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Dense and sparse aggregations in complex motion: Video coupled with simulation modeling

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ABSTRACT

Investigations into the complex behaviors of aggregations of highly mobile animals have not used the link between image processing technology and simulation modeling fruitfully to address many fundamental ecological issues. Examples include population censusing, which remains difficult despite the demonstrated ecological importance of assessing abundance and density of organisms. We introduce a theoretical framework that connects thermal infrared video imaging with an individual-based simulation model—an approach that appears to be applicable to a diverse set of aggregated, highly mobile, nocturnal animals. To demonstrate the framework two applications are presented. The first is a dense aggregation of Brazilian free-tailed bats (*Tadarida brasiliensis*) that exhibits an emergence pattern that has complex dynamics and the second is a sparse local aggregation of agricultural pest moths whose dynamics are insipid. The first application uses individual-based modeling to mimic the behavior in the video of bats during a nightly emergence from a cave and to provide reliable estimates of the numbers, and associated error bounds. The second application uses video recordings of sparse aggregations to provide consistent estimates of the numbers of flying noctuid moths recorded over a corn and cotton-dominated agroecosystem in south-central Texas. This does not use a mathematical model because error estimates tend to be small.

1. Introduction

1.1. Background information for data

Various taxa ranging from moths (*Helicoverpa zea*—Westbrook et al., 1997; Wolf et al., 1986), to desert locust (*Schistocerca gregaria*; Baron, 1972; Rainey, 1989) and to bats (Davis et al., 1962; Cockrum, 1969; McCracken, 2003; Russell and McCracken, 2006) engage in spectacular flights over great distances. These flights can involve aggregations of hundreds of thousands, to even billions of individuals. For example, swarms of desert locusts have been estimated at 10 billion individuals (Sanchez-Arroyo, 2005) and similarly, flocks of the extinct passenger pigeon (*Ectopistes migratorius*) were estimated in the billions (Sullivan, 2004; Schorger, 1955). Given the magnitude of the numbers and the methods available at the time, estimates should be viewed with caution. Vigilance also extends to the antipodal end of this spectrum where censuses for small numbers of organisms such as those made for rare and endangered species (Thompson, 2004).

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Fig. 1. Thermal infrared image of an emergence at Frio Cave, Uvalde, TX. In this field of view, bats are flying from right to left. The double-column exodus, caused by the geometry of the opening of the cave, is merging into a single column on the left.

During summer months, south-central Texas becomes the home of some of the largest aggregations of mammals known to mankind, both in total numbers and in population density. For example, the colony of Brazilian free-tailed bats at Frio Cave, near Uvalde, TX, has recently been estimated to contain more than 1 million individuals (Betke et al., 2008). Maternity colonies of Brazilian free-tailed bats emerge nightly from caves and bridges in massive, spectacular assemblages that can continue for several hours. Spatial-temporal patterns of emergence can be complex, ranging from apparently random dispersal to more organized formations. The most common emergence formation is that of a single undulating, serpentine-like column. Fig. 1 provides a snapshot of an emergence from Frio Cave, which has two major exits. This emergence configuration initially is that of a double column that eventually merges into a single column. The thermal infrared video, recorded at Frio Cave in summer 2000, shows column configuration and the complex emergence dynamics of the bats emerging over a period of approximately 6 s (see online materials: Video Betke_BW_filtered_Frio.mpeg).

Brazilian free-tailed bats are active in the Winter Garden area, an 8 county region of south-central Texas, largely because of an abundance of prey, many of which are agricultural pest moths (Kunz et al., 1995; Lee and McCracken, 2002; Cleveland et al., 2006). The prey of *T. brasiliensis* includes adults of several Lepidopteron species in the family Noctuidae (Whitaker et al., 1996; Lee and McCracken, 2002, 2005), whose larvae are known agricultural pests, such as fall armyworm (*Spodoptera frugiperda*), cabbage looper (*Trichoplusia ni*), tobacco budworm (*Heliothis virescens*) and corn earworm (*Helicoverpa zea*), also known as the cotton bollworm. A 15-s video segment of a moth survey is presented in the online materials (Kennard_WG_moth.video).

1.2. The modeling background

Brazilian free-tailed bats are aerial predators of nocturnal insects; both predator and prey are known to engage in related seasonal, long distance migrations (Davis et al., 1962; Westbrook et al., 1997). The bat–moth interactions in cotton agricultural systems have recently been modeled using two different approaches. The first approach uses a model based on a system of stochastic difference equations to access economic impact of bats on agroecosystems (Federico et al., 2008). The second is a rule-based approach, which is an extension of the rule-based population model for an emergence of bats, BATOIDS (Hallam et al., 2006). The latter approach uses a BATOID-INSECTOID model based upon an energetics model of bats (Hallam et al., unpublished manuscript). Both methods require census data of moth aggregations and bat colonies as inputs.

1.3. Objectives

The objectives of this paper are to indicate a theoretical framework grounded in modeling that allows application to important problems related to ecological complexity. This framework is utilized to present and develop a methodology to estimate numbers of bats and moths based on video recordings and to provide error estimates for numbers of these organisms as they disperse or forage in airborne aggregations. The novelty of this research is the construction of a mathematical model that mimics the complex behavioral dynamics of individuals in an aggregation, to use this model to develop a video of the simulated dynamics and to generate estimates of error.

We illustrate the simulation model framework with examples where the data are presented in video. The first example depicts a dense aggregation and employs a thermal infrared video of an emergence of Brazilian free-tailed bats (*Tadarida brasiliensis*) from a cave located in south-central Texas. The second represents a sparse aggregation and uses a reflectance infrared video of noctuid moths in a corn field in south-central Texas. The illustrations are based on different methodologies because they differ in scope, perspective and, to some extent, in scale.

2. Methods

2.1. A dense aggregation that exhibits complex dynamic behavior

The method for assessing a dense aggregation that exhibits complex dynamic behavior consists of four main steps: (1) develop a rule-based individual-based mathematical model that depicts flight behavior; (2) create a video from the simulation that has similar flight characteristics to those observed in the thermal infrared video; (3) employ a counting algorithm that yields error estimates that can be corroborated by the simulation video; and (4) apply the counting algorithm to enumerate and infer error estimates for the number of individuals in the censusing video. The novel issues here are the construction of the model and to find the error estimates.

2.2. Video processing

The video of a bat emergence from Frio Cave was processed using a Bayesian method described by Betke et al. (2008). Objects shown as white dots were considered bats identified by using temporal and spatial analysis of thermal intensity values. Temporal analysis involved building a model of mean and standard deviation of intensity values measured at each pixel over time. A current pixel value that differed considerably from the mean value measured at that pixel indicated that a bat may have appeared at that pixel. The method then examined the likelihood that bats were detected by additional spatial analysis of high-intensity regions in each video frame in which significant unidirectional motion was detected. These regions represented the warm bats and the relatively warm vegetation. To avoid false detections of bats where vegetation was present, the method also analyzed the intensity profile of the entire field of view. The profiles that included vegetation were relatively flat, whereas regions of pixels formed by bats contained high-intensity peaks that corresponded to the warm thorax of the bats and lower intensity values of their wings. Because the three-dimensional scene is projected onto the 2D image frame, occlusion may occur and more than one bat may be imaged in the same high-intensity region. The method by Betke et al. (2008) used the locations of the peak intensity values in a candidate region to represent the locations of single bats (white dots).