Wildlife Under Siege: System Dynamics Modeling for Strategic Intervention

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Abstract. The Illegal Wildlife Trade (IWT) poses a significant threat to global biodiversity, ecosystems, and public health, with an estimated annual value of $26.5 billion. This study introduces a methodology for evaluating and analyzing the risks associated with IWT reduction programs using a system dynamics approach. We present a program aimed at reducing IWT in the United States by 30% over five years, focusing on interventions in law enforcement, public education, international cooperation, and data sharing. Through the system dynamics model, we assess the potential effectiveness and identify critical determinants impacting program outcomes. Our findings, based on an illustrative example, indicate that the program could achieve a success rate of approximately 58.8798%. The study emphasizes the importance of enforcement and regulation as key factors influencing success. This methodology provides a data-driven framework for assessing wildlife conservation strategies and offers valuable insights for policymakers and conservationists.

Keywords: System Dynamics Model; Program Evaluation; Risk Analysis; Biodiversity Conservation

1 Introduction

The Illegal Wildlife Trade (IWT) is the fourth largest illegal trade globally, with an estimated annual value of $26.5 billion. It fuels criminal activities like smuggling and poaching, spreads diseases, destroys ecosystems, and severely impacts species diversity, especially endangered species. Despite significant efforts by governments and NGOs to combat IWT, these actions often increase the scarcity and value of illegal wildlife products, further motivating illegal activities. As the saying goes, when something becomes scarce, its value is realized. Therefore, a fundamental approach starting at the source is crucial to effectively curb IWT and protect wildlife.

To reduce IWT, relevant laws need improvement and loopholes should be closed. For example, Xinhua News Agency highlighted that China's wildlife protection laws

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lack clear definitions, leaving some animals unprotected in legal "grey areas" [1]. Similarly, the U.S. Endangered Species Act does not specify criteria for determining protected species, leaving room for illegal trade [2]. Thus, amending laws to clarify the boundaries of illegal trade is urgent.

Enhancing law enforcement efficiency is equally important. Reports from the United Nations Development Programme (UNDP) and the United States Agency for International Development (USAID) suggest that increasing financial and human resources, training personnel, and enhancing inter-agency cooperation and information sharing can improve law enforcement effectiveness [3][4]. Civil society organizations can also help by training personnel and providing advanced equipment.

Additionally, Andersson et al. noted that although CITES aims to protect species from international trade threats, it increasingly shows limitations in its coverage [5]. Therefore, CSOs can organize regulatory bodies and appeal to the U.S. government to address regulatory loopholes and strengthen international IWT regulation.

Noe et al. found that in economically disadvantaged areas, people often resort to illegal hunting due to weak wildlife protection awareness, even when legal resources are available [6]. This highlights the need for public awareness and education to reduce illegal demand. Education increased awareness of legal resource use and reduced illegal hunting, emphasizing the importance of public education and outreach. Media channels should be used to strengthen public awareness, especially in countries like the U.S. that are large importers of IWT [7].

International cooperation is critical, as most IWT is cross-border. Jiao et al. [8] highlighted the significant progress made through cooperation between China and Southeast Asian countries, calling for similar efforts at the international level. We plan to collaborate with international animal protection organizations and establish partnerships, as well as a unified open-source data sharing platform to facilitate IWT response and resource use globally.

In order to effectively protect wildlife, we must take proactive action and develop a plan. This paper will outline a plan based on specific animal conservation objectives and assess its effectiveness based on a data-driven modelling approach. Additionally, a sound assessment method is equally necessary for the uncertainties and risks of reality. This study will develop a rational plan to address these issues, providing a concrete, well-developed solution that will serve as a scientific reference for wildlife conservation efforts.

2 Method

2.1 Description of the Data-Set

The data-set used in this study are mainly from the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) trade database, compiled by the United Nations Environment Programme World Conservation Monitoring Center (UNEP-WCMC). The data-set contains approximately 25 million data entries that meticulously document international trade data from 1975 to 2022 for all species protected under the CITES Appendices for each State Party to the CITES Convention.

2.2 Data Pre-Processing

In the CITES data, all trade categories are mixed in the data-set, and the different scales between trade records do not allow for direct processing. After observing the data-set and reading the documentation describing the data-set, we perform the following operations on each record in the data-set:

- If the record has a unit that represents an individual animal, keep the record.
- If the record does not have a unit, but the value is an integer, retain the record.
- If the record has no units and the value is not an integer, discard the record.

2.3 Program Target Setting

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The growing illegal wildlife trade (IWT) endangers biodiversity, damages ecosystems, and can lead to the spread of epidemics. As the world's largest economy and a major participant in IWT (as shown in Figure 1), the United States has a responsibility to address these issues and set an example. The U.S. respects the rights and interests of organisations and programmes and supports the advancement of related initiatives.The primary driver of IWT is continued consumer demand; therefore, to effectively reduce IWT, efforts must focus on reducing this demand. Our programme aims to reduce the illegal wildlife import trade in the United States by 30%.

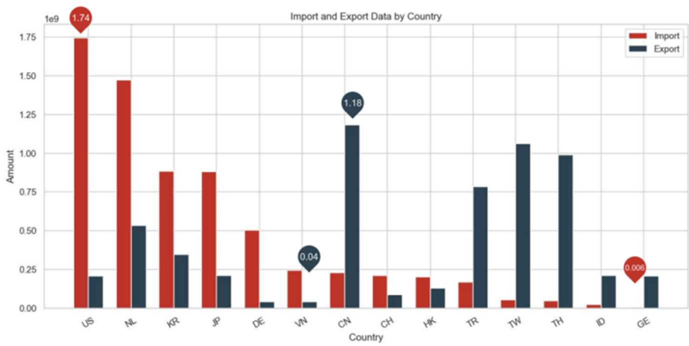

Fig. 1. Map of Illegal Trade in Wildlife Populations

2.4 Resource Allocation

Based on Introduction Chapter, we have collated 7 specific measures, and divided the 7 specific measures mentioned above into 4 categories, shown below:

1. Law Enforcement and Regulatory Intensity: including improving relevant laws and regulations, enhancing law enforcement efficiency, and strengthening regulatory intensity.
2. Public Education and Awareness: including raising public awareness of protection, popularizing animal protection education, and improving media publicity.
3. International Cooperation: synergizing the fight against cross-border IWT.
4. Data Sharing and Exchange: Promote data exchange between organizations.

The proportion of resource inputs for these four types of measures will be part of the parameters in the model below.

2.5 Projections of Program Effectiveness

We will construct a system dynamics model to simulate the effects of reducing the illegal wildlife import trade in the United States when our plan is implemented.

2.5.1 Variable Definition.

In conjunction with the implementation plan constructed in Section D, we define the variables used for model solving as follows:

- ✧ Illegal Wildlife Import Trade (IWIT): this variable is the target indicator to be reduced by our program.
- ✧ Enforcement and Regulatory Intensity (ER): This includes the degree of improvement of laws and regulations and the intensity of regulation.
- ✧ Public Education and Awareness (PEA): affects the level of public awareness of wildlife conservation. This indicator is a collection of public education aspects.
- ✧ International Cooperation (IC): The extent of cooperation between countries.
- ✧ Data Sharing and Communication (DSC): The extent and efficiency of information sharing and communication.

In addition, we considered some of the variables that were outside the program of our project, but were related to the variables in our project and potentially related to the IWT. Definitions are provided below:

- ✧ Economic Factors (EF): economic motives for promoting illicit trade, e.g., poverty, profit-driven, etc.
- ✧ Socio-Cultural Factors (SCF): include traditional practices, consumption habits, etc., which may facilitate illicit trade.

2.5.2 Variable Interactions.

A system dynamics model is a mathematical model that describes the behavior of a dynamic system evolving over time by defining the variables and the rules of action between them, and by constructing causal relationships and feedback loops between them. Therefore, it is also necessary to define the interactions between variables in order to perform a dynamic simulation of the effects of program implementation. According to the program plan, the interactions between variables are developed as follows:

EF, SCF have positive effects on IWIT. The inculcation of socio-cultural may lead to an increase in related demand. Meanwhile, poverty will give rise to illegal trade.

ER, PEA, IC and DSC have a negative impact on IWIT. Improved enforcement and regulatory efficiency, public awareness, international cooperation, data sharing and exchange can help reduce demand and trade in illegal imports.

PEA has a negative impact on EF and SCF. The contribution can be reduced by raising public awareness.

ER has a negative impact on EF and SCF. The contribution can be reduced through increased enforcement and regulation.

There is a positive interaction between IC and DSC, with increased international cooperation contributing to the efficiency of data sharing and exchange, and vice versa.

PEA can mitigate the effects of EF and SCF on IWIT. Education and public awareness can reduce the role of economic and cultural drivers in illegal import trade behavior.

2.5.3 Model Establishment.

To better understand the variables affecting IWIT, we introduce Economic Pressure (EP) and Socio-Cultural Change (SCC) indicators. EP drives individuals towards illegal trade for income, notably in economically deprived areas. SCC influences demand for wildlife products, potentially decreasing demand for traditional uses or enhancing conservation awareness. These indicators are crafted manually to analyze their impact on illegal trade dynamics.

Here, the system dynamics are modeled as follows:

$$\frac{dIWIT}{dt} = \eta EF + \lambda SCF - \alpha ER - \beta PEA - \gamma IC - \delta DSC \tag{1}$$

$$\frac{dER}{dt} = \phi_1 - \sigma_1 EF - \sigma_2 SCF \tag{2}$$

$$\frac{dPEA}{dt} = \phi_2 - \omega_1 EF - \omega_2 SCF \tag{3}$$

$$\frac{dIC}{dt} = \phi_3 + \xi DSC \tag{4}$$

$$\frac{dDSC}{dt} = \phi_4 + \rho IC \tag{5}$$

$$\frac{dEF}{dt} = -\psi_1 ER - \tau_1 PEA + \chi_1 \times (EP) \tag{6}$$

$$\frac{dSCF}{dt} = -\psi_2 PEA - \tau_2 PEA + \chi_2 \times (SCE) \tag{7}$$

Where $\alpha, \beta, \gamma, \delta, \eta, \lambda, \sigma_1, \sigma_2, \omega_1, \omega_2, \xi, \rho, \psi_1, \psi_2, \tau_1, \tau_2, \chi_1, \chi_2$ represent the strength of the influence of the different factors, and $\phi_1, \phi_2, \phi_3, \phi_4$ represents the amount of resources that are used in terms of the ER, PEA, IC, DSC.

2.6 Solution Methods

2.6.1 Baseline Data Definitions.

To predict the effectiveness of our program implementation with this model, the following data are needed to be determined:

- Initial estimates of Illegal Wildlife Import Trade (IWIT).
- Initial level of Enforcement and Regulatory Intensity (ER).
- Initial state of Public Education and Awareness (PEA).
- Initial level of International Cooperation (IC).
- Initial level of Data Sharing and Communication (DSC) efficiency and extent.
- Influence parameters such as α, β, γ, etc.

In order to scientifically and objectively predict the effectiveness of our program implementation, we reviewed the relevant literature [9,10,11,12,13] and determined the approximate order of influence of each aspect. In this regard, we combined the data of each aspect with the actual practice of random assignment based on the ranking.

2.6.2 Oscillation Factor Introduction.

For the intensity parameter of the influence between different factors, we took our resource allocation as a reference. The example plan resource allocation ratios we used are as follows:

Considering the uncertainty in the actual implementation process, we followed the literature to rank the assignment in reverse order, and assigned an oscillation interval of 40%. The specific formula is as follows:

Here, we denote the oscillation factor by $\aleph$. Then:

$$value(\aleph) = 0.02 \times (total - rank(\aleph)) \tag{8}$$

$$\aleph = value(\aleph) \pm 0.4 \cdot value(\aleph) \tag{9}$$

2.6.3 Calculating Project Effect Assessments.

In rating the effectiveness of the programme, the initial IWIT value was set to 100 to extend the predictive range of the programme's effect. Given the stochastic nature of the parameters, we will run the solution procedure several times iteratively, and at each iteration we calculate the impact by subtracting the IWIT value after the program intervention from the IWIT value without the intervention.

On this basis, it is a complementary process considering that the wildlife conservation programme will involve many other areas such as ER, PEA, DSC, etc. as mentioned above. From this, in order to visually demonstrate the effectiveness of our programme and its impact on other domains, we will show the results of one random iteration.

2.6.4 Calculating Project Success Rate.

We have already fully considered the randomness and uncertainty at the reality level in the process of building the dynamics model for this program, and have introduced float and probability into our model. Therefore, for the success rate of the program, it is only necessary to iterate the model cyclically until the success rate has leveled off, and the statistical results reach the cyclic percentage of the program target.

Let $IWIT_{final}$ be the amount of U.S. illegal wildlife import trade in the fifth year under the program's role, and $IWIT_{predicted}$ be the amount of U.S. illegal wildlife import trade in the fifth year predicted without intervention. Then the success condition is:

$$\frac{IWIT_{final}}{IWIT_{predicted}} \leq 0.7 \tag{10}$$

Let N be the number of model iterations and S be the number of selected generations that satisfy the above success condition. Then the success rate P is:

$$P = \frac{S}{N} \times 100\% \tag{11}$$

2.6.5 Finding Determinants in Project: Sensitive Analyses.

In order to assess the impact of the different programme inputs on the results, the inputs for each programme area were adjusted by ±20% in 2% increments, independent of the percentage of total inputs. This approach allows the impact of each aspect on programme outcomes to be assessed separately. By substituting these adjusted inputs into the forecasting model and calculating the relative error between the fluctuating values and the original values, we were able to determine the sensitivity of the model to the different programme aspects in order to derive a correlation between the relative error and the input fluctuations, which allowed a comparative analysis of the impact of the different programme components.

3 Results

3.1 Effect Assessment

The results showing the program's effect on curbing illegal wildlife import trade in the United States are illustrated in Figure 2.

As shown in the Figure 2, our program was able to have an effective deterrent effect on the illegal wildlife import trade in the U.S., capable of producing at least 24% containment, and was able to reduce the amount of import trade by an average of about 30.2%.

In order to visualize the effectiveness of our program, and the impact our program has had on other areas, we show the results of one random iteration, plotted below in Figure 3:

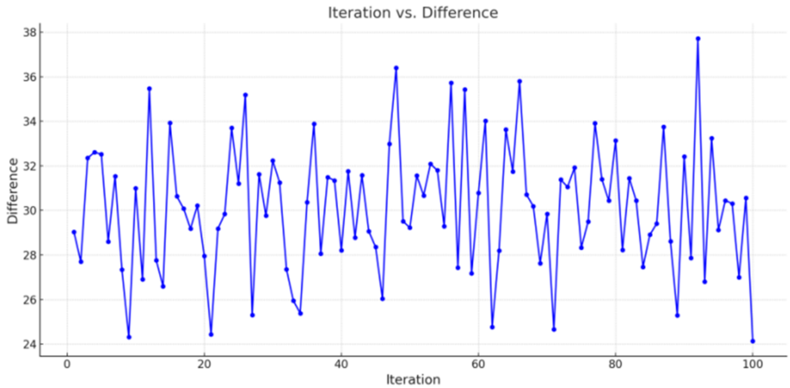

Fig. 2. Illegal Trade Deterrent Effect (%)

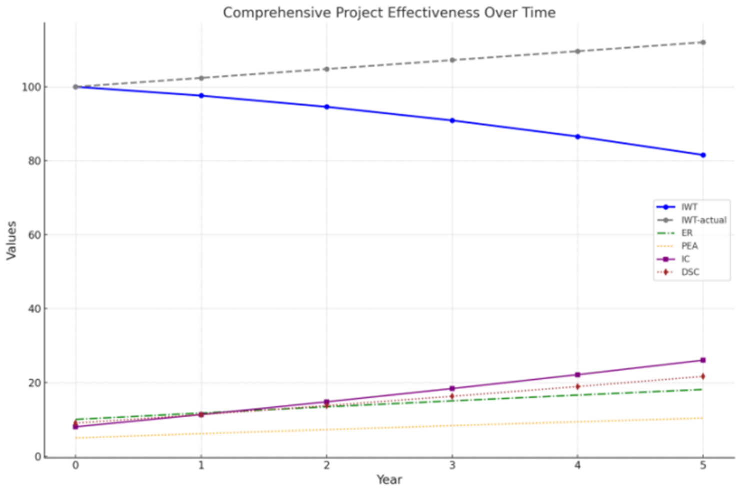

Fig. 3. Project Results Presentation

It shows that besides effectively reducing illegal import trade, we've also enhanced enforcement and regulation, international cooperation, public education, and data sharing. This indicates that our program created a virtuous cycle, with these factors growing through interaction.

3.2 Project Success Rate

Based on the definition above, 500,000 iterations of the model were looped in order to evaluate the success rate. The results are shown in Figure 4:

As seen, the success rate of our program leveled off as the number of iterations increased. The final success rate of our program is about 58.8798%.

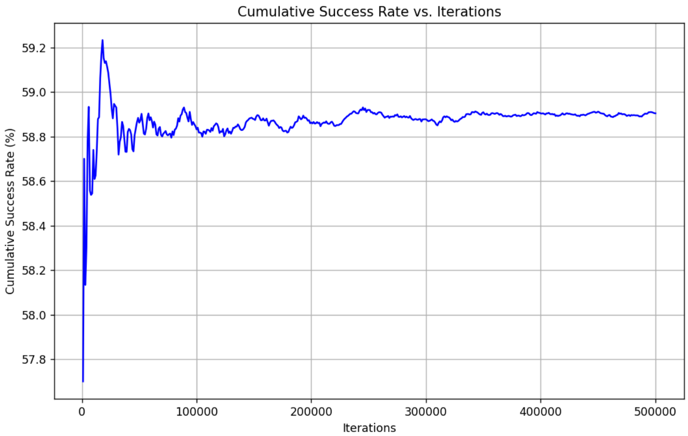

Fig. 4. Project Success Rate

3.3 Determinants of Inquiry: Sensitivity Analysis

Here, the inputs for each area are adjusted according to the definitions. The results are shown in Figure 5:

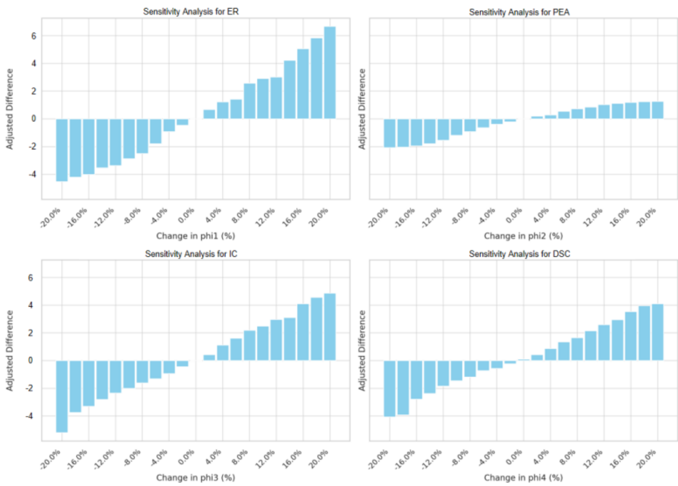

Fig. 5. Relative Error Relationship

From the figure, changes in the inputs of Enforcement and Regulation (ER) were found to have the greatest impact on the program results, with relative errors of 4.3%-6.8% for a 20% change, followed by the inputs of International Cooperation (IC), which can cause relative errors of more than 5%. This suggests that similar "determinants" exist in our program. Even small changes in inputs in these areas can have a significant impact on the volume of U.S. trade in illegal wildlife imports.

Based on this, the following risks can be identified for this project: if there are negative fluctuations in the effectiveness of the law and the level of regulation in a given region - such as a public crisis - the effectiveness of our program will be significantly reduced, reducing the success rate.

4 Conclusions

The illegal wildlife trade (IWT) continues to be a critical issue with wide-reaching implications for biodiversity, ecosystems, and public health. In this study, we developed a system dynamics model to evaluate the potential effectiveness and risks of a program aimed at reducing IWT in the United States by 30% over five years. Our approach highlighted the importance of various factors, including law enforcement, public education, international cooperation, and data sharing, in combating IWT.

The results demonstrated that the proposed program could significantly curb illegal wildlife imports, with a potential success rate of around 58.88%. Key determinants such as enforcement and regulation were identified, indicating that even small changes in these areas could substantially influence the program's outcomes. These findings underscore the necessity of a comprehensive and well-coordinated effort to address IWT, involving multiple stakeholders and robust international collaboration.

This study provides a framework for systematically evaluating conservation strategies and assessing associated risks. The methodology can be adapted to real-world scenarios, offering practical insights for policymakers and conservationists aiming to develop effective wildlife protection initiatives. Furthermore, the model's flexibility allows for its application to different regions and contexts, enhancing its utility as a tool for global conservation efforts. By leveraging this model, stakeholders can better understand the dynamic interactions within the IWT landscape and make informed decisions to protect wildlife and preserve biodiversity.

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