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An Analysis of an Ecological–Economic Model of Asian Elephant Population Development under the Influence of Human Disturbance

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Abstract: The population development of Asian elephants (*Elephas maximus*) has been greatly affected by the intensification of human activities. In this study, development of the Asian elephant population under the influence of human disturbance was analyzed logically, with expansion of the rubber forest area as the main influencing factor. The ecological–economic model of Asian elephant population development was constructed using the logical analysis method, the population growth model and the integrated environmental–economic control model. The results are as follows: (1) Theoretically, the ecological–economic model could be applied to the analysis of wildlife conservation and regulation and management policies; (2) The data show that in 2016, the intrinsic growth rate of Asian elephants in Xishuangbanna was 0.0216 head/day, which has a strong proliferation capacity, meaning the population will continue to grow under natural conditions. However, at present, the population development of Asian elephants has been negatively affected by human interference, which has reduced the population growth rate of Asian elephants to 0.0193 head/day, and this impact has a tendency to intensify; (3) From 2004 to 2016, the investment rate of Asian elephants increased by 0.182, while the anti-interference protection rate of Asian elephants decreased by 0.227. The overall development trend of Asian elephants was from equilibrium point one (golden age) to equilibrium point two (dark age).

Keywords: human disturbance; Asian elephants; population growth; rubber forest

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1. Introduction

With the development of science and technology, the impact of human beings on the global ecosystem is increasing. Even if ecological prudence were to compensate for the negative impact of human behavior on the environment, it is impossible for humans to deny the changes in the natural environment caused by technology [1]. The increasing erosion of wildlife habitats has caused changes in animal communities, resulting in an increasing number of wildlife becoming endangered [2]. Research on changes in the quantity, distribution and diffusion of wildlife population has shifted from focusing on the traditional pure biological and ecological changes to a comprehensive study that considers various factors.

From the perspective of ecology, the change in wildlife population is similar to that of other general organisms, which reflects the change rule of the wildlife population in time and space [3]. It is of great theoretical and practical value to study the population quantity and factors affecting the change in number and distribution for the protection of biodiversity, ecological balance and rational utilization of wildlife resources [4]. During this process, human encroachment on wildlife habitats or intensified activities in wildlife habitats have seriously affected the development of wildlife population, and inevitably brought conflicts between human and wildlife.

Asian elephants (*Elephas maximus*) are a Class I nationally protected animal in China. According to the statistics, the number of Asian elephants in China is about 200–300, mainly distributed in Xishuangbanna, Puer and Lincang, Yunnan Province, among which Xishuangbanna is the main area [5–9]. The number of wild Asian elephants in China has been on the rise in the past 35 years [10]. The relationship between Asian elephants and the surrounding farmers has mainly progressed through five stages. From 1959 to 1971, humans and elephants did not violate each other's territory [11]. From 1972 to 1990, humans and elephants frequently made contact [12]. From 1991 to 1995, the conflict between humans and elephants intensified [13]. From 1996 to 2005, Asian elephants were strictly protected, but serious accidents also occurred [14]. From 2006 to date, the relationship between humans and elephants has maintained a state of endless confrontation [15].

According to the Ecological Niche Factor Analysis (ENFA) model, the habitat status of Asian elephants in Xishuangbanna was evaluated and a suitable habitat was predicted [16]. The results showed that Asian elephants were selective and tolerant to environmental conditions, but their niche was not wide, and their specialization was high [17–19]. Natural forest is their main habitat [20]. Human disturbances affect the wildlife habitat by changing vegetation types [21,22]. Since the 1950s, long-term development of the rubber plantation industry in the Xishuangbanna area of Yunnan Province has transformed a large area of tropical rain forest, primitive forest and secondary forest into economic forest land. Artificial disturbance leads to fragmentation of forests in protected areas. The fragmentation results in loss of the environment on which animals in the forests depend, and these animals will be replaced by the species on the edge of the forest or on nearby open land. The impact of rubber planting on tropical forest resources, biodiversity, climate and water resources in Xishuangbanna has resulted in the islanding of some nature reserves in Asian elephant habitats, which has attracted the attention of many scholars [23–27]. Previous studies have shown that habitat fragmentation and isolation are the main factors causing wildlife to become endangered [28]. The isolation effects, area effects and edge effects directly interfere with the processes of gene exchange, population dynamic diffusion and interspecific relationships between wildlife [29]. Permanent agricultural land, secondary forests and temporary farmland have also been transformed into rubber forests [30,31]. The planting area of rubber forests in Xishuangbanna increased from 329.7 km^2 in 1987 to 2287.2 km^2 in 2018, with the fastest growth rate occurring from 2000 to 2010, an increase of 1374.1 km^2 in 10 years, accounting for 70.2% of the total growth area in 32 years [28]. The expansion of rubber plantation and the process of land-use changes will affect the energy, water and carbon fluxes in the region, which will have a negative impact on the ecosystem [32–34]. In Xishuangbanna, only protected areas have suitable habitats in which relatively complete and concentrated habitats are reserved. Most areas outside the protected areas are no longer suitable for Asian elephants to survive; therefore, the Asian elephant habitat in Xishuangbanna has been severely islanded [6,18].

