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Estimation of Sustainable Harvest Quota and Financial Analysis of *Rusa timorensis* in Intensive Captive Breeding

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Abstract

Captive breeding of *Rusa timorensis* is one of the conservation efforts aimed at maintaining a balance between conservation and sustainable utilization. To effectively manage this balance, it is crucial to establish a utilization level that does not compromise the population's viability, which requires a thorough understanding of its demographic parameters. Furthermore, the sustainability of the breeding program itself is contingent upon its financial feasibility. This study aims to estimate demographic parameters, determine sustainable harvest quotas, and assess the financial feasibility of deer breeding in the Dramaga Research Forest, Indonesia. Methods included logbook analysis, observation, literature review, and interviews. Results show that the sustainable harvest quota under the intensive breeding system is 10 *Rusa timorensis* over the 2019–2023 period. The financial analysis demonstrates strong economic viability, with a Net Present Value of IDR 643 million at a 10% discount rate. The project demonstrated a Benefit-Cost Ratio exceeding 1, an Internal Rate of Return reaching 54%, and a rapid Payback Period of only 1.68 years. These findings suggest that intensive breeding can support both conservation objectives and economic profitability. Efficient management remains essential to ensure population sustainability and optimize benefits.

Keywords: captive breeding, financial analysis, harvest quotas, *Rusa timorensis*, sustainable harvest

1. Introduction

Wildlife captive breeding is one of the key strategies to maintain a balance between conservation efforts and the sustainable use of natural biological resources [1]. In the context of *Rusa timorensis*, known locally as rusa Timor, captive breeding serves as a solution to reduce pressure on wild populations while legally and sustainably meeting market demand [2]. The government has established regulations on captive breeding practices through the Minister of Forestry Regulation No. P.19/Menhut-II/2005, which states that, besides serving conservation purposes, captive breeding also offers economic potential through controlled harvesting. However, determining the sustainable harvest quota remains a challenge in *Rusa timorensis* breeding [3].

One approach used to determine a sustainable harvest quota is the Minimum Viable Population (MVP) method, which considers demographic parameters to ensure long-term population viability [4]. Population demographics are essential in determining the sustainable harvest limits that ensure population stability remains uncompromised [5]. In an intensive captive breeding system, deer management is conducted under controlled conditions, including the provision of feed, health monitoring, and reproductive regulation. Calculating the harvest quota becomes even more critical to maintaining a balance between productivity and population sustainability [6,7].

In addition to harvest quota considerations, the cost analysis of captive breeding is a crucial factor in determining the sustainability of *Rusa timorensis* breeding operations [3]. Intensive breeding systems require significant investment in feed provision, health management, infrastructure, and labor, and as population growth rates increase, resource requirements also rise, leading to higher operational costs [8–11]. Therefore, an in-depth study on the relationship between breeding costs and sustainable harvest quotas is necessary to ensure efficient and sustainable management. This study aims to estimate the sustainable harvest quota for *Rusa timorensis* using the MVP approach and analyze the financial aspects of intensive captive breeding systems to provide recommendations for optimal harvesting strategies and effective financial planning.

2. Materials and Methods

2.1. Study Area

This study was conducted within an intensive captive breeding program located in the Dramaga Research Forest, West Bogor District, Bogor City. The facility operates under the management of the Research and Development Center for Conservation and Rehabilitation [12]. Primary data collection, consisting of direct observations and semi-structured interviews, was carried out from December 2023 to February 2024. The analysis in this study utilized retrospective secondary data, specifically demographic logbooks and financial records, covering a five-year period from 2019 to 2023.

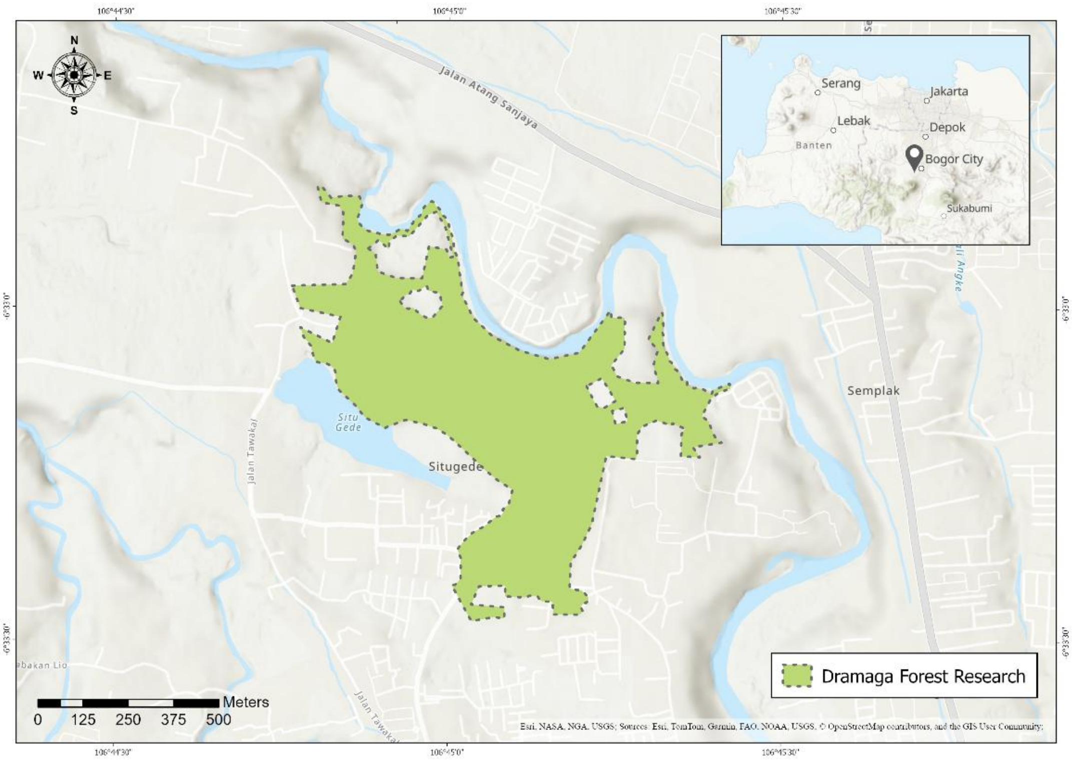

Figure 1. Map illustrating the study site within the Dramaga Research Forest, located in West Bogor, Bogor City, West Java, Indonesia.

3. Objects, Instruments, Tools, and Materials

This study examines *Rusa timorensis* and various related aspects, including breeding locations, feeding practices, and management within an intensive captive breeding. The data utilized in this study encompass the demographic characteristics of the deer and the financial aspects of the breeding operation from 2019 to 2023. Data processing and analysis were conducted using Microsoft Excel, specifically its financial analysis functions, including NPV, BCR, IRR, and PP, with results cross-checked through manual calculations to ensure accuracy. The research instruments used include writing tools for interviews with the captive breeding staff and a camera to document the facility conditions.

3.1. The types of data

To address the research objectives, a clear identification of the variables and relevant data collection methods is required. These variables were selected based on biological, ecological, and financial aspects that serve as the main focus of the intensive captive breeding study of

Rusa timorensis. Furthermore, the data collection methods were adjusted to the characteristics of each variable, including logbook analysis, observations, interviews, and literature review. The details of the research objectives, variable types, and data collection methods are presented in **Table 1**.

Table 1. Research objectives, variables, and data collection methods.

