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COMMENTARY

Individual-based monitoring is critical for small populations

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Abstract
Monitoring small and/or threatened animal populations using methodologies that provide accurate information is critical for effective and timely conservation decision-making. In recent years, "unmarked" methods that combine passive sampling of unidentifiable individuals with statistical models that purport to estimate demographic parameters (e.g., abundance) have proliferated. We highlight the risks of using such methods for small populations and the considerable value of individual-based monitoring.

Keywords Animal · Monitoring · Population · Threatened · Unmarked

As quantitative ecologists who work with conservation practitioners, we often encounter situations in which practitioners wish to estimate the abundance of small and/or threatened populations. Abundance is a direct line of evidence to characterize extinction or extirpation risk (Pimm et al. 1988; Callaghan et al. 2024) and thus is of significant value for monitoring small populations. In recent years, we are increasingly asked about monitoring threatened populations with "unmarked" methods. Generally, these methods combine passive sampling (e.g., camera traps, acoustic recorders, eDNA, etc.) to record detections or counts of a species at unique spatial locations (without individual identification) with statistical models that rely on strict design and model assumptions (Gilbert et al. 2021). These methods face limitations due to required assumptions, and these limitations are accentuated for small populations. In general, unmarked methods (without auxiliary information such as radio/GPS telemetry data) are perhaps best interpreted as generating indices of abundance (i.e.,

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relative abundance that is assumed to be correlated with absolute abundance) due to their heavy reliance on assumptions (Gilbert et al. 2021). For small populations, issues such as data sparsity (e.g., few detections of a focal species, or data from only a few locations) and underdispersion (less variation in counts than expected by the statistical model used to estimate abundance) undermine the assumptions underpinning unmarked methods. This jeopardizes their inferential reliability.

In contrast, individual-based monitoring (i.e., sampling identifiable individuals and tracking them through space and time) is a time-tested and reliable approach for characterizing wildlife populations (Williams et al. 2002). Individual-based monitoring focuses on the fundamental unit of the population (the individual), captures demographic and sampling variation, and ultimately leads to a nuanced understanding of how and why animal populations change (Clutton-Brock and Sheldon 2010; Stillman et al. 2015). Importantly, individual-based monitoring is more robust than unmarked methods to the issues presented by small populations. As technology (e.g., camera traps, autonomous acoustic recorders, eDNA, drones) and statistical models advance to estimate population parameters (e.g., abundance) without individual identification (Gilbert et al. 2021), it is important to emphasize the continued value of individual-based monitoring, especially for small and/or threatened populations.

Individual-based monitoring is at the core of many methods for robust estimation of population abundance and demographic change (Seber and Schofield 2019). Robust abundance estimation relies on an appropriate sampling design and statistical model (Yoccoz et al. 2001). However, models are not all the same; statistical models use different types of data, rely on varying assumptions, and differ in their ability to estimate abundance accurately and precisely. Methods fall along a continuum of data requirements ranging from detections or counts (Royle and Nichols 2003; Ramsey et al. 2015; Chandler and Royle 2013, Royle 2004; Lucas et al. 2015; Moeller et al. 2018) to tracking identifiable individuals (Seber and Schofield 2019; Royle et al. 2013). In general, the less that is known about individuals (e.g., unmarked models), the more and/or stronger statistical assumptions or auxiliary information are required to estimate abundance.

Identifying individuals via tags or natural marks can be logistically or financially prohibitive, impeding the use of models that require individual identification. Tagging individuals also often requires physical capture, which presents ethical concerns and can put individuals at risk of injury or mortality. 'Unmarked models' are thus attractive because they eliminate the constraint of identifying and tracking individuals and represent an ostensible improvement over population indices (Anderson 2001). However, the utility of these models may be minimal or even risky for certain contexts. First, the data do not lead to a minimum number of individuals known to be alive, an often-critical and conservative measure of a small population. Second, evaluations of unmarked models have shown them to be inaccurate and/or imprecise when estimating abundance, to be sensitive to assumptions and unique data characteristics, and to be capable of detecting only catastrophic changes in abundance (Barker et al. 2018; Amburgey et al. 2021; Morin et al. 2022; Sun et al. 2022; Twining et al. 2022). This poor reliability is concerning if applied to monitoring small populations and especially small populations of threatened species. Specifically, the concern is that use of unmarked models may lead to poor conservation decisions for these at-risk populations. Furthermore, using sampling designs focused on unmarked individuals may not lead to other benefits of individual-based monitoring.

Individual-based monitoring (invasive or non-invasive) provides details that may be obscured when sampling only at the population level. Individuals vary in fundamental ways that are important to a population's growth and genetic diversity. This includes demographic (e.g., age and sex) and behavioral (e.g., social dominance or boldness) variation, which are both important for conservation decision-making (Williams et al. 2002; Greggor et al. 2016). Individual-based monitoring can lead to learning about animal movement, behavior, habitat use, genetics, health, reproduction, demography, and more. This level of learning is especially important when monitoring small populations and even more important when these small populations are of a threatened species. Further, management decisions (e.g., translocation, vaccination) of small populations are often centered on individuals (Caughley 1994). By not focusing on individuals, important insights may be missed (Richardson et al. 2019), potentially leading to less effective conservation decisions.

We have two take-home messages. First, individual-based monitoring can lead to important insights about a population (abundance, behavior, and beyond) and allows robust estimation of demographic change which can be critical in conservation decision-making. Second, the questionable reliability of unmarked models with detection/count data from passive sampling and the limited insight these methods provide make them riskier for monitoring threatened species and informing conservation decisions. While there is utility in all sampling and statistical advancements, we look forward to the continued evaluation of the reliability of unmarked methods for small populations. In the meantime, individual-based monitoring remains a reliable approach, providing the most information. But tracking individuals needs to be practical and feasible. A compromise approach may be one where a limited number of individuals are tracked, such that information from unmarked and marked individuals are used simultaneously to estimate abundance (Whittington et al. 2018; Margenau et al. 2022); in these cases, being thoughtful about the compromise is important to balance all information needs.

Small population size is the rule rather than the exception in ecology (McGill et al. 2007). Further, many wildlife populations are declining (Finn et al. 2023) such that small populations will become more prevalent, though small population size does not necessarily portend extinction (Wiedenfeld et al. 2021). Individual-based monitoring has led to important insights and conservation direction for many threatened species or small populations, including mountain gorillas (*Gorilla beringei beringei*; Robbins et al. 2011), African elephants (*Loxodonta africana;* Wittemyer et al. 2014), humpback chub (*Gila cypha*; Yackulic et al. 2021), Amur leopard (*Panthera pardus orientalis*; Wang et al. 2017; Vitkalova et al. 2018), Whooping cranes (*Grus americana*; Servanty et al. 2014), hihi (*Notiomystis cincta*; Panfylova et al. 2019), and lynx (*Lