

$$C_{vaccine\_ani1} = p_{vaccine1} * n_{animal1}$$

$$C_{owner\_time} = S_{day\ farmer}/t_{holding} * (n_{animal1} + n_{animal2})$$

$$C_{max\_vax\_pri} = C_{vaccine\_ani2} + C_{equipment} + C_{vaccinator} + C_{supporter}$$

In which:

$$C_{vaccine\_ani2} = p_{vaccine2} * n_{animal2}$$

$$C_{equipment} = p_{needle\_syringe} * n_{animal2}$$

$$C_{vaccinator} = n_{working\_day1} * S_{day1} * N_{vaccinator} * n_{district1}$$

$$C_{supporter} = n_{working\_day1} * S_{day4} * N_{supporter} * n_{district1}$$

Legend:

$n_{working\_day2}$ = number of working days of employees at the Sub-Department of Animal Health (Sub-DAH) for vaccination monitoring purposes
$n_{supervisor}$ = number of provincial supervisors
$n_{commune1}$ = number of communes supervised per year by a Sub-DAH employee
S_{day2} = daily salary for employees
$p_{transportation}$ = price of transportation for vaccination monitoring
$t_{transportation}$ = number of transportation events
$n_{working\_day3}$ = number of working days of district veterinarians for vaccination
$n_{district\_vet}$ = number of district-level supervisors
$n_{commune2}$ = number of communes supervised per year in each district veterinary
$p_{gasoline}$ = gasoline price
n_gasoline = number of gasoline liters
$p_{vaccine1}$ = price of one dose of the rabies vaccine (paid by farmer)
$n_{animal1}$ = number of animals to be vaccinated without private sector support
S_{hour_farmer} = hourly salary of farmer
$t_{holding}$ = time the animal was held for vaccination purposes (hours)
$p_{vaccine2}$ = price of one dose of the rabies vaccine (paid by farmer, with support from private sector)
$n_{animal2}$ = number of animals to be vaccinated (with support from private sector)
$p_{needle\_syringe}$ = price of needle and syringe used for vaccination
$n_{working\_day1}$ = number of working days for vaccination
S_{day1} = daily salary for volunteers
$N_{vaccinator}$ = number of volunteers
S_{day4} = daily salary for supporters
$N_{supporter}$ = number of supporters
$n_{district1}$ = number of districts

Cost of post-vaccination monitoring ($C_{monitoring}$)

After a 21–day mass vaccination campaign, post-vaccination monitoring (blood sampling) was implemented. Representative samples were taken from selected communes for antibody titer testing using enzyme-linked immunosorbent assay (ELISA).

$$C_{monitoring} = C_{test} + C_{equip\_sampling} + C_{labour} + A_{collaborator} + C_{transportation} + C_{subvention}$$

In which:

$$C_{test} = n_{test} * C_{ELISA}$$

$$C_{labour} = n_{test} * S_{day3}$$

$$A_{collaborator} = n_{labour\_day} * n_{commune3} * S_{day2}$$

$$C_{transportation} = n_{labour\_day} * n_{commune3} * n_{litre\ per\ labor} * p_{litre} + C_{send\_samples} + n_{send\_samples} * S_{day2}$$

$$C_{subvention} = n_{test} * p_{subvention}$$

Legend:

C_{test} = cost of the ELISA test for rabies antibodies
n_{test} = number of ELISA tests performed per year
C_{ELISA} = cost of one ELISA test
$C_{equip\_sampling}$ = cost of sampling equipment
C_{labour} = labor cost of sampling
S_{day3} = salary for sampling
$A_{collaborator}$ = stipend for collaborators conducting post-vaccination monitoring activities
n_{labour_day} = number of laborers working per day per commune
$n_{commune3}$ = number of communes monitored annually
$C_{\_transportation}$ = transportation cost
$n_{litre\ per\ labor}$ = liters of gasoline per laborer
p_{litre} = price of one liter of gasoline
$C_{send\_samples}$ = cost of hiring a car to transport samples to the laboratory
$n_{send\_samples}$ = number of laborers transporting samples to the laboratory
$C_{subvention}$ = subvention for sampling
$p_{subvention}$ = subvention fee for one sample (in form of disinfecting substance).

Cost of confirmatory testing in a dog with suspected rabies (C_{diag_ani})

This cost included both the testing cost at the laboratory and the cost of collecting the sample from the animal. The number of suspect animals ($n_{suspect\_ani}$) is predicted in the annual plan but is often lower than predicted.

$$C_{diag\_ani} = n_{suspect\_ani} * (c_{laboratory} + C_{collect} + C_{transport\_1} + C_{transport\_2} + A_{employee} + A_{collaborator})$$

In which:

$$A_{collaborator} = n_{collaborators} * n_{suspect\_ani} * S_{day2}$$

Legend:

$n_{suspect\_ani}$ = number of suspected rabies samples submitted to the regional laboratory annually for confirmatory testing
$c_{laboratory}$ = cost for rabies testing in the laboratory (reverse transcription-polymerase chain reaction test)

$C_{collect}$ = cost of sample collection
$C_{transport\_1}$ = sample transportation cost from the district veterinary station to sub-DAH (provincial) laboratory
$C_{transport\_2}$ = sample transportation costs from the Sub-DAH (provincial) laboratory to the regional laboratory
$A_{employee}$ = stipend for sub-DAH employees who send samples
$A_{collaborator}$ = stipend for employees involved in the investigation of suspected rabies dog cases
$n_{collaborators}$ = number of employees involved in the case investigation.

Cost of disease investigation (trace back from human suspected cases) ($C_{investigation}$)

When receiving information about a suspected case of rabies in a human from the hospital, a veterinary team led by the district veterinarian will trace the case back to the field to identify potential animal sources of the infection. This team would normally include 2–3 people (district veterinarian, commune veterinarian, and/or village chief) and through interviews and physical inspection, identify any suspected animal cases; suspect animals are monitored daily with follow-up by telephone up to 10 days later.

$$C_{investigation} = n_{suspect\_human} * A_{case}$$

Legend:
$n_{suspect\_human}$ = number of human cases that need to be traced annually
A_{case} = Stipend provided per case.

Cost of animal management (C_{mana_ani})

The cost of animal management includes a fee for village chiefs and para-veterinarians to conduct surveys of the animal population and to print survey documents. Animal population survey data are collected twice per year according to the regulations of the sub-DAH.

$$C_{mana\_ani} = (A_{village\_chef} + D_{village}) * n_{village} + (A_{commune} + D_{commune}) * n_{commune}$$

Legend:
$A_{village\_chef}$ = stipend to village chefs
$D_{village}$ = cost of statistical documents at the village level
$A_{commune}$ = stipend to commune veterinarians
$D_{commune}$ = cost of survey documents at the commune level
$n_{village}$ = number of villages
$n_{commune}$ = number of communes.

Cost of vaccination in the rabies-free zones of Tan An town

The implementation and maintenance of rabies-free zones are the objectives of the official rabies control plan of Long An province. The definition of a zone is highly specific but can be modified according to the resources in each province; thus, it is included in Scenario 2.

$$C_{vac\_freezone} = C_{vac\_ani2} + C_{supervisor3} + C_{owner\_time2}$$

In which:

$$C_{vac\_ani2} = n_{animal3} * p_{vaccine1}$$

$$C_{vac\_transportation} = n_{time} * p_{vac\text{-}transportation}$$

$$C_{owner\text{-}time2} = n_{animal3} * S_{hour\text{-}farmer} * t_{detach}$$

Legend:
$n_{animal3}$ = number of animals vaccinated in the free zone
$p_{vaccine1}$ = price of vaccine dose (includes only equipment and labor cost)
n_{time} = frequency of transportation vaccines from sub-DAH to free zone location (commune)
$p_{vac\text{-}transportation}$ = cost of one-time vaccine transportation
$C_{supervisor3}$ = cost of vaccination monitoring in the rabies-free zone
$C_{owner\text{-}time2}$ = Farmers' time costs of restraining animals for vaccination purposes.

Cost of control measures in humans (CMHs)

The cost of human rabies control measures for Scenario 1 was separated into four components. The components were pre-exposure treatment costs ($C_{Pre\text{-}Exposure}$), post-exposure treatment (PET) costs (C_{PET}), awareness program costs ($C_{awareness}$), and costs for training veterinary and health-care staff on rabies surveillance and prevention ($C_{training\_PH}$).

In Scenario 2, two additional components ($C_{awareness\text{-}school}$ and $C_{training\text{-}DAH}$) were included to reflect local conditions. Rabies awareness programs in schools (supported by a university and private company) were included to strengthen students' knowledge of rabies and rabies control in primary schools in the Duc Hue district. This activity was organized and delivered by veterinary students through the performance of a "mini gameshow," accompanied by a question-and-answer session. Additional community training and awareness programs were also organized by the DAH in 2022, similar to the annual training performed by the Centers for Disease Control and Prevention (CDC) and the Sub-DAH in Long An.

Pre-exposure treatment ($C_{Pre\text{-}Exposure}$)

Pre-exposure treatment for rabies is useful for people working closely with animals and therefore at high risk of exposure. At present, some government veterinary staff at varying administrative levels are included in the study, but other high-risk people such as laboratory staff and dog owners are excluded from the calculation. Pre-exposure treatment is defined as three injections of the vaccine (Verorab rabies vaccine [Sanofi Pasteur, Lyon, France] by intramuscular or subcutaneous injection on day 0, 7, and 21 or 28).

$$C_{Pre\text{-}Exposure} = n_{Pre\text{-}Exposure} * 3 * p_{vaccine\_human} * per_{vaccine\_pre}$$

Legends:
$n_{Pre\text{-}Exposure}$ = number of high-risk individuals (veterinarians at commune, district, and provincial level)
3 = number of vaccine doses (per treatment)
p_{vacine_human} = cost of one vaccine dose (Verorab)
$per_{vaccine\_pre}$ = percentage of high-risk individuals who comply with pre-exposure vaccination.