The main types and formation paths of the Asian elephant population's development and conflicts include main two aspects. One is the impact on habitat area. Artificial disturbances cause wildlife to avoid areas of human activity [35]. At the same time, humans feeding other herbivores has created a food competition relationship with wild Asian elephants. The other aspect is the impact on the population of Asian elephants. The demand for elephant tooth products by some consumers has led to Asian elephant poaching. The Lebensraum overlap between humans and Asian elephants has caused large-scale human–elephant conflicts [36,37]. According to statistics, from 1966 to 2005, 116 Asian elephants were killed in Yunnan Province [38]. Both aspects eventually exacerbated the conflicts between humans and Asian elephants. Therefore, analysis of the impact path of human interference on these two aspects forms the basis of the impact degree model. Increasingly more studies have focused on the relationship between humans and nature, which means more researchers paying attention to the interaction between the economy and the ecosystem [39]. On a broader basis, the need for a harmonious relationship between the natural environment and human behavior is discussed. This would combine the production process of human governance with the process of natural ecology, regard the development of the natural process as a technological process, and form an economic–ecological control system. The specific processes include measurement (monitoring), modeling and control. These three processes are mutually supportive and inseparable. Among them, measurement is the foundation, modeling is key to decision-making, and decision-making shows the result [40,41]. How to quantify the impact of socio-economic activities on the development of the Asian elephant population, analyze the degree of conflict between Asian elephant activities and the proliferation and socio-economic activities under these influences, and explore the regularity of the changes can not only help to protect Asian elephants and adopt more scientific and rational policies, but also avoid Asian elephants having a negative impact on people's production and life and also promote a harmonious coexistence between humans and elephants.

2. Research Methods and Data Processing

2.1. Research Methods

The study, taking the combined effects of exogenous and endogenous factors and the lag in population change into consideration, is based on the Verhulst–Pearl model: a dynamic model of a single-species population with nonlinear variation. A dynamic equilibrium model of wildlife population change was constructed. For the change in wildlife population distribution, a comprehensive model combining population growth and diffusion was established using the stochastic diffusion model and population growth change. Based on the actual data obtained through the survey, this study, combined with the research results of wildlife management and ecology experts on some typical wildlife ecology and behavior, extracted the relevant technical parameters of the model and then incorporated these into human production and life activities. External impact changes such as wildlife conservation and management measures were considered to establish the changes in and distribution of the population and diffusion models of typical wildlife species.

(1) Verhulst–Pearl Model

The basic form of the model is as follows:

$$\frac{dN(t)}{dt} = \mu N(t)\left(1 - \frac{N(t)}{K}\right) \tag{1}$$

N(t)—Number of a wild animal population at time t;
μ—Growth rate of a wildlife population;
K—Maximum carrying capacity of wildlife population.

If a wild animal has the ability of self-regulation and can be adjusted after a period of population growth, the model can be amended to:

$$\frac{dN(t)}{dt} = \mu N(t)\left(1 - \frac{N(t)}{K} - \int_0^t f(t-\tau)N(\tau)d\tau\right) \tag{2}$$

τ—Initial moment;
N(τ)—Number of a wild animal population at time τ.

Based on these models, further considering the impact of exogenous changes on population changes, the relevant constraints were formed. Under different constraints, the corresponding dynamic equilibrium model of wildlife population can be established.

(2) Comprehensive Model of Economic–Environmental Control

The negative impacts of human disturbance on the ecosystem can be summarized as a control model coupling economic systems and ecosystems, similar to those used to analyze the impacts of environmental pollution. This is used to simulate the impact of the environment on human beings; that is, the utility of the environment for human society. The specific models are as follows:

Objective function: $G(C,Z)$ can be regarded as a function of consumer goods C and negative interference Z. The normal form is as follows:

$$G(C(t),Z(t)) = c_1 C(t)^{\alpha} - c_2 Z(t)^{\beta} 0 < \alpha < 1,\ \beta > 1 \tag{3}$$

the goal at a certain stage is to achieve the maximum $g(C, Z)$.

$$\text{Constraint condition:Max } I(s_1,s_2) = \text{Max} \int_{t_0}^{T} e^{-qt} g(C(t),Z(t))dt \tag{4}$$

Production function:

$$Q(t) = A(t)F(K(t),L(t)) \tag{5}$$

Output distribution function:

$$Q(t) = C(t) + S(t) + E(t) \tag{6}$$

$$S(t) = s_1 Q(t) \tag{7}$$

$$E(t) = s_2 Q(t) \tag{8}$$

Capital growth function:

$$\frac{dK}{dt} = s_1 Q(t) - \mu K(t) \tag{9}$$

Labor growth function:

$$\frac{dL}{dt} = \eta L(t) \tag{10}$$

Variation function: linearity of human impact on ecosystem:

$$\frac{dZ}{dt} = (\varepsilon - \delta s_2)Q(t) - \gamma Z(t) \tag{11}$$

Variation function: nonlinearity of human impact on ecosystem:

$$\frac{dZ}{dt} = (\varepsilon - \delta s_2)Q(t) - \gamma G(t)Z(t)^{\alpha} 0 < \alpha < 1 \tag{12}$$

in the above equations:

Q—Total output of a certain area;
C—Amount of consumer goods used in total output;
S—Cumulative production in total output (total investment);
L—Quantity of labor;
K—Capital (fixed assets);
s_1—Investment rate;
s_2—Proportion of environmental recovery expenditure (E) in total output (Q), $0 \le s_1, s_2 \le 1; s_1 + s_2 \le 1$;
Z—Total negative interference impact;
E—Output used to eliminate negative effects on total production;
E—Negative interference in total production, $0 < \varepsilon < 1$;
δ—One unit E reduces the negative effects of δ units, $\delta > 1$;
γ—Recovery ratio of negative disturbances caused by environmental self-purification, $\gamma > 0$;
q—Discount rate.