No.	Research Objective	Variable Type	Data Collection Method
1	Estimating demographic parameters of *Rusa timorensis* in intensive breeding	Natality, Mortality, Fecundity, age distribution, Sex ratio, Number of individuals in a specific age class	Logbook analysis, Interviews, Observations, Literature review
2	Estimating the minimum viable population (MVP) of *Rusa timorensis* in intensive breeding	Minimum Viable Population, Sustainable Harvest Quota	Logbook analysis, Literature review
3	Financial analysis of intensive captive breeding with a scenario where deer are sold live.	NPV, $Net\frac{B}{C}$, IRR, PP	Logbook analysis, Observations, Interviews, Literature review

NPV= Net Present Value, BCR= Benefit Cost Ratio, IRR= Internal Rate of Return, PP= Payback Period

3.2. Data Collection

Data collection was conducted using multiple approaches to ensure the completeness and accuracy of the information obtained. Each method was selected according to its relevance to the research variables analyzed. Logbook analysis served as the primary source of quantitative data, while interviews and observations were employed to validate and enrich the information. Additionally, a literature review was conducted to support the interpretation of primary data and to compare the findings with those of previous studies. The combination of these methods was expected to provide a comprehensive overview of the research parameters.

3.2.1. Logbook Analysis

The logbook maintained by the breeding facility served as the main source of primary data in this study. The records included individual identification, births, deaths, and relevant reproductive parameters. These data were used to calculate demographic indicators, including natality, mortality, sex ratio, and fecundity. Furthermore, the logbook allowed population analysis based on age and sex classes, providing a quantitative description of population dynamics. Thus, the logbook functioned as the primary basis for estimating the demographic parameters of *Rusa timorensis*.

3.2.2. Interviews

Semi-structured interviews were conducted with a veterinarian, a financial officer, and two staff members responsible for daily activities in the captive breeding facility. The questions explored topics such as reproductive procedures, animal health protocols, records of births and deaths, financial transactions within the facility, and the informants' views on the challenges encountered in captive breeding. These interviews served to validate information from the logbooks and to obtain in-depth qualitative perspectives on the management system.

3.2.3. Observations

On-site observations were carried out within the enclosure area. These observations aimed to validate the data recorded in the logbook and to monitor enclosure conditions, animal behavior, visible health issues, and feeding activities. Observations also served to confirm the age class categorization recorded in the logbook, particularly in cases where documentation was incomplete.

3.2.4. Literature review

The literature review was used to complement and support the interpretation of primary data, particularly regarding the ideal sex ratio in captive breeding of *Rusa timorensis*. Additionally, it served as a scientific reference for comparing the observed demographic patterns—such as birth rates, mortality rates, and age structures—with findings from previous studies. Relevant literature also provided supporting data for estimating population viability thresholds and evaluating sustainable harvest levels within captive systems.

3.3. Data Analysis

Data analysis was conducted to calculate the demographic parameters of *Rusa timorensis* based on information obtained from logbooks, interviews, observations, and literature review. The main parameters analyzed included natality, mortality, sex ratio, and fecundity. Each parameter was calculated using formulas adapted from previous studies and adjusted to the conditions of intensive captive breeding. These calculations aimed to provide a quantitative description of population dynamics and serve as the basis for evaluating population viability and sustainable harvest quotas. The formulas used to calculate the demographic parameters are presented in the following section [13]:

$$N = \frac{\sum B_i}{\sum D_i} \quad (1)$$

$$M_x = \frac{N_{(x+1,t)} - N_{x,t}}{N_{(x,t)}} \quad (2)$$

$$S = \frac{J_i}{B_i} \quad (3)$$

$$F = \frac{x}{B} \quad (4)$$

Where:

N	:	Total population size
M_x	:	Mortality rate at age class x
S	:	Survival rate at age class x
F	:	Fecundity (offspring per breeding female)
B_i	:	Number of newborn individuals at site i
D_i	:	Number of females capable of reproduction
J_i	:	Number of males
$N_{x,t}$	:	Population size within age class x at time t
x	:	Number of offspring
B	:	Number of breeding females actively reproducing

The estimation of the *Minimum Viable Population* (MVP) was carried out using the Leslie matrix model, which represents reproduction patterns and survival rates of each age class. This matrix allows for a quantitative analysis of population dynamics based on age distribution and reproductive potential. From the matrix, a set of linear algebraic equations was derived to calculate the MVP size. The elimination method was applied to obtain accurate solutions, as presented in the following equations [14]:

$$\begin{vmatrix} A_x \\ R_x \\ D_x \end{vmatrix} = \begin{vmatrix} \delta_A & F_R & F_D \\ p_1 & \delta_R & 0 \\ 0 & P_2 & \delta_D \end{vmatrix} X \begin{vmatrix} A_0 \\ R_0 \\ D_0 \end{vmatrix}$$