PET (C_{PET})

PET for animal bite cases includes injection with tetanus toxoid ($C_{tetanus}$), injection with one dose of immunoglobulin ($C_{immunoglobulin}$), and five doses of the rabies vaccine ($C_{vaccine\_human}$). Depending on the severity of the wound, as assessed by a physician, tetanus toxoid may be administered. Wound severity was classified into four levels, and patients with wounds classified at the third level or higher were recommended for treatment with vaccine (five doses) and immunoglobulin (one dose). Patients with wounds at the second level received the rabies vaccine only, whereas those with wounds at the first level were not administered any treatment [22]. The TCs also include transportation from home to the health-care facility and support.

$$C_{PET} = C_{tetanus} + C_{immunoglobulin} + C_{vaccine\_human} + C_{tranportation} + C_{supporter\_patient}$$

In which:

$$C_{tetanus} = p_{tetanus} * n_{bitten} * per_{tetanus}$$

$$C_{immunoglobulin} = p_{immunoglobulin} * n_{bitten} * per_{immunoglobulin}$$

$$C_{vaccine\_human} = p_{vacine\_human} * n_{bitten} * n_{doses} * per_{vaccine}$$

$$C_{tranportation} = n_{doses} * km * p_{per\text{-}km} * n_{bitten}$$

$$C_{supporter\_patient} = n_{doses} * S_{day\text{-}farmer} * n_{bitten} * 2$$

Legend:
$C_{tetanus}$ = Total annual tetanus vaccine cost
$p_{tetanus}$ = Price of one tetanus vaccine per patient
n_{bitten} = Number of animal bite cases per year
$per_{tetanus}$ = Percentage of patients who received tetanus vaccines
$C_{immunoglobulin}$ = Total annual immunoglobulin injection cost
$p_{immunoglobulin}$ = Price of one immunoglobulin dose per patient
$per_{immunoglobulin}$ = Percentage of patients administered immunoglobulin
$C_{vaccine\_human}$ = Total annual cost of rabies vaccine
n_{doses} = Number of vaccine doses per rabies treatment
Km = Average distance from home to the healthcare facility
$p_{per\text{-}km}$ = Cost per motorcycle (VND per km)
$S_{day\text{-}farmer}$ = Daily salary for farmer (×1000 VND)
$per_{vaccine}$= Percentage of animal-bite cases that get PEP.

Awareness program costs ($C_{awareness}$)

The rabies awareness program included radio ($R_{awareness}$) and television ($R_{awareness}$) broadcasts at the commune level, as well as a mobile awareness program ($M_{awareness}$) and distribution of printed leaflets (L).

$$C_{awareness} = R_{awareness} + M_{awareness} + L + TV_{awareness}$$

In which:
$R_{awareness} = n_{commune} * p_{radio}$
$M_{awareness} = n_{commune} * p_{mobile}$
Legend:
p_{radio} = Cost of broadcast in each commune
p_{mobile} = Cost of broadcasting using the motorbike.

Awareness programs for secondary schools

As part of the support for rabies awareness provided by a private company and veterinary students, several primary schools in one district will be selected for the awareness program. The activities included the performance of a "mini gameshow," accompanied by a question-and-answer session as described above.

$$C_{awareness\text{-}school} = n_{school} * p_{awareness\text{-}school}$$

Legend:
n_{school} = Number of schools to implement the awareness program
$p_{awareness\text{-}school}$ = Price of each awareness program.

Training healthcare and veterinary staff on rabies surveillance and prevention measures by provincial authorities

Each year, one training was organized by provincial authorities to improve the behaviors and skills of healthcare and veterinary staff in all districts in Long An province. This event was led by the sub-DAH and the Center of Disease Control of Long An province.

$$C_{training\text{-}PH} = n_{staff\text{-}district} * n_{district} * (Allowance_1 + Accommondation_1) + O_{training}$$

Legend:
$n_{staff\text{-}district}$ = Amount of healthcare and veterinary staff

per district
$n_{district}$ = Number of districts
$Allowance_1$ = Daily stipend per staff member
$Accommondation_1$ = Daily cost of accommodation per staff member
$O_{training}$ = Organization fees for training (package).