2.2. Data Source and Data Processing

The data on Asian elephants come from two sources: one is indirect data. These are mainly the result of wildlife ecology and management research. They include the basic technical parameters of population changes in specific typical species and the possible degree of interaction among populations. Data and information on wildlife protection and management departments included wildlife activities and situations causing harm. The other source is direct survey data. This includes data obtained from investigations and interviews with the residents of the area around the wildlife habitat, the relevant protection agencies and patrol personnel.

The data on social and economic development in Xishuangbanna were mainly derived from the yearbook and bulletin of social and economic statistics of the state's statistical bureau. In the model, these basic data were used to make adjustments according to the correlation coefficient obtained from the field survey. Data such as investment in elephant conservation and the output value dedicated to Asian elephants were derived from field surveys of local forestry authorities. The specific impact data regarding human disturbance come from the research results in ecology and other fields, as well as the relevant statistical reports and summary reports on development of the local forestry industry obtained from field surveys. The relevant technical parameters of the model were mainly derived from the relevant research results and the estimations of relevant management departments and specific business personnel during the field survey. The specific data collection information is detailed in Table 1.

Table 1. Data sources.

Data Sources	Data Content
Yunnan Provincial Forestry Department	Published data on Asian elephant, including research on Asian elephant in China, research on human–elephant conflicts in China, etc.
Xishuangbanna Forestry Bureau	Data on the protection, prevention, control and compensation of Asian elephant in Xishuangbanna
Xishuangbanna Bureau of Statistics	Annual statistical bulletin on the national, economic and social development of Xishuangbanna Dai Autonomous Prefecture
Xishuangbanna National Nature Reserve Research Institute	Asian elephant population and the changes, ecological environment, human–elephant conflicts and other data
Xishuangbanna Asian Elephant Breeding Center	Status of Asian elephant breeding center, breeding costs, breeding facilities and other data

3. An Ecological and Economic Model for the Development of Asian Elephant Population Affected by Human Disturbance

3.1. Theoretical Framework Analysis

Human activity interference with the development of Asian elephant populations and the negative impacts of this can be logically analyzed from the following two aspects.

The first is the impact on the habitat of Asian elephants. From previous monitoring and research, Asian elephant activity areas are mainly concentrated in the designated protected areas. Most of the areas used for migration between different protected areas belong to collective forest land. Most of the collective forest land in the past was in an unmanaged state, basically forming a primitive secondary forest, open forest land or wasteland state, which is suitable for the survival of Asian elephants. In the short-term food season, the Asian elephant will also enter the village to obtain food from farmland. Overall, Asian elephants have a relatively wide habitat. In recent years, in order to meet the needs of socio-economic development, especially after changes in forestry policies, increasingly more farmers have started planting economic tree species represented by rubber forests [42]. Rubber forest is mainly pure forest, with dense trees and a lack of shrubs and grass. This not only reduces the range of activities of Asian elephants, but also reduces their food supply, resulting in a reduction in their habitat [43]. As a result, the frequency of Asian elephants obtaining food from village farming areas has increased, and the human–elephant conflict has intensified.

The second aspect is the impact on the population of Asian elephants. With their declining population worldwide, the protection of Asian elephants has been strengthened all over the world. To protect them, the Chinese government has delimited protected areas, increased patrols, strictly guarded against hunting and established food bases for Asian elephants in China. These conservation measures have led to a certain increase in the Asian elephant population. At the same time, the decline in the area and quality of their habitats in Myanmar, Laos, Thailand and other countries has also led to perennial activities of some Asian elephants in China [44]. As a result, their number and activities have considerably increased in China. Rubber forests have produced huge economic benefits, which have driven the development of the local economy. Villagers have gradually established the concept of protecting wild animals. At the same time, the government increased their investment in protecting the habitat of Asian elephants. An increase in the population of Asian elephants necessarily requires a larger area of activity to obtain food and space for movement. Therefore, there will be more Asian elephants in collective woodlands and farming areas outside the reserve. The range, frequency and extent of Asian elephant activities endangering the economic forests and farmland has considerably increased, and the conflict between human beings and elephants has intensified.

The above-mentioned human activities leading to changes in the human–elephant conflict and their relationship are shown in Figure 1.

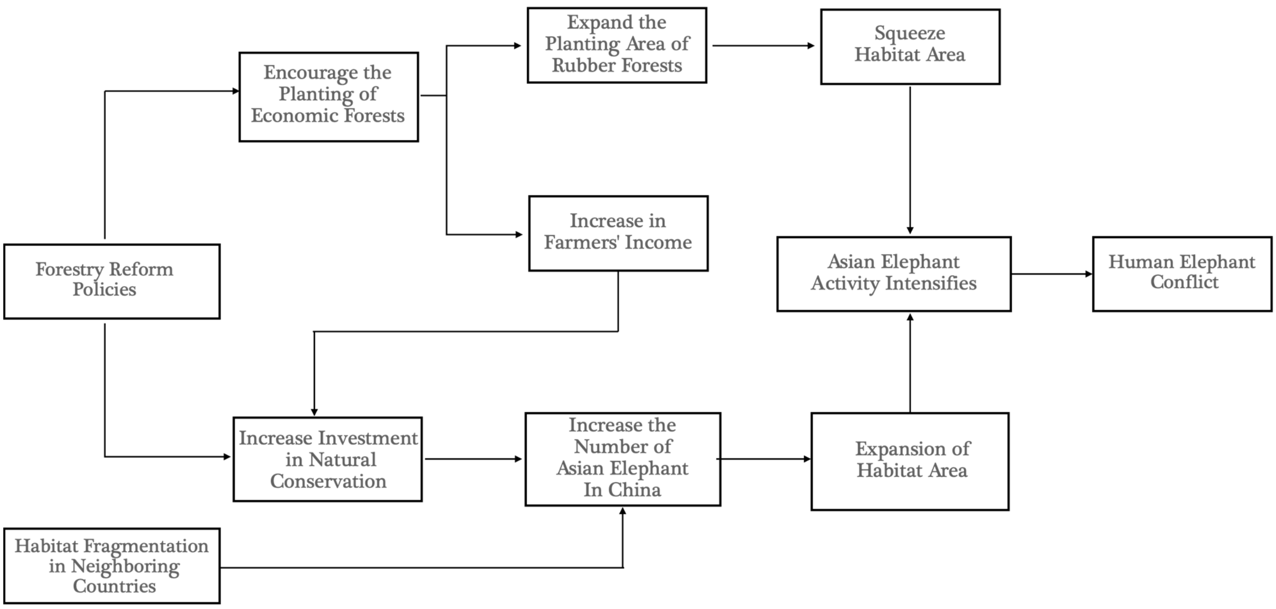

Figure 1. Logical diagram of human interference affecting Asian elephants.

Whether the government protects Asian elephants or grows rubber forests to develop the economy, it is necessary to comprehensively balance the input and output of local development and seek rapid socio-economic development in the region on the basis of protecting Asian elephants. The division of the input–output income of the government is based on the main objective regarding Asian elephants and rubber plantations. The government's investment mainly includes firstly, protecting capital investments in Asian elephants; secondly, delimiting protected areas and potential protected areas to reduce development spaces and opportunities; thirdly, protecting the limited areas reserved for

Asian elephants and restrictions on industrial development in surrounding areas. The government's output includes firstly, an increase in the elephant population in Asia, benefits of habitat ecosystem restoration and optimization, and protection of species diversity as one of the criteria to measure the effectiveness of natural conservation; secondly, the government's management of nature reserves has improved, providing experience for effective management of nature reserves; thirdly, the benefits of Asian elephant-related tourism and activities are utilized. Thus, the cost–benefit components of local governments are as follows.

Total return = local Gross Domestic Product (GDP) (excluding Asian-elephant-related industries) + value of Asian elephants population growth and habitat improvement + value added of Asian-elephant-related industries.

Total cost = local governments' protection of Asian elephants and hazard prevention and control costs + hazard loss + opportunity costs of restricting industrial development.

Net income = total income − total cost

3.2. Ecological–Economic Model

Based on the cost–benefit analysis of the above-mentioned local governments in the protection and development of Asian elephants, a theoretical model of ecological and economic balance between population development and harm to Asian elephants is established. The model is as follows:

The total income function for year t:

$$\mathrm{TE(t) = Q_{GDP}(t) + N_{el}(t)q_{el}(t) + Q_{egdp}(t)} \tag{13}$$

The total cost function in year t:

$$\mathrm{TC(t) = Y_{el}(N_{el}(t)) + G(N_{el}(t)) + J\ (t)} \tag{14}$$

Net income function in year t:

$$\pi(\mathrm{t}) = \mathrm{TE(t) - TC(t)} \tag{15}$$

The goal is to maximize the total net income in a certain period of T years under various balances. Therefore, the objective function is:

$$\mathrm{Max}\ \pi = \mathrm{Max} \int_{t_0}^{T} e^{-rt}\pi(t)dt = \mathrm{Max} \int_{t_0}^{T} e^{-rt}[TE(t) - TC(t)]dt \tag{16}$$

$$\mathrm{Max} \int_{t_0}^{T} e^{-rt}\Big[\mathrm{Q_{GDP}(t) + N_{el}(t)q_{el}(t) + Q_{egdp}(t) - Y_{el}(N_{el}(t)) - G(N_{el}(t)) - J\ (t)}\Big]dt \tag{17}$$

This section analyzes the corresponding constraints. The first is the population growth and change of Asian elephants. Since the Asian elephant population in China is still in an endangered state, and their population growth is still in the recovery process of the endangered state, the initial expansion model was chosen for the population change model of Asian elephants. The population diffusion of Asian elephants is mainly affected by the habitat environment. At present, the habitat area of Asian elephants is limited, which slows their diffusion process. At the same time, it is precisely because of the interlaced existence of habitat and human activities that human activities around the habitat have a significant negative impact on the population of Asian elephants. The main form of this impact is the shrinkage of habitats, including potential habitats. The population growth model of Asian elephants was established as follows:

$$\mathrm{\frac{dN(t)}{dt} = \mu N(t)\left(1 - \frac{N(t)}{U(t)}\right)} \tag{18}$$

N(t)—Population number of Asian elephants at time t;

μ—Growth rate of Asian elephant population;

U(t)—Maximum carrying capacity of Asian elephant habitats in the region.

The regional production function is also important. From the perspective of economic growth, in view of the fact that China's economy as a whole is in a transition from high-speed to medium speed, this is nearing economic equilibrium. In this study, the social and economic development in Xishuangbanna is still simulated by the C-D function (consumption–depreciation) according to Solow model, which satisfies the four constraints of the production function. Therefore, the production function is as follows:

$$\mathrm{Q_{GDP}(t) = A(t)F}(K(t), L(t)) = \mathrm{A}(t)\mathrm{K}(t)^{\tau}\mathrm{L}(t)^{\nu} \tag{19}$$

$\mathrm{Q_{GDP}(t)}$—Xishuangbanna's GDP in year t;

L(t)—Number of employees in Xishuangbanna in year t;

K(t)—Fixed asset investment in Xishuangbanna in year t;

τ, ν—Output elasticity coefficient of capital and labor, $0 < \tau < 1$ $0 < \nu < 1$.

The composition functions of the overall economic growth related to the production function include the output distribution function, the capital growth function and the labor force growth function. The output allocation function mainly classifies the total output. Traditionally, the output is mainly allocated to consumption and investment. Considering the human disturbance to Asian elephants and the protection of Asian elephants, we should allocate part of this output to protect Asian elephants and combat the negative effects. This part is expressed in E(t). The whole output is then divided into three parts: consumption, investment and Asian elephants' protection against negative interference. Then, the output distribution function is adjusted to:

$$\mathrm{Q_{GDP}(t) = C(t) + S(t) + E(t)} \tag{20}$$

$\mathrm{Q_{GDP}(t)}$—GDP of Xishuangbanna in year t;

C(t)—Consumption of total output in year t;

S(t)—Investment in the first year of total output;

E(t)—Protection, harm prevention and control and compensation costs in Xishuangbanna for Asian elephants in year t.

Among them, the total investment is proportional to the total output, while $\mathrm{S_1}$ is the investment rate:

$$\mathrm{S(t) = s_1Q_{GDP}(t)} \tag{21}$$

There is also a linear relationship between the total output and the cost of protection, hazard prevention, and control and compensation of Asian elephants. Let $\mathrm{S_2}$ denote the anti-interference effect of the output per unit of consumption:

$$\mathrm{E(t) = s_2Q_{GDP}(t)} \tag{22}$$

In addition, according to the composition of Solow's economic growth model, the capital growth function is as follows:

$$\frac{\mathrm{dK(t)}}{dt} = \mathrm{s_1Q_{GDP}(t) - \mu K(t)} \tag{23}$$

In the formula, μ denotes the loss rate.

The growth function of labor force is as follows:

$$\frac{\mathrm{dL(t)}}{dt} = \mathrm{\eta L(t)} \tag{24}$$

In the formula, η denotes the relative change rate of labor force.

The study of the impact of human activities on the population size and development of Asian elephants was conducted as follows. From the above theoretical framework analysis, the current impact was mainly determined to be the large-scale planting of expanded rubber forests in Xishuangbanna, which affects the actual habitat area and food sources of Asian elephants. In this study, the change in rubber plantation area was initially determined as a factor in the human population development's influence on Asian elephants. It was preliminarily determined that the number and incremental changes in rubber forest area directly changed the habitat area of Asian elephants, and then affected the environmental carrying capacity U(t). Therefore, the rubber plantation area is used as the negative disturbance Z(t). E indicates that, for Asian elephants, the cost of protection, hazard prevention and control, and compensation for Asian elephants, which is necessary to allow them to grow at natural growth rates, is allocated by the total economic output. Here, ε represents the proportion of output value brought by the rubber plantation to total economic output and γ indicates the proportion of Asian elephants adapting to habitat changes to reduce the impact of rubber forest expansion. The non-linear change function is used to express the impact of rubber forest expansion on Asian elephant population development in Xishuangbanna and on the economic system. Its specific form is as follows:

$$\frac{\mathrm{dZ}}{dt} = (\varepsilon(\mathrm{t}) - \delta \mathrm{s}_2)\mathrm{Q}(\mathrm{t}) - \gamma \mathrm{g}\mathrm{Z}(\mathrm{t})^{\alpha} \tag{25}$$

Z(t)—Rubber plantation area in Xishuangbanna in year t;

E(t)—Protection, harm prevention and control, and compensation costs of Xishuangbanna for Asian elephants in year t;

$\varepsilon(\mathrm{t})$—Proportion of output value brought by rubber plantation, $0 < \varepsilon(t) < 1$;

δ—Reduced negative impact of rubber forest expansion on Asian elephant conservation and hazard prevention, control and compensation, $0 < \delta < 1$;

γ—The proportion of Asian elephants adapting to habitat changes to reduce the impact of rubber forest expansion, $0 < \gamma < 1$;

g—Coefficient of influence of rubber plantation changes, $0 < \mathrm{g} < 1$;

α—Expansion multiplier of rubber forest effect, $0 < \alpha < 1$.

Under general conditions, these expenditures are closely related to the number of Asian elephants. Generally speaking, the relationship between Asian elephants' protection, prevention and control funds, and the number of Asian elephants can be linear, but the change in loss caused by the change in the number of Asian elephants will have an accelerating trend and can be fitted by an exponential model. The change function of Asian elephants' protection input and prevention control is set as follows:

$$\mathrm{Y_{el}}(\mathrm{N_{el}}(\mathrm{t})) = \mathrm{Y}_0 + \mathrm{s}_3\mathrm{N_{el}}(\mathrm{t}) \tag{26}$$

The change function of the amount of loss caused is as follows:

$$\mathrm{G}(\mathrm{N_{el}}(\mathrm{t})) = \mathrm{s}_4 \exp(\mathrm{N_{el}}(\mathrm{t})) \tag{27}$$

This paper analyzes the estimation of opportunity costs caused by elephant protection and hazards in Asia as a whole. Estimating the opportunity costs of Asian elephant protection and hazards to regional socio-economic development requires the consideration of multiple factors, such as the degree of impact of protection policies on different industries, and the difference in requirements for land and ecological protection policies in different industries. Detailed investigations are needed for a more precise estimation. In this study, the net land return of the protected area for Asian elephants was temporarily taken as the opportunity cost of industrial development caused by the protection of Asian elephants. Therefore, the function can be set as:

$$\mathrm{J}(\mathrm{t}) = \mathrm{J}_0 + \mathrm{s}_5\mathrm{M}(\mathrm{t}) \tag{28}$$

J(t)—Opportunity cost of socio-economic development caused by Asian elephants' conservation in year t;

M(t)—Area of Asian elephants' reserve in year t;

J_0, s_5—Constant coefficient, $J_0 \geq 0$, $0 < s_5 < 1$.

Based on the above analysis, an ecological–economic theoretical model system for the development of and harm to the Asian elephant population can be obtained. The specific composition is as follows:

Objective function:

$$\text{Max} \int_{t_0}^{T} e^{-rt} \Big[\mathrm{Q_{GDP}(t) + N_{el}(t) q_{el}(t) + Q_{egdp}(t) - Y_{el}(N_{el}(t)) - G(N_{el}(t)) - J\,(t)} \Big] dt \tag{29}$$

Constraints:

$$\frac{\mathrm{dN(t)}}{\mathrm{dt}} = \mathrm{\mu N(t)} \left(1 - \frac{\mathrm{N(t)}}{\mathrm{U(t)}} \right) \tag{30}$$

$$\mathrm{Q_{GDP}(t) = A(t)F}(K(t), L(t)) = \mathrm{A}(t)\mathrm{K}(t)^{\tau}\mathrm{L}(t)^{\nu} \tag{31}$$

$$\mathrm{Q_{GDP}(t) = C(t) + S(t) + E(t)} \tag{32}$$

$$\mathrm{S(t) = s_1 Q_{GDP}(t)} \tag{33}$$

$$\mathrm{E(t) = s_2 Q_{GDP}(t)} \tag{34}$$

$$\frac{\mathrm{dK(t)}}{dt} = \mathrm{s_1 Q_{GDP}(t) - \mu K(t)} \tag{35}$$

$$\frac{\mathrm{dL(t)}}{dt} = \mathrm{\eta L(t)} \tag{36}$$

$$\frac{\mathrm{dZ}}{dt} = \mathrm{(\varepsilon(t) - \delta s_2)Q(t) - \gamma g Z(t)}^{\alpha} \tag{37}$$

$$\mathrm{Y_{el}(N_{el}(t)) = Y_0 + s_3 N_{el}(t)} \tag{38}$$

$$\mathrm{G(N_{el}(t)) = s_4 \exp(N_{el}(t))} \tag{39}$$

$$\mathrm{J(t) = J_0 + s_5 M(t)} \tag{40}$$

The control variables and state variables are discussed further below. In the above model, the main variables for artificial control were s_1 and s_2. Among them, s_1 is the investment rate and s_2 represents the proportion of investment in total output Q due to the protection, hazard control and compensation of Asian elephants. The constraints of control variables s_1 and s_2 are: $0 \leq s_1, s_2 \leq 1$, $s_1 + s_2 \leq 1$.

3.3. Analysis of Theoretical Model Results

Based on the above model, the optimization of Asian elephants' population development under the influence of regional socio-economic development is analyzed. According to the maximum principle, the optimal control model solution method and Hamilton function are constructed. The ecological–economic model, optimal control variables and optimal state variables of the Asian elephants' population development under the influence of regional socio-economic development can be obtained using the adjoint equation. From the perspective of control variables, the model analysis shows that after Q(t), Z(t), K(t) and N(t) reach some steady-state values and there are two equilibrium points in the whole model; that is to say, the equilibrium of two paths can be achieved.

(1) Equilibrium point 1: (s_1*, s_2*), $0 < s_1^* < 1$, $0 < s_2^* < 1$. Equilibrium point 1 shows that there a set of control variables can achieve an effective balance, that is, allocate the investment part of the total output within a reasonable range to achieve an effective balance between regional economic development and Asian elephant protection under the condition that the Asian elephant population is close to the maximum carrying capacity. This is what we need to achieve, and some people call this balance the "golden age". To achieve this goal, all types of constraints will play a role in accelerating or delaying the time to reach equilibrium, and the magnitude of impact is also quite different, which is also the key content when optimizing control management.

(2) Equilibrium point 2: (s_1**, s_2**), $0 < s_1^{**} < 1, s_2^{**} = 0$. Equilibrium 2 shows that if the negative impact is too large, it will inevitably lead to investments which will not mitigate the negative impact. The reduction in and disappearance of Asian elephants in the region has become an irreversible, inevitable result. This is an undesirable result of control and management, and a situation that policymakers, as coordinators of the regional development and protection of Asian elephants, are trying to avoid. This is a negative equilibrium, also known as the "Dark Age". In this equilibrium state, since the total output C**, allocated to consumption, is much larger than the total output C*, the negative impact of human disturbance activities, Z**, is also much greater than the negative impact Z*, which is under the first equilibrium state. With the disappearance of Asian elephants, the ecological stability of the region is gradually weakening, which will eventually affect the stability and potential of economic development.

4. Application Research

4.1. Data

Based on the above literature data and the interval data, the missing year's data were used to determine the population of Asian elephants, which was substituted into the model by interpolation. The population growth model was fitted by considering the number of surveys N(t) and the number of poaching deaths. In addition, considering that poaching and damage to Asian elephants will lead to the displacement of local villagers, it will also bring about changes in the number of Asian elephants in the region. In this study, the loss rate of Asian elephants from their habitats in China was determined to be between 1% and 5% based on the amount of loss caused by Asian elephants.

4.2. Model Fitting Results

Based on the above data processing, the fitting model of Asian elephant population changes under the presupposed non-interference condition is as follows:

$$\mathrm{N(t)} = \frac{450}{1 + \mathrm{e}^{-0.0216\mathrm{t}}} \qquad \mathrm{R_2} = 0.7252 \tag{41}$$

If the disturbance is taken into account, the fitting model of Asian elephant population changes is as follows:

$$\mathrm{N(t)} = 212.77\mathrm{e}^{0.0193\mathrm{t}} \qquad \mathrm{R_2} = 0.7131 \tag{42}$$

Combined with the social and economic statistics of Xishuangbanna, the data were adjusted according to the hypothesis of production function. The regression analysis was carried out according to the C-D function, and the fitting regression equation was obtained as follows:

$$\ln \mathrm{Q_{GDP}(t)} = 0.3202 + 0.2830\mathrm{lnK(t)} + 0.5527\mathrm{lnL(t)} \quad \mathrm{R_2} = 0.9906 \tag{43}$$

The fitting model of production function is as follows:

$$\mathrm{Q_{GDP}(t)} = 1.3774\mathrm{K}(t)^{0.2830}\mathrm{L}(t)^{0.5527} \tag{44}$$

According to the situation of workers in Xishuangbanna, the function of labor force change is fitted as follows:

$$\ln L(t) = 3.9821 + 0.0162t \qquad R_2 = 0.7252 \tag{45}$$

The fitted model of labor force change function is as follows:

$$L(t) = 53.6295e^{0.0162t} \tag{46}$$

The variation function of loss caused by Asian elephants is fitted as follows:

$$G(Nel(t)) = 30.867e^{0.0163Nel(t)} \tag{47}$$

Based on the planting area of rubber plantation in Xishuangbanna, the quantity and output value of dry rubber per year, and the influence degree of the rubber plantation on Asian elephants in previous studies, the model parameters were determined. The negative impact rate of reduced rubber forest expansion on Asian elephant conservation and hazard prevention, as well as control and compensation, is $\delta = 0.5$; the proportion of Asian elephants adapting themselves to habitat changes to reduce the impact of rubber forest expansion is $\gamma = 0.1$. According to the general laws of environmental pollution and purification, the more precise changes in the adaptability of environmental purification should be non-linear. However, it is still difficult to determine the non-linear trajectory of the self-adaptability of Asian elephants after the expansion of the rubber forest. Therefore, the influence of human disturbance was fitted by a linear model. The specific values of control variable investment rate s_1 and Asian elephant anti-interference protection rate s_2 can be determined as shown in Table 2.

Table 2. List of fitting values of control variables s_1 and s_2 (dimensionless).

Control Variable	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
s_1	0.4379	0.4808	0.5228	0.5559	0.5439	0.5560	0.5566	0.5858	0.6051	0.6196	0.6224	0.6288	0.6199
s_2	0.2891	0.2431	0.2050	0.1734	0.1719	0.1444	0.1291	0.1071	0.0888	0.0711	0.0666	0.0617	0.0621
$s_1 + s_2$	0.7270	0.7239	0.7278	0.7293	0.7158	0.7004	0.6857	0.6929	0.6939	0.6906	0.6890	0.6905	0.6820

4.3. Result Analysis

In application research, to verify the feasibility of the whole theoretical model, some parameters are simplified, but the results of application research still have a strong impact. The above fitting results were analyzed as follows:

Firstly, human disturbance, which is mainly caused by the expansion of rubber plantation area, has a great impact on the development of the Asian elephant population. Fitting results showed that the population growth model of Asian elephants was affected to some extent during the rapid expansion of rubber forest, and the intrinsic growth rate decreased slightly. Under natural conditions, the intrinsic growth rate of Asian elephants is 0.0216 (head/day), while human activities reduced the population growth rate to 0.0193 (head/day).

Secondly, the loss caused by Asian elephants shows a rapid growth trend, which reflects the intensification of human–elephant conflict. From the current loss curve caused by Asian elephants, an exponential growth trend can be seen. The whole growth model enters the acceleration stage.