Age-specific fecundity (Fx) describes the average number of offspring produced by individuals belonging to a specific age group. In contrast, age-specific survival (px) indicates the likelihood that individuals within a certain age class will survive and transition to the next age group. In addition, δx indicates the proportion of individuals in age class x that stay within the same age class in the subsequent year. A set of linear algebraic equations was derived from Leslie's matrix. The MVP size was obtained by applying the elimination method to solve these equations. The following equations were used in the process [15]:

$$N_0 = A + R + D$$

$$N_1 = (F.R + F.D + \delta_A) + [(A.p_1) + (\delta_R)] + [((1 - \delta_R)R.p_2) + \delta_D D]$$

N_2 = $\{F.[(A.p_1) + (\delta_R R)] + F.[(1-\delta_R)R.p_2 + \delta_D D] + \delta_A [F.R + F.D + (\delta_A A)]\} + \{p_1(F.R + F.D + (\delta_A A))\} + \delta_R[(A.p_1) + (\delta_R R)]\} + \{p_2(1-\delta_R)[(A.p_1) + (\delta_R R)] + \delta_D[((1-\delta R)R.p_2) + \delta_D D]\}$

Where:

A_x, R_x, D_x	:	Number of individuals in juvenile, sub-adult, and adult age classes at time x
A_0, R_0, D_0	:	Initial number of individuals in each class
F_D, F_R	:	Fecundity rates of sub-adults and adults
δ_A, δ_R, δ_D	:	Proportion of individuals remaining in the same age class
p_1, p_2	:	Transition probabilities between classes
F_x	:	Number of females capable of reproduction
p_x	:	Age-specific fecundity.

Next, the determination of the sustainable harvest quota can be calculated using the following equation:

$$Q_{ij} = N_{tij} - MVP_{ij} \quad (5)$$

Where

Q_{ij}	:	Sustainable harvest quota assigned to individuals in age category I and sex j.
N_{tij}	:	Number of individuals in age category i and sex j during year t.
MVP_{ij}	:	Minimum Viable Population required for age category i and sex j.

The assessment to determine the optimal and most efficient system for breeding *Rusa timorensis* is carried out by analyzing the sustainable harvest quota and evaluating the financial performance of the breeding operations. This financial evaluation involves calculating indicators such NPV, $Net\frac{B}{C}$, IRR, and PP, as detailed below [16,17]:

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} \quad (6)$$

$$Net\frac{B}{C} = \frac{\sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{C_t - B_t}{(1+i)^t}} \quad (7)$$

$$IRR = i_1 \frac{NPV_1}{NPV_1 - NPV_2} (i_2 - i_1) \quad (8)$$

$$PP = \frac{Initial\ investment}{Annual\ Cash\ Flow} \quad (9)$$

Where

B_t	:	Total benefits obtained in year t
C_t	:	Total costs incurred in year t
t	:	Operational year (time period), starting from 0, 1, 2, …, N
N	:	Total number of years (project duration)
i	:	Discount rate (%) used in financial evaluation
NPV	:	Net Present Value, representing the difference between discounted benefits and costs
$Net\frac{B}{C}$	:	Net Benefit–Cost Ratio, representing the ratio between total discounted benefits and total discounted costs
IRR	:	Internal Rate of Return, the discount rate at which NPV = 0
NPV_1	:	Positive Net Present Value (feasible scenario
NPV_2	:	Negative Net Present Value (unfeasible scenario)
i_1	:	Discount rate generating a positive NPV
i_2	:	Discount rate generating a negative NPV.
PP	:	Payback Period, representing the time required to recover the initial investment
Initial Investment	:	Total capital invested at the beginning of the project
Annual Cash Flow	:	Average annual net income (benefits minus costs)

In a business feasibility assessment, NPV serves as the primary indicator. A business is considered financially feasible when the NPV is greater than zero, as this signifies that the venture yields a profit. If the NPV equals zero, the project is at a break-even point, indicating that revenues and costs are balanced, resulting in neither profit nor loss. Conversely, a negative NPV implies that the business is not financially feasible due to incurred losses [18]. Another financial metric used to determine feasibility is the Net Benefit-Cost Ratio (Net B/C). A Net B/C greater than one indicates that the project is viable since the benefits outweigh the costs. If the Net B/C equals one, it implies the project is at a break-even point [19]. However, when the Net B/C is below one, the business is not feasible, as the benefits are insufficient to cover the costs.

The Internal Rate of Return (IRR) is also a key indicator. If the IRR exceeds the applied discount rate, the business is considered viable because it delivers returns higher than the expected rate. Conversely, if the IRR is below the discount rate, the project is considered unfeasible as it generates returns lower than the cost of capital [20,21]. The Payback Period (PP) serves as an indicator to measure the time required to recover a project's initial investment cost. A shorter payback period is considered more favorable as it signifies a quicker return on investment and implies lower risk [22]. A project is therefore typically deemed viable if its payback period is shorter than the maximum timeframe established by management or investors.

4. Results and Discussion

4.1. Results

4.1.1. Demographic Parameters of the Population

The demographic analysis of *Rusa timorensis* under intensive captive breeding at the Dramaga Research Forest involved four aspects: population size, age structure, sex ratio, and natality. These parameters were estimated using data compiled from daily logbooks that recorded births, deaths, and individual age development. Estimating these parameters is essential for evaluating population dynamics and reproductive success, particularly in the context of ex-situ conservation, which prioritizes population sustainability. Age structure was categorized into infant (0–9 months), juvenile (9–15 months), and adult (>15 months), based on biological growth stages [23]. The analysis results are presented in **Table 2**.

Table 2. Structure and trends of *Rusa timorensis* population in Dramaga Research Forest 2019– 2023.

Year	Age Structure						Total Population	Growth rate	Mortality rate	Fecundity
	Infant		Juvenile		Adult					
	M	F	M	F	M	F				
2019	0	5	0	0	21	8	34	-	-	-
2020	1	1	0	2	21	11	36	0.06	-	0.18
2021	1	1	0	2	21	12	37	0.03	0.03	0.17
2022	2	1	0	2	18	13	36	- 0.03	0.11	0.23
2023	0	2	1	1	18	14	36	-	0.06	0.14
Average								0.01	0.05	0.18

M= Male, F=Female

Over the observation period, based on logbook data analysis, the *Rusa timorensis* population ranged from 34 to 37 individuals. In 2019, there were 34 individuals, increasing to 36 in 2020 and reaching 37 in 2021. The population then decreased to 36 in 2022 and remained at the same level in 2023. These changes indicate minor fluctuations that had no significant impact on population stability. Overall, the population remained stable throughout the five-year observation period.

Across the five years, based on logbook data analysis, the average population growth rate was 0.01. The highest value was recorded in 2020 at 0.06, while the lowest occurred in 2022 at -0.03. Positive growth rates indicate an increase in the number of individuals, whereas negative values reflect a population decline. These variations were influenced by birth and death dynamics recorded in captivity. This condition suggests that the population can maintain itself despite annual fluctuations.

During the observation period, based on logbook data analysis, the average mortality rate was 0.05. The highest value occurred in 2023 at 0.11, while the lowest was recorded in 2021 at 0.03. In certain years, the mortality rate exceeded the natality rate, which could potentially lead to a decline in population size if it persists. Mortality exceeding births indicates pressure on population growth.

The average fecundity value of the population, based on logbook data analysis, was recorded at 0.18. Peak fecundity occurred in 2022 at 0.23, while the lowest was recorded in 2023 at 0.14. A comparison between fecundity and mortality shows that in some years, births were insufficient to offset deaths. Overall, although fecundity levels were moderate to high in certain years, this imbalance has the potential to negatively influence the long-term population trend.

4.1.2. Estimating the Minimum Viable Population (MVP) and Determining the Sustainable Harvest Quota

The Minimum Viable Population (MVP) analysis was conducted to determine the minimum population size required under captive breeding of *Rusa timorensis*. The demographic parameters analyzed included fecundity, mortality, and population structure during the 2019–2023 period. These MVP values were used as the basis for determining the Sustainable Harvest Quota (SHQ) that could be applied sustainably. **Table 3** presents the estimated MVP values across different age categories and sexes. In addition, the table also shows the estimated sustainable harvest quota that could be implemented during the observation period.

Table 3. MVP values and estimated sustainable harvest quota of *Rusa timorensis* 2019-2023.

Year	MVP						Sustainable Harvest Quota					
	Infant		Juvenile		Adult		Infant		Juvenile		Adult	
	M	F	M	F	M	F	M	F	M	F	M	F
2019	0	29	0	0	36	14	0	0	0	0	0	0
2020	34	34	0	43	49	26	0	0	0	0	0	0
2021	3	3	0	7	16	9	0	0	0	0	5	3
2022	41	20	0	50	44	32	0	0	0	0	0	0
2023	0	4	0	0	18	14	0	0	1	1	0	0

MVP= Minimum Viable Population, M= Male, F=Female

Based on **Table 3**, the *Minimum Viable Population* (MVP) values of *Rusa timorensis* in Dramaga Research Forest captive breeding exhibited considerable fluctuations during the 2019–2023 period. The peak MVP value was recorded for the juvenile male category in 2022, with a total of 50 individuals. In contrast, zero MVP values were recorded in several categories at the beginning of the observation period, particularly in 2019 for infant males, as well as juvenile males and females. The sustainable harvest quota could only be established in two out of the five observation years, namely in 2021 (a total of 8 individuals) and in 2023 (a total of 2 individuals). In 2019, 2020, and 2022, no harvest quota was applicable.

The highest MVP value was recorded in 2022, with 50 individuals in the juvenile male category. The lowest MVP values were recorded in 2019, with zero individuals in the infant male, infant female, juvenile male, and juvenile female categories. Sustainable harvest quotas were found only in 2021 and 2023, with totals of eight and two individuals, respectively. No harvest quotas were recorded in 2019, 2020, and 2022.

The number of individuals in the adult category tended to be higher than in the infant and juvenile categories in most observation years. Harvest quotas appeared when the number of adults exceeded the minimum population requirement. In 2020, MVP values were high across all age categories, but no harvest quota was generated. In 2021, harvest quotas were recorded in the adult male and adult female categories. The table data also record the minimum number of individuals per age and sex category for each observation year. This information is used to describe population conditions in intensive captive breeding during the study period. The MVP and sustainable harvest quota calculations are presented as data from population assessments.

4.1.3. Estimation of Effectiveness and Efficiency of Intensive Captive Breeding: Live Deer Sales Scenario

The financial feasibility of the *Rusa timorensis* captive breeding program, under an intensive management system at the Dramaga Research Forest, was assessed using investment and operational data collected over a five-year period (2018–2023). This analysis simulates a scenario in which income is generated through the sale of live deer. To evaluate the project's effectiveness and efficiency, four primary financial indicators were calculated: Net Present Value (NPV), Benefit-Cost Ratio (BCR), Internal Rate of Return (IRR), and Payback Period (PP). These indicators were assessed under two interest rate assumptions**:** 10% and 18%**.** The results of the financial analysis are shown in

Table 4.

Table 4. Financial analysis of captive breeding at Dramaga Research Forest (live deer sales).