Training healthcare and veterinary staff on rabies surveillance and prevention measures implemented by the DAH

In 2022, Long An province was selected to participate in a project aimed at improving the rabies surveillance skills of public health and veterinary staff. Therefore, the associated costs of this activity were included in Scenario 2. As the specific costing information related to this training was unavailable, the costs associated with similar previous health-care training programs for which the cost was known were used to estimate it.

$$C_{training\text{-}DAH} = n_{staff\text{-}district} * n_{district} * (n_{day} * Allowance_2 + (n_{day}-1) * Accommondation_2) + O_{training}$$

Legend:
n_{day} = Number of training days
$Allowance_2$ = Daily stipend per staff member
$Accomondation_2$ = Daily cost of accommodation per staff member.

Assumptions and data analyses

A deterministic economic model was built using R software version 4.3.0 (R Core Team. [2024]. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing retrieved from https://www.r-project.org) using the framework described by Wera *et al*. [13]. In summary, the TCs of control measures included the costs of control measures in dogs and cats (CMA) plus the cost measures in humans (CMH).

All human animal bite wounds that healed without any treatment were assumed to have no cost to the program. Half of the animal bite cases that did have wounds requiring treatment were assumed to have received tetanus vaccine, 20% of high-risk individuals were assumed to have received pre-exposure treatment, and none of the animal bite cases were assumed to have received pre-exposure treatment. In addition, all animal bite cases were assumed to have received at least five doses of the rabies vaccine at a medical center.

The cost of each measure was ranked according to its contribution to the TC. They were also classified according to whether they were of a public nature (paid by the provincial or district governmental budget) or a private nature (paid by dogs' owners, animal-bite patients, or private companies).

A sensitivity analysis was also conducted to identify the input parameters that were most influential on the overall cost of the program. To complete the sensitivity analysis, a univariate analysis was conducted in which each input parameter was increased and decreased by 10% around a default input value while simultaneously holding the value of all other input parameters constant. The percentage change in the output was recorded and compared.

Results

TC of control measures

The cost of control measures for rabies in animals (Table-1) [21] and humans (Table-2) [21–24], which were input data for economic analysis, are presented separately with their source of information.

Under the two scenarios, the TC of rabies control in Long An province was estimated to be VND 62.62 and 62.77 billion in 2022 (equivalent to USD 2.67 and 2.68 million) for Scenario 1 (with external support) and Scenario 2 (without external support). The costs of CMHs in each scenario (84.95% and 84.81%) were approximately five times higher than those in animals (15.05% and 15.19%). When ranked individually, regardless of control measures in animals or humans, the cost of PEP in humans contributed the highest proportion to the TC, accounting for 84.52% and 84.30% of the TCs, followed by the cost of mass vaccination on the animal population paid by the animal's owner (14.28% and 13.90%), cost of animal management (0.42% and 0.42%), and awareness campaigns (0.33% and 0.33%). In Scenario 2, the cost of mass vaccination in the animal population (paid by a private company) accounted for 0.27% of the TC, followed by the cost of vaccination in the rabies-free zone (0.24%). The other costs in both scenarios accounted for <0.20% of the TCs (Table-3).

Of the TCs of rabies control measures, the percentage paid by private sectors for Scenarios 1 and 2 (98.83% and 98.75%) were higher than those paid by the public sector (1.17% and 1.25%). Usually, the person responsible for the cost of vaccination in the animal population is the owner, except in some rabies-free zones (12 of 188 communes) where the vaccine cost was paid for by the government and the labor cost for vaccination was paid by animal owners (included in the calculations under Scenario 2). Private costs (84.50% and 84.30%) incurred by animal bite patients were associated with PEP. For clarification, a small budget within the Sub-DAH is available for the treatment of staff when PEP is needed. However, this cost was excluded from the analysis as insufficient detail about this internal funding was available to represent it accurately in the analysis.

Distribution of costs of control measures in animals

Under the two scenarios, the TC of the animal rabies control measures over 1 year was estimated to be VND 9.4 or 9.5 billion (equivalent to USD 402 and USD 406 thousand), respectively. The cost of mass vaccination in the animal population (paid by the animal's owner) was the most costly measure, accounting

Table-1: Description of the cost of controlling rabies in animals.

Input data	Abbreviation	Value		Source information
		Scenario 1	Scenario 2	
Cost of mass vaccination in the animal population				
Cost of government				
Number of working days of Sub-DAH employees for vaccination monitoring	$n_{working\_day2}$	1	1	[21]
Number of province-level supervisors	$n_{supervisor}$	6	6	[21]
Number of communes supervised per year by sub-DAH employee	$n_{commune1}$	10	10	[21]
Daily salary for employees (×1000 VND)	S_{day2}	130	130	[21]
Price of transportation for vaccination monitoring purpose (×1000 VND)	$p_{transportation}$	1800	1800	[21]
Number of transportation times	$t_{transportation}$	10	10	[21]
Number of working days of district veterinarians for vaccination purposes	$n_{working\_day3}$	1	1	[21]
Number of district-level supervisors	$n_{district\_vet}$	2	2	[21]
Number of communes supervised per year in each district veterinary	$n_{commune2}$	188	188	[21]
Price of one liter gasoline (×1000 VND)	$p_{gasoline}$	25	25	[21]
Amount of gasoline (liter)	$n_{gasoline}$	752	752	[21]
Cost of animal owner				
Price of one dose rabies vaccine (×1000 VND)	$p_{vaccine1}$	25	na	Field survey
Number of animals to be vaccinated in Long An province (exclude Duc Hue district)	$n_{animal1}$	79,500	79,500	[21]
Number of animals to be vaccinated in the Duc Hue district (100%)	$n_{animal2}$	5664	5664	[21]
Hourly salary of farmer (×1000 VND)	S_{hour_farmer}	20	20	Author estimation
Time to remove the animal for vaccination (hour)	t_{detach}	0.25	0.25	Author estimation
Costs for private companies and universities				
Price of one dose rabies vaccine (×1000 VND)	$p_{vaccine2}$	na	16	Field survey
Price of needle and syringe used for vaccination (×1000 VND)	$p_{needle\_syringe}$	na	1.85	Field survey
Number of working days for vaccination	$n_{working\_day1}$	na	7	Field survey
Daily salary for volunteers (×1000 VND)	S_{day1}	na	170	Pilot study
Number of volunteers	$N_{vaccinator}$	na	50	Pilot study
Number of districts where volunteers performed vaccinations	$n_{district1}$	na	1	Pilot study
Daily salary for supporter (local guide) (×1000 VND)		na	150	Pilot study
Number of supporters		na	11	Pilot study
Cost of postvaccination monitoring				
Number of tests per year	n_{test}	61	61	[21]
Cost of one ELISA test (×1000 VND)	C_{ELISA}	160	160	[21]
Cost of sampling equipment (one package) (×1000 VND)	$C_{equip\_sampling}$	2133	2133	[21]
Salary for sampling (×1000 VND)	S_{day3}	18	18	[21]
Number of laborers working per day per commune	n_{labour_day}	4	4	[21]
Number of communes monitored annually	$n_{commune3}$	7	7	[21]
Quota gasoline per unit of labor	$n_{litre\ per\ labor}$	2	2	[21]
Cost of hiring a car to transport samples to the laboratory (×1000 VND)	$C_{sending\_samples}$	1000	1000	[21]
Number of labors follow-up sample's transportation to laboratory	$n_{send\_samples}$	1	1	[21]
Subvention fee for one sample (×1000 VND)	$p_{subvention}$	180	180	[21]
Cost of diagnosing suspected rabies				
Number of suspected animals submitted to the regional laboratory annually	$n_{suspect\_ani}$	6	6	Sub-DAH estimation
Cost of diagnostic laboratory (Reverse transcription–polymerase chain reaction) (×1000 VND)	$c_{laboratory}$	555	555	[21]
Cost of collecting samples (×1000 VND)	$C_{collect}$	177	177	[21]
Transportation cost from district veterinarian station to Sub-DAH (provincial level) (×1000 VND)	$C_{transport1}$	29	29	Author estimation
Transportation cost from Sub-DAH (provincial level) to regional laboratory (×1000 VND)	$C_{transport2}$	1800	1800	[21]
Allowance for Sub-DAH employees to send samples (×1000 VND)	$A_{employee}$	130	130	[21]
Number of employees involved in the case investigation	$n_{collaborators}$	4	4	[21]

(*Contd...*)

Table-1: (*Continued*).

Input data	Abbreviation	Value		Source information
		Scenario 1	Scenario 2	
Cost of disease investigation (track back from suspected cases in humans)				
Number of human cases that should be tracked annually	$n_{suspect\_human}$	201	201	Field survey
Allowances per case (×1000 VND)	A_{case}	400	400	Field survey
Cost of animal management				
Allowance for village chefs (×1000 VND)	$A_{village\_chef}$	200	200	[21]
Cost of statistical documents at village level (×1000 VND)	$D_{village}$	30	30	[21]
Allowance for commune veterinarians (×1000 VND)	$A_{commune}$	150	150	[21]
Cost of statistical documents at the commune level (×1000 VND)	$D_{commune}$	25	25	[21]
Number of villages in each village	$n_{village}$	997	997	[21]
Cost of vaccination-free zones				
Number of animals to be vaccinated in free zones	$n_{animal3}$	na	3834	[21]
Amount of vaccine transportation times from sub-DAH to the free zone location (commune)	n_{time}	na	12	[21]
Price of one vaccine transportation time (×1000 VND)	$p_{vac\text{-}transportation}$	na	1800	[21]
Cost of vaccination monitoring activity in the rabies free-zone (×1000 VND)	$C_{supervisor3}$	na	37,290	[21]

DAH=Department of Animal Health, na= not attempted

Table-2: Description of cost of controlling rabies in humans.

