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Integrating citizen-science data with movement models to estimate the size of a migratory golden eagle population

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ABSTRACT

Estimating population size is fundamental to conservation and management. Population size is typically estimated using survey data, computer models, or both. Some of the most extensive and often least expensive survey data are those collected by citizen-scientists. A challenge to citizen-scientists is that the vagility of many organisms can complicate data collection. As a result, animal-movement effects on data collection can adversely affect modeling of those data. Thus, it would be helpful to develop methods that integrate citizen-science datasets with models that account for animal movement. We used hawk-count data collected by citizen-scientists to estimate the number of golden eagles (*Aquila chrysaetos canadensis*) migrating through Pennsylvania, USA. To do this, we designed a computer model to simulate migratory flights of eagles to estimate what proportion of the population is *available* (i.e., within visible range or close enough) to be counted at hawk-count sites in Pennsylvania. We then conducted a multi-state mark–recapture analysis to estimate *detection probability* (i.e., the rate at which birds within visible range are observed) of migrating eagles. Finally, we used availability rates and detection probabilities to adjust raw hawk-count data to produce estimates of population size. Our models suggest that 24% (±14; mean ± SE) of migrating golden eagles are available to be counted at hawk-count sites, and that 55% (±1.6) of the available eagles are detected by hawk-count observers. We estimate that 5122 (±1338) golden eagles migrate annually through Pennsylvania. Our analysis provides the first quantitative estimate of the size of the eastern golden eagle population, and we demonstrate the utility of one approach to use citizen-science data to address a pressing conservation goal—population size estimation.

1. Introduction

Estimating the size of wildlife populations is fundamental to conservation and management. However, estimating population size is rarely straightforward. For example, the vagility of many organisms can influence population-level monitoring, affecting survey methods and demographic estimates (Katzner et al., 2007; Yoccuz et al., 2001). Measurement of demographic parameters is also difficult and sometimes inefficient when animals are broadly distributed (Lewis and Gould, 2000; Link and Nichols, 1994). For instance, secretive and low-density raptors are hard to study in that monitoring of their populations can be both expensive and logistically demanding (Dunn and Hussell, 1995; Zalles and Bildstein, 2000). However, such monitoring is often critical because raptors are apex predators indicative of the health of ecosystems (Sergio et al., 2006).

Monitoring programs are most effective and likely to be long-lasting when they are low-cost and simultaneously gather large amounts of reliable information on populations (Good et al., 2007; Kéry, 2008). There are many examples of enduring and relatively inexpensive monitoring programs that use citizen-science volunteers to collect data (Braschler, 2009; Cohn, 2008; Devictor et al., 2010; Katzner et al., 2005; Mulder et al., 2010; Silvertown, 2009). These include the Breeding Bird Surveys (BBS) and Christmas Bird Counts (CBC), which occur across North America and which gather massive amounts of information, especially about passerines, at relatively low-cost yet also without accounting for detection probabilities (Dunn et al., 2005; Thogmartin et al., 2006). Nevertheless, owing to their small population sizes and low detection probabilities, in general, most raptors are poorly monitored by BBSs and CBCs (Bildstein, 2006; Zalles and Bildstein, 2000).

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Numerous raptors migrate, and counts during migration are useful to monitor raptor species of conservation concern (Ainslie et al., 2014; Bildstein, 1998; Farmer et al., 2010; Sattler and Bart, 1984). Worldwide, hawk-count data are collected at sites where geography concentrates migrant raptors in large numbers (Zalles and Bildstein, 2000). In North America, these data are collected, stored digitally in the HawkCount database (www.hawkcount.org), and made available by the Hawk Migration Association of North America (HMANA; Hawk Migration Association of North America, 2014). Because volunteers staff most sites, collection costs of hawk-count data are typically minimal to the monitoring organizations and scientific community at large.

Hawk-count data are inherently variable, and some sources of variation among hawk-count sites include: (a) poor standardization of counting coverage; (b) different local landscape traits and their impacts on detection; (c) variable numbers of observers; (d) disparity among observers' proficiencies; (e) weather effects on detection; and (f) temporal sampling variation (Bildstein et al., 2008a; Dunn and Hussell, 1995; Dunn et al., 2008; Heath and Nolte, 2009; Lewis and Gould, 2000; Margalida et al., 2011). In spite of this variability, a great deal of effort has gone into analyzing population trajectories over time (Bednarz et al., 1990; Broun, 1935; Hoffman and Smith, 2003; Farmer and Smith, 2010; Farmer et al., 2008a, 2008b; Hull et al., 2010; Nagy, 1977). However, fewer studies have attempted to assess observer ability to detect migrating raptors (Allen et al., 1996; Berthiaume et al., 2009; Farmer et al., 2007, 2010; Heath and Nolte, 2009; Nolte, 2012). Hawk-count observers sample all visible migrants using a systematic approach, and detecting a migrant includes two components. Birds that are *available* to be counted represent the proportion of the population within visible range (or close enough to be observed) at hawk-count sites. *Detection probability* is the rate at which those birds within the visible range are actually observed (counted) at hawk-count sites.

Golden eagles (*Aquila chrysaetos canadensis*) are rare in eastern North America and little is known about their demography, movements, or behavior (Katzner et al., 2012; Kochert and Steenhof, 2002). The species breeds throughout northeastern Canada, and it is thought that the majority of the population migrates through the central Appalachian Mountains to overwinter in the eastern United States (Brodeur et al., 1996; Katzner et al., 2012; Millsap and Vana, 1984). In western North America, migratory populations may be in decline (Hoffman and Smith, 2003; Smith et al., 2008), whereas resident populations are stable (Millsap et al., 2013). In contrast, the eastern population likely increased through the late 20th century (Farmer et al., 2008a). Estimates of the size of the eastern population ranges between 1000 and 5000 individuals (Katzner et al., 2012; Ombalski and Brandes, 2010), less than a quarter of the number of golden eagles in western North America—i.e., 19,000–35,000 (Good et al., 2007; Millsap et al., 2013; Nielson et al., 2011). Eastern golden eagles are counted in the hundreds at hawk-count sites in the central Appalachians. We integrated these citizen-science data with modeling efforts to better understand their demography. Our process involved three steps. First, we estimated the proportion of golden eagles that migrate near hawk-count sites and that are available to be counted by observers. We modeled southbound autumn migration of golden eagles to estimate this parameter. Second, we estimated what proportion of available golden eagles is detected at hawk-count sites. We used a mark–recapture analysis to estimate this second parameter. Third, we combined parameters of eagle availability and detection with historic hawk-count data to estimate population size for eastern golden eagles. Finally, we compared past to present estimates of population size in the context of golden eagle conservation in eastern North America.

2. Materials and methods

2.1. Study area

We focused our research on an area of the central Appalachian Mountains roughly outlined by the state of Pennsylvania, USA (Fig. 1a). We chose to focus our research in Pennsylvania because eastern golden eagles move through this area in autumn in large numbers, and because it extends from the Great Lakes to the Atlantic Ocean, a large portion of eastern migrants must cross the state during their travels. Topography in Pennsylvania includes many long-linear ridges, lowland valleys, forested highlands, and mountain foothills (United States Forest Service, 2007). Local autumn weather is temperate, overcast, and characterized by westerly winds that interact with the steep topography of the ridge and valley regions to generate uplift (Miller et al., 2014). Of 32 established hawk-count sites, approximately 12 are active and regularly staffed in Pennsylvania, although others once operated intermittently. Peak migration of golden eagles through Pennsylvania occurs in November (Katzner et al., 2012).

2.2. Hawk-count data

HMANA volunteers and others collect, organize, and post hawk-count data from sites across North America (Hawk Migration Association of North America, 2014). Hawk-count data are the property of the individual monitoring sites while the HMANA web site acts as a data storage repository. At a subset of sites, hawk-count observers collect but do not post additional data on age and timing of movements of individual eagles. With permission of the individual sites, we downloaded posted data from Novembers 2002–2011 from 32 hawk-count sites and we requested detailed unposted data, when available.

2.3. Modeling golden eagle migration

To understand what proportion of migrant eagles are available to be counted at hawk-count sites (i.e., our first objective), we designed a computer model (migration model; implemented in Visual C# 4.0; Microsoft Corporation, 2010), to simulate migratory movements of golden eagles in the central Appalachian Mountains. The model was necessary because (a) hawk-count sites do not randomly sample the migrant eagle population (if they did, then we would only need detection rates to estimate population size) and (b) because telemetry data (Miller et al., 2014) are too sparse to use to estimate this parameter. We briefly describe the migration model here. Its decision steps are described in greater detail elsewhere (Dennhardt et al., in press).

Each simulated flight route begins at a randomly selected starting position on the north–northeastern Pennsylvania border between the easternmost and westernmost routes used by telemetered eagles (Miller, 2012). The migration model estimates uplift in five grid-cells (i.e., east, west, southeast, southwest, and south; 90-m resolution) surrounding each eagle's position based on weather conditions from a random sample of 33 November days between 2002 and 2011 from the North American Regional Reanalysis dataset (Mesinger et al., 2006). Movement of the simulated eagle into one of the five grid cells is based on a directed random walk determined in part by relative strength of uplift in those cells. This process is repeated until the simulated eagle reaches the southernmost border of the modeling region to complete its migration.

The following rules govern movements in this migration model:

1. Eagle movement decisions are based only on the interaction of topography and weather (i.e., uplift).