Commun Nonlinear Sci Numer Simulat 34 (2016) 199–209

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

An impulsive state feedback control model for releasing white-headed langurs in captive to the wild

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ARTICLE INFO

Article history:
Received 22 June 2015
Revised 20 October 2015
Accepted 23 October 2015
Available online 10 November 2015

Keywords:
White-headed langurs
Artificial breeding
Migration
Impulsive state feedback control
Model
Order-1 periodic solution

ABSTRACT

In this paper, an impulsive state feedback control model for releasing white-headed langurs in captive to the wild is investigated. By using the geometric theory of semi-continuous dynamic system, the method of successor functions and the analogue of the Poincare criterion, it is proved that under certain conditions the system has an order-1 periodic solution with trajectory asymptotical stability, and this periodic solution remains above some critical value. The theoretical results are verified by the numerical simulations. The conclusion is that simultaneously taking the measures of both population migration and artificial breeding can effectively protect wild white-headed langurs, so that the population can continue to survive and can avoid becoming extinct.

1. Introduction

The white-headed langur is a rare and endangered species endemic to China, listed as one of the world's top 25 most endangered primates by the 19th International Primatological Society Congresses [1]. This primate was newly found during the 1950s in China, and there are no living specimens in foreign countries [2]. Now white-headed langurs only occupy in three karst regions with an area of less than 200 square kilometers in Chongzuo City of Guangxi Province, and the total number of wild white-headed langurs in these regions is less than 1000 [3]. The habitat loss and fragmentation becomes more and more severe, since the range of white-headed langurs distribution is narrow, their habitat is unique, and human activities disturb the life of white-headed langurs. Rock hills inside the habitat are surrounded by farmlands and arable lands, which make the living environment of white-headed langurs like isolated islands. Habitat fragmentation results in population isolation, hindrance of population migrations, and inbreeding. All of these have a strong impact on the gene exchange of white-headed langurs living in different habitat patches, and affect the survival and reproduction of white-headed langurs. Therefore, how to effectively protect white-headed langurs in vulnerable plaque environment is a topic that is worthy of in-depth study.

Usually two methods can be applied for the wild animal protection in the vulnerable plaque environment. One method is to restore habitats and build ecological corridors, promoting the population migration and the gene exchange between patches. This method can balance populations in different patches. The other method is to establish special protection centers for critically endangered wild animals. By artificial breeding and feeding, when the population size reaches to a certain amount, animals

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http://dx.doi.org/10.1016/j.cnsns.2015.10.015
1007-5704/

can be gradually released to the wild, which increases the number of wild animals and hence revives the population. Artificial breeding and feeding is an important method to protect endangered wild animals. Successfully protecting species like the elk and the Chinese alligator are examples of such a method.

The behavior of releasing white-headed langurs in captive into the wild, however, is not continuous. By monitoring the population size of the wild white-headed langurs, when it drops to a certain threshold (such as survival threshold, i.e. Minimum Viable Population [3]), a certain amount of white-headed langurs in captive will be released to the wild. In the development and the management process of biological species, we can see many of such threshold control behaviors. For example, in pest control, pesticides will be sprayed to control pests when the observed amount of pests reaches a certain threshold (e.g., economic threshold). In the process of microbial cultivation, certain amount of nutritional foundation will be input to control microorganism concentration when it reaches a threshold. The common feature of these behaviors is: the corresponding control measures are performed depending on the state of the target species. The control measures are called state dependent feedback control strategy. In mathematics, using impulsive state feedback control dynamic system can accurately describe those behaviors.

Impulsive state feedback control dynamic system has both the properties of the continuous dynamic system and the impulsive semi-dynamical system [4-7], so impulsive state feedback control dynamic system was called the semi- continuous dynamic system (SCDS) by the literature [8]. The study of SCDS is still in the development stage at home and abroad, and there is a great distance away from the requirement of practical applications. Therefore, it becomes a hot topic in the current biology mathematics research. In recent years, the theoretical research of SCDS has great achievements [6-10]. In [6-8], the basic definitions and the terminology are provided; the limit properties, the geometric theory, and the topological conjugation of SCDS are studied; and the criteria for the existence and stability of periodic solutions of SCDS are presented. The Lyapunov stability and the Poisson stability of SCDS are discussed in [9] and [10], respectively.