Input data	Abbreviation	Value		Source information
		Scenario 1	Scenario 2	
Pre-exposure treatment				
Number of high–risk people (veterinary at commune, district and Province level)	$n_{Pre\text{-}Exposure}$	334	334	Author calculation
Price of one dose vaccine Verorab (×1000 VND)	p_{vacine_human}	290	290	Field survey
Percentage of high-risk individuals who received pre-exposure vaccination	$per_{vaccine\_pre}$	0.2	0.2	Author estimation
Post-exposure prophylaxis				
Price of one dose of tetanus vaccine (×1000 VND)	$p_{tetanus}$	85	85	Field Survey
Number of bitten cases	n_{bitten}	15,221	15,221	[23]
Percentage of patients who received tetanus vaccines	$per_{tetanus}$	0.5	0.5	Author assumption
Price of immunoglobulin (×1000 VND)	$p_{immunoglobulin}$	700	700	[23]
Percentage of patients administered immunoglobulin	$per_{immunoglobulin}$	0.43	0.43	[23]
Number of doses of the rabies vaccine (PEP)	n_{doses}	5	5	[24]
Average distance from home to the healthcare center		40	40	Field survey
Quota for motorbike (VND/km)		625	625	Author estimation
Daily salary for farmer (×1000 VND)		160	160	Author estimation
Percentage of bitten cases with PEP		0.96	0.96	[23]
Awareness program costs				
Price of broadcast in a commune (×1000 VND)	p_{radio}	200	200	[21]
Price of broadcast using motorbike (×1000 VND)	p_{mobile}	500	500	[21]
Leaflets (×1000 VND)	L	50,000	50,000	[21]
Broadcast on television (×1000 VND)	$TV_{awareness}$	25,000	25,000	[21]
Awareness program for primary school children				
Number of schools that organize awareness programs	n_{school}	na	2	Field survey
Price of each awareness program	$p_{awareness\text{-}school}$	na	2,500,000	Field survey
Training on surveillance and prevention measures				
Number of healthcare and veterinary staff members per district	$n_{staff\text{-}district}$	2	2	Field survey
Number of districts	$n_{district}$	15	15	Field survey
Daily allowance per staff (×1000 VND)	$A_{llowance1}$	80	80	Field survey
Daily accommodation per staff (×1000 VND)	$Accomondation_1$	80	80	Field survey
Organization fee for training (package) (×1000 VND)	$O_{training}$	12,000	12,000	Field survey
Training on surveillance and prevention measures implemented by the DAH				
Number of training days	n_{day}	na	2	Field survey
Daily allowance per staff (×1000 VND)	$Allowance_2$	na	150	Field survey
Daily accommodation per staff (×1000 VND)	$Accomondation_2$	na	430	Field survey

DAH=Department of Animal Health, na= not attempted

Table-3: Distribution of cost of rabies control measures in animals and humans at the province level (in VND and USD).

Item	Scenario 1			Scenario 2			Distribution of costs (%)
	Value (×1000 VND)	Value (USD)	%	Value (×1000 VND)	Value (USD)	%	
Cost of animal control measures	9,427,717	401,863	15.05	9,533,899	406,389	15.19	
Cost of mass vaccination of the animal population paid by the government	93,480	3984	0.15	93,480	3984	0.15	Public
Cost of mass vaccination of animal population paid by owners	8,942,220	381,169	14.28	8,723,940	371,864	13.90	Private
Cost of mass vaccination of animal population paid by private company	na	na	na	172,152	7338	0.27	Private
Cost of postvaccination monitoring	30,141	1285	0.05	30,141	1285	0.05	Public
Cost of diagnosing suspected rabies	19,266	821	0.03	19,266	821	0.03	Public
Cost of disease investigation	80,400	3427	0.13	80,400	3427	0.13	Public
Cost of animal management	262,210	11,177	0.42	262,210	11,177	0.42	Public
Cost of vaccination in rabies-free zones	na	na	na	152,310	6,492	0.24	Public (0.06) + Private (0.18)
Cost of human control measures	53,195,952	2,267,517	84.95	53,234,852	2,269,175	84.81	
Pre-exposure treatment costs	58,116	2,477	0.09	58,116	2477	0.09	Private
Post-exposure treatment costs	52,914,436	2,255,517	84.50	52,914,436	2,255,517	84.30	Private
Awareness	206,600	8,806	0.33	206,600	8806	0.33	Public
Annual training by the Sub-DAH and CDC	16,800	716	0.03	16,800	716	0.03	Public
Awareness of primary and secondary schools	na	na	na	5,000	213	0.01	Private
DAH training	na	na	na	33,900	1445	0.05	Public
Total costs	62,623,670	2,669,380	100.00	62,768,752	2,675,564	100.00	

*1 USD=23,460 VND (value reference in December 2022), DAH: Department of Animal Health, CDC: Centers for Disease Control and Prevention

for 94.85% and 91.50% of the total annual costs of rabies control in the animal sector (USD 381 and 372 thousand, respectively), followed by the cost of animal management at 2.78% and 2.75% (USD 11.2 thousand in each scenario), cost of vaccination paid by the government at 0.99% and 0.98% (USD 3.98 thousand/each scenario), cost of disease investigation at 0.85% and 0.84% (USD 3.43 thousand), cost of post-vaccination monitoring at 0.32% (USD 1.29 thousand in each scenario), and the cost of confirmatory testing for rabies in suspect dogs at 0.2% (USD 821 in each scenario). The other costs in both scenarios accounted for <1.00% of the total animal sector control expenditure. In addition, in Scenario 2, the cost of mass vaccination in the animal population (paid by a private company) accounted for 1.81% (USD 7.34 thousand), followed by the cost of vaccination in the rabies-free zone at 1.60% (USD 6.49 thousand).

Distribution of costs of CMHs

Under both scenarios, the TCs of human rabies CMHs for the year under study were estimated at VND 53.19 and 53.23 billion (equivalent to USD 2.27 million). PEP was the costliest measure in both scenarios at 99.47% and 99.40% (USD 2.26 million), followed by costs of awareness at 0.39% and 0.39% (USD 8.81 thousand in each scenario), cost of pre-exposure treatment at 0.11% and 0.11% (USD 2.48 thousand in each scenario), and the cost of annual training at 0.03% and 0.03% (USD 716 in each scenario). The other costs in Scenario 2 contributed 0.07% of the total annual cost of rabies control.

Sensitivity analysis and prediction of the future cost for the period of 2023–2030

An increase or decrease of any single input value in the economic model by 10.00% changed TC very little (median change of 0.01%) in both scenarios. The TC of control measures was the most sensitive to changes in the PEP treatment cost. An increase in PEP cost by 10.00% resulted in 8.45% (Scenario 1) and 8.41% (Scenario 2) increases cost. The mass vaccination cost (paid by the owner) was the second most influential input. Increasing or decreasing this cost by 10% resulted in a change of 1.42% (Scenario 1) and 1.38% (Scenario 2) in the TC. The least influential input parameters were the annual training cost (in both scenarios) and the awareness program for schools (Scenario 2). The forecasted cost of the rabies control program from 2023 to 2030 was calculated using the pre-defined inflation percentage, as presented in Table-4.

Discussion

Following the implementation of the One Health approach for rabies control strategy in Vietnam, the current economic study was conducted, focusing on understanding the component costs associated with activities to prevent and fight against rabies in

Table-4: Estimation of future costs.

Year	Scenario 1 (×10⁶ VND)	Scenario 2 (×10⁶ VND)
2022	62,623	62,768
2023	66,381	66,535
2024	70,364	70,527
2025	74,586	74,758
2026	79,061	79,244
2027	83,804	83,999
2028	88,833	89,039
2029	94,163	94,381
2030	99,817	100,044

the human and animal sectors. Unlike other published models that focused predominantly on the cost-effectiveness of rabies control at the national level over an extended time period, the current study represents an economic model that helps explain the value of adopting a One Health approach for rabies control over a 1-year period, specifically focused at the provincial level in Vietnam. The economic model results can help provincial veterinary authorities estimate activity-based and total program costs using primary input data, thereby providing valuable insights for local policymakers in effectively planning and optimizing budgets for rabies control programs. The model has been tested in some pilot areas in Southern and Central Vietnam with positive feedback. Based on the feedback, the final model is presented as an Excel file displaying the TCs of the program, stratified according to whether the costs are borne by public or private sources. The model suggested that rabies control comes at a significantly higher cost than what has been reported by the government's economic model (referenced as the budget planned of Sub-DAH Long An) [21], mainly because the current model included community costs (combine of public and private costs), unlike the government's model, which only considers public sector expenses and underscores the importance of considering all costs when assessing a rabies control program. In addition, it highlights the difference between the cost of vaccinating animals and the potential expenses (i.e., hospitalization and PEP) that pet owners may incur if their animals are involved in bite incidents. This awareness could influence owners' attitudes and practices regarding animal vaccination. Consequently, the model could serve as a valuable reference for provincial veterinary authorities' planning efforts.

Others have reported that the ideal program for addressing rabies should include mass vaccination of dogs, dog population management, and integrated management of bite cases (i.e., a One Health approach that involves follow-up in the field by veterinary authorities) that is complemented by judicious use of PEP and a 1-week intradermal rabies vaccine regimen for humans [25].

The costs of disease investigation, post-vaccination monitoring, and confirmatory diagnosis of suspected rabies in dogs account for <1% of the TCs in the current model. These costs could be underestimated because limited input data were available to compute these costs. For example, the cost of diagnosing suspected rabies dogs was based on six suspected animals per year, which is consistent with the average number of suspected cases reported in Southern Vietnam from 2017 to 2021 [26]. However, it should be noted that there were more than 190 suspected cases of rabies in Long An province in 2022 [23]. The high fluctuation of this number suggests that it needs to be reconsidered in any future modeling efforts. The cost of mass vaccination of the animal population significantly contributes to the TC of rabies control, reflecting the government's effort or commitment to rabies control through this measure.

Animal rabies vaccination is relatively inexpensive (varies from USD 0.72 to 2.13 per single dose) in Vietnam, similar to the estimated cost of vaccination in other parts of the world [27, 28]. However, it could be a valuable expense for farmers in rural or remote areas. Subsidizing the cost of dog rabies vaccination among low-income households could improve vaccination coverage rates [24]. The rationale behind this is that households manage the broad economic challenges confronted by impoverished households, which often limit their ability to access and finance vaccination services for their animals [29]. This issue may explain the considerable variation between provinces in vaccination coverage of the animal population, which has been previously observed by the Department of Animal Health [6].

This model could be a valuable tool to assist veterinary authorities in estimating the cost of rabies control in their region, especially for areas that have yet to implement a vaccination program. Moreover, implementing subsidies would help to alleviate the financial burden on such households, making the vaccination process more economically viable and accessible. The imperative to enhance vaccination coverage among low-income households is of paramount importance in the context of effective rabies control given that dogs within these socioeconomically challenged settings may act as vectors transmitting rabies to humans. Ensuring collective access to and affordability of vaccination services, particularly for low-income households, promises to elevate overall vaccination coverage. This intervention is expected to fortify rabies control measures within a broader population [30].

The very low proportion of program costs related to rabies awareness programs (<1%) demonstrates the limited resources allocated to these activities in the prevention and control plan. Currently, rabies awareness programs in Vietnam are based on simple, conventional methods, such as distributing leaflets to raise awareness among animal owners. Future initiatives should allocate more resources to adopt diverse approaches to enhance effectiveness, considering avenues such as radio broadcasts, postcards, and awareness campaigns targeting secondary and high school students. An important point in these awareness programs should continue to be urging animal owners to proactively seek vaccination for their animals, underscoring the responsibility for their health and the communities' well-being.

The importance of PEP in the endemic context of rabies in Vietnam plays a critical role in averting rabies-associated mortality. Nevertheless, despite vaccine availability, a deficit exists in adherence to the prescribed treatment guidelines, as evidenced by a 50% completion rate for PEP among individuals who are expected to undertake the recommended five-dose intramuscular injections [30].

There are limitations regarding the data available for analysis in the current study. Since the deterministic economic model was developed by integrating available epidemiological and economic data, scientific literature, official documents and plans, and information from multi-disciplinary experts who were directly involved in rabies control measures at different levels, the resulting estimates are associated with uncertainty because some input data were known to be highly variable or were influenced by the author's subjectivity. In Vietnam, there is no available field data on the cost of rabies vaccination that animal owners actually pay at veterinary clinics. In addition, the model does not account for a wide range of options when vaccine prices fluctuate (both for humans and animals) or when other patterns change. Subsequently, the model's accuracy in predicting outcomes under varying economic conditions in particular provinces remain constrained. However, the current model (available as supplementary data) provides an important first step toward improving Vietnam's rabies control over time. A planned next step involves the development of a stochastic model, broadly based on the previously presented deterministic model, to address these limitations. The new model will incorporate distributions of actual costs rather than only fixed values and potentially incorporate a method to determine the effect of changes in policy implementation (such as adjustments in the projected vaccination rates on the animal side or an increase in preventive vaccination uptake on the human side). The new model will also attempt to integrate a function to help non-experts better understand the numeric results produced by the model. Moreover, the model will be expanded to cover a broader range of geographical areas across Vietnam, reassuring its feasibility in various contexts and enhancing its ability to accurately reflect real-life conditions.

Conclusion

Using a One Health approach, this study presents a transparent and reproducible way to calculate the economic costs of rabies control at the provincial level. Rabies has a significant economic impact on dog owners, patients, and governments. The control of rabies through mass vaccination is a more effective way to prevent rabies in humans than PEP. Although this approach is costly for dog owners, it is less expensive than PET for dog bite patients. The findings offer valuable insights for local policymakers to optimize resource allocation and sustain effective control measures. This model can be used by other provincial Peoples' Committees, which are the official authority responsible for rabies control activities in Vietnam and other rabies-endemic regions, to provide an overall economic assessment of the rabies control program.

Authors' Contributions

BDT: Conceived and designed the study. TPT, NTTD, and NTPT: Field survey. MTD, SHL, DTTD, and VTKO: Designed and aided in data collection. BDT, PP, BTTM, and DHP: Data analysis and interpretation. BDT, TPT, and NTTD: Drafted the manuscript. BDT, DHP, PP, MTD, SHL, and BTTM: Revised the manuscript. All authors have read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

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