Year	Investment Cost (IDR)	Operational Cost (IDR)	Revenue (IDR)	NPV		IRR	BCR		PP
				10%	18%		10%	18%	(year)
0	498,762,100.00	-	-	643,461,342.70	446,669,394.23	54%	1.72	1.54	1.68
1		104,000,000.00	400,767,000.00						
2		104,000,000.00	400,767,000.00						
3		105,400,000.00	483,163,500.00						
4		105,750,000.00	368,030,000.00						
5		108,000,000.00	372,467,000.00						

NPV= Net Present Value, BCR= Benefit Cost Ratio, IRR= Internal Rate of Return, PP= Payback Period

The initial investment of IDR 498,762,100.00 was allocated for infrastructure development, including the construction of enclosures, procurement of breeder stock, and provision of supporting facilities. During the operational phase, the main revenue source was the sale of 10 live deer over five years (based on the harvest volume shown in **Table 3**), consisting of adult males (IDR 8,600,000/head), juvenile males (IDR 7,000,000.00/head), adult females (IDR 10,363,000/head), and juvenile females (IDR 7,000,000.00/head). In addition to individual sales, supplementary income was generated from secondary products such as deer velvet—harvested three times annually from adult males, valued at IDR 4,700,000.00 per harvest—and organic fertilizer [12]. The fertilizer, available in both solid (IDR 730,000.00/head/year) and liquid forms (IDR 2,836,050.00/head/year), contributed to the annual revenue stream by integrating waste utilization into the production system [12].

Total revenue from all products during the five-year period amounted to IDR 2,025,167,500.00, while total operational costs reached IDR 527,150,000.00. Positive annual cash flow was recorded in every operational year. At a 10% discount rate, the Net Present Value (NPV) was IDR 643,461,342.70, the Benefit–Cost Ratio (BCR) was 1.72, and the payback period was 1.68 years. These values indicate that operational revenues exceeded both the investment and operational costs under this discount rate scenario.

Under the 18% discount rate scenario, the NPV was IDR 446,659,394.00 and the BCR was 1.54. Although the financial indicators were slightly lower compared to the 10% scenario, all values remained positive. This confirms that the captive breeding operation generated profitable returns under both discount rate scenarios.

Financial feasibility was analyzed using Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period (PP) approaches, under two discount rate scenarios: 10% and 18%. The 10% scenario is a conservative benchmark commonly used in public investment analysis, while the 18% scenario reflects higher risks or inflation [24]. Results showed that at a 10% discount rate, NPV reached IDR 643,461,342.70, BCR was 1.72, and the payback period was 1.68 years. At an 18% discount rate, the NPV dropped to IDR 446,669,394.23.

4.2. Discussion

4.2.1. Implications of Demographic Parameter Estimations

Between 2019 and 2023, the *Rusa timorensis* population at HP Dramaga remained stagnant, fluctuating between 34 and 37 individuals. Analysis revealed an average growth rate of only 0.01, with a relatively high annual mortality rate of 0.05. This suggests that births have not kept pace with deaths, likely due to limited space and high enclosure density. Such conditions increase stress risk, compromise animal health, and raise mortality rates [25,26]. This phenomenon contrasts with the general expectation that intensive captive breeding should promote significant population growth. Therefore, a comprehensive evaluation of facility capacity and population management systems is required.

The population's age structure displays an inverted pyramid pattern, with fewer young individuals (infants and juveniles) compared to adults [27]. This pattern indicates low population regeneration and a potential risk of long-term decline [3,28,29]. Such an imbalance reflects low recruitment into the reproductive group, threatening the population's future viability. This issue is likely aggravated by an imbalanced sex ratio, with an excess number of males. Male dominance triggers intraspecific competition, increases aggression, and raises mortality risk among adult males and young females [30–32]. These conditions hinder reproductive success and exacerbate population stagnation.

These findings align with research in West Java deer farms, which demonstrated that reproductive success improved significantly when enclosure density was regulated, feed was nutritionally balanced, and the male-to-female ratio was maintained optimally at around 1:4 to 1:5 [33]. Studies on intensive systems also emphasize that animal welfare factors—such as sufficient space for movement, access to shelter, and reduced social stress—play a crucial role in enhancing population productivity [34]. Therefore, improving both the physical and social environments in captive facilities is essential to stimulate population regeneration. Implementing management practices tailored to field conditions is expected to restore population growth rates to sustainable levels. Such changes are important not only for the success of captive breeding but also for broader ex-situ conservation efforts.