The study of applications of SCDS also has a great progress. In [11], impulsive state dependent differential equation is first applied to the integrated pest management (IPM). IPM strategies are described by constructing a SCDS. And the existence, the stability of order-1 periodic solutions and the existence of order-2 periodic solutions of the system are discussed. After that, many researchers have studied the various types of SCDS for pest management [12-18]. These literatures use a variety of different mathematical methods and analysis techniques, such as Poincare mapping method [12], qualitative analysis method [15], square approximation method [16], successor function method [16-18], bifurcation theory [13, 14], Poincare–Bendixson theorem [15, 17] and rotation vector field theory [18], to obtain the existence and stability of periodic solutions of a system. In [12, 18], more complex dynamics, such as Chaos, Homoclinic cycle and bifurcation, are studied.

Microbial culture model with feedback control also arouse the interest of more and more Biomathematics researchers. In [19], the authors take microbial biomass as the output variable, the dilution rate as the control variable, and establish an impulsive state feedback control model. They prove that under certain conditions two kinds of microbes can coexist in a positive equilibrium with global asymptotic stability, and consider the robustness of the system and its application in the reorganization of the cell culture. In [20], the authors generalize the result of [19] to a case that the functional response function is a more general monotone function, and show that the system has more complicated dynamic behaviors. In [21-26], various types of chemostat ecosystems of microbial cultures and single cell protein production with threshold control are investigated, and the corresponding dynamic properties are obtained.

SCDS is also used in plant protection, disease control and pharmacology. In [27], a Korean pine forest model with impulsive thinning measure is presented. The authors use an impulsive state feedback system to investigate the periodicity of the regeneration process of the forest. The HIV virus control dynamic system is studied in [28, 29]. In [30, 31], a pharmacological control system of tumors and diabetes is investigated. In [31], the authors describe impulsive injections of insulin or its analogues treatment for type 1 and type 2 diabetes mellitus through the mathematical model, obtain the existence and the stability of order-1 periodic solution, and prove that the blood sugar levels can be controlled by injecting insulin in the method of state feedback.

These applications further promote the development of the theoretical research of SCDS.

The population diffusion model is very suitable to describe the migration states of a biological population under the patch environment. In [32], a dynamics model of the population ecosystem in the patch environment is built to illustrate that an unstable system can become stable via diffusion. A class of single-species non-autonomous diffusion models with time delay as well as the effect of diffusion on population survival and extinction is studied in [33]. In [34], the authors investigate a class of non-autonomous diffusion system with positive periodic function coefficient, and obtain the conditions under which the system has a positive equilibrium point with global asymptotical stability.

From some early literatures [35, 36], we can see that mathematical models are applied to study the wildlife protection and management. In recent years, there are more research results. In [37], a non-autonomous two-species competition model of the rare migratory birds and economical birds with the Holling-type II functional response and pulse culling is studied. By using analysis methods, the authors obtain the sufficient conditions on permanence and extinction of the two species, and discuss the existence and stability of positive periodic solutions. In [38], the authors study an infectious disease model of migratory bird populations, and get the conditions on permanent and extinction of disease. However, these literatures investigate continuous dynamic systems or periodic impulsive systems, without considering the state feedback threshold control strategy. In this paper, we use state dependent feedback control strategy to study the effectiveness of simultaneously taking the methods of (1) establishing corridors for promoting population migration and (2) artificial breeding for protecting the endangered white-headed langur species.

The rest of the paper is organized as follows. In Section 2, we establish an impulsive state feedback control model with artificial breeding of white-headed langurs and releasing them into the wild, and give some preliminaries. In Section 3, we prove