Thirdly, from the perspective of the protection of Asian elephants and maximization of comprehensive benefits, under the influence of the expansion of the rubber plantation area, the protection of Asian elephants is a very serious issue. According to the theoretical analysis of the ecological–economic model of Asian elephant population development under the influence of artificial disturbances, the changes in two variables, i.e., the control variable investment rate s_1 and the Asian elephants' anti-jamming protection rate s_2, show a trend of increasing and decreasing. The decline in s_2 is very large. The overall trend of change is from equilibrium point 1 (golden age) to equilibrium point 2 (dark age).

The results of this study show that the human interference behavior represented by planting rubber trees will have a negative impact on the population development of Asian elephants, showing a rising trend year by year, and remedial measures need to be taken as soon as possible. This result is similar to the results reported by Li [2], Dai [9], Ya [10], Liu [20], Guan [29], Zhang [33] and Hu [36].

5. Conclusions and Discussion

This study constructed an ecological–economic model for the population development of Asian elephants by using the logical analysis method, the population growth model and the integrated environmental–economic control model and collected relevant data of Asian elephants in Xishuangbanna from 2004 to 2016. At the same time, using the data of social and economic development in Xishuangbanna, we systematically analyzed and measured the impact of human disturbance represented by rubber tree expansion on the population development of Asian elephants. This paper not only analyzes and explains the intrinsic influencing factors of the current changes in human–elephant conflict, but also measures the extent of the impact of human activities on the changes of the Asian elephant population and its future development trend, which has important practical guiding significance for their protection and development. The following conclusions can be drawn at present.

First, in theory, the integrated environmental–economic model can be applied to the analysis of wildlife conservation and regulation management policies, ensuring the measurability, operability and applicability of the theoretical model. Based on the data of Asian elephant activity sites, the government investment in protecting the population development of Asian elephants and the change of rubber forest area were used as the impact factors of humans on the population development of Asian elephants. It was preliminarily determined that the quantity and increment change of rubber forest area directly changed the habitat area of Asian elephants, and further affected the environmental carrying capacity. The calculation results have good ecological interpretability.

Secondly, the impact of human disturbance on the population development of Asian elephants can be measured, and the equilibrium point between the regional economic growth and protection of Asian elephants can be determined. However, it is still difficult to describe the equilibrium path. There are two equilibrium points in the development model of this study, which means that the balance of two paths can be achieved. Equilibrium point 1: the investment part of the total output is allocated within a reasonable range to ensure that the population of Asian elephants is close to the maximum carrying capacity, and to achieve an effective balance between regional economic development and the protection of Asian elephants, which is a positive balance, namely the "golden age". Balance point 2: if the negative impact is too large, it will inevitably lead to no investment to mitigate the negative impact. The reduction and disappearance of Asian elephants in the region has become an irreversible inevitable result, which is a negative balance, that is, namely the "Dark Age".

Third, from the practical application model, the intrinsic growth rate of Asian elephants in Xishuangbanna is 0.0216 head/day, in the absence of other external interference (such as rubber forest area expansion, railway construction, etc.), and the population has a strong ability to proliferate under natural conditions. However, at present, the population development of Asian elephants has been negatively affected by human interference. As humans continue to expand the planting area of rubber forests, the habitat of Asian elephants continues to be fragmented. The interference of human activities has reduced the population growth rate to 0.0193 head/day, and this impact is increasing.

Fourth, under the dual influence of the expansion of rubber forest and the population growth of Asian elephants, the ecological stability in the region has been weakening, and the human–elephant conflict has become increasingly serious and shows an accelerated development trend. From 2004 to 2016, although the investment rate of Asian elephant protection continued to increase, the anti-interference protection rate of Asian elephants continued to decline, and the decline was higher than the increase of the investment rate. From the perspective of Asian elephant protection and the maximization of comprehensive benefits, under the influence of the expansion of rubber plantation area, the situation of Asian elephant protection is very serious. The overall trend of change is developing from equilibrium point 1 (Golden Age) to equilibrium point 2 (Dark Age). From 2004 to 2016, the living environment of Asian elephants has been disturbed by human activities for a long time, and the suitable living environment of Asian elephants has been invaded by a cash crop planted by human beings. The fragmentation phenomenon of habitat has increased year by year, which has led to the reduction or shortage of natural food of Asian elephants, forcing them to enter villages or farmland to obtain food, and then causing human–elephant conflict. This will have a great impact on the protection of Asian elephants in Xishuangbanna and the poverty and prosperity of farmers in Xishuangbanna. This contradiction will become more acute. The case of killing Asian elephants in Xishuangbanna in the last two years is an important manifestation of this sharp contradiction.

From the point of view of the current analysis, the future period will be very critical. If various policies are not properly handled, the conflict between human figures will be further aggravated and habitat fragmentation will also be aggravated. This is highly likely to result in a reduction in the Asian elephant population and a reduction in the number of activities that may occur in the country until they disappear. Therefore, in the coming period, taking advantage of the changes in the input mechanism of the newly revised Wildlife Protection Law, we should accelerate establishment of the mechanism for protection of Asian elephants and the coordinated development of regional socio-economic development. Some advice is as follows: (1) Central finance should be directly involved in the habitat protection of Asian elephants; (2) An ecological corridor should be constructed to maintain the integrity of Asian elephants' habitat, a food source base should be established and the habitat's scope should be expanded; (3) Asian elephant national parks should be established as soon as possible, as well as trying to establish a multi-national joint-protected area and protection mechanism, such as the China–Laos joint protected area, established in January 2013; and (4) Cross-border anti-poaching cooperation should be continued to protect the population and habitat security of Asian elephants.

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