Based on the analysis, several managerial interventions are recommended to improve the sustainability of the *Rusa timorensis* population at HP Dramaga. First, evaluate enclosure capacity and set population limits to prevent overcrowding. Second, adjust sex composition through rotation, segregation of surplus males into bachelor enclosures, or selection of hyper-aggressive individuals. Third, reformulate feed and provide environmental enrichment to enhance thermal comfort, reduce stress, and improve reproductive success. With these strategies in place, the population is expected to emerge from stagnation and achieve a more stable demographic condition.

4.2.2. Financial Feasibility and Broader Sustainability Contributions of the Captive Breeding Program

The financial analysis of the captive breeding program shows strong economic viability under both conservative (10%) and stringent (18%) discount rate scenarios. At a 10% discount rate, the Net Present Value (NPV) reached Rp643,461,343.00 with a Benefit-Cost Ratio (BCR) of

1.72 and a Payback Period of 1.68 years. Even under the more stringent 18% discount rate, used to reflect inflation or investment risk, the project remains profitable, with an NPV of IDR 446,669,394.00 and a BCR of 1.54. These results indicate the project's resilience to changes in capital costs and confirm its financial attractiveness in both public and private investment contexts. These results indicate the project's resilience to changes in capital costs, proving that it is highly prospective financially.

Compared to previous studies, the financial indicators in this research demonstrate superior performance. A study conducted at Sadhana Arifnusa, East Lombok, reported a Net Present Value (NPV) of IDR428,748,935.00, a Benefit-Cost Ratio (BCR) of 1.66, an Internal Rate of Return (IRR) of 28.89%, and a Payback Period of 4.60 years [3]. These figures, while indicating financial feasibility, remain below the outcomes observed in the Dramaga Research Forest program. The higher financial efficiency in Dramaga may be attributed to optimized resource use, stronger market access, and integrated management strategies.

Moreover, the project generates qualitative benefits that contribute to long-term sustainability. These include environmental education programs for school visitors, research opportunities for universities, and the creation of alternative livelihoods for surrounding communities. Employment is supported both directly through facility operations and indirectly via local feed sourcing, such as cassava and forage grass. These initiatives enhance the project's social integration and foster community engagement.

From a conservation standpoint, the captive breeding model contributes to ex-situ conservation while promoting public awareness of local biodiversity. Educational tourism and academic collaboration further strengthen the ecological and scholarly value of the initiative. Conservation facilities that integrate economic and educational functions tend to yield more sustainable outcomes and broader biodiversity impacts [35]. This program exemplifies a model in which conservation objectives are pursued alongside economic rationality, without compromising ethical or ecological standards.

In conclusion, the captive breeding program demonstrates strong financial viability supported by solid economic indicators, while also offering meaningful qualitative contributions. The integration of conservation, education, and community empowerment reflects a comprehensive approach to sustainable development. This model may serve as a reference for designing future ex-situ conservation strategies, particularly in tropical regions where biodiversity is abundant but financial resources are limited.

5. Conclusions

The intensive captive breeding program for *Rusa timorensis* at Dramaga Research Forest, while demonstrating strong financial feasibility with a positive Net Present Value, a Benefit-Cost Ratio above 1, a high Internal Rate of Return of 54%, and a rapid Payback Period of 1.68 years, faces significant biological challenges that severely limit its sustainable harvest quota to a mere 10 individuals over five years. This low harvest potential stems from critical demographic issues, including population stagnation, an inverted age structure, and an imbalanced, male-dominated sex ratio, all exacerbated by the facility's limited spatial capacity, which leads to overcrowding, increased stress, and higher mortality rates. Therefore, to achieve both conservation objectives and economic profitability, efficient management is essential; this must include a re-evaluation of enclosure capacity, implementation of population limits, adjustment of the sex ratio, and provision of environmental enrichment to improve animal health, reduce stress, and enhance reproductive outcomes, ultimately ensuring long-term population sustainability.

Author Contributions

JS: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing**; YS, NFH**: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

Conflicts of interest

There are no conflicts to declare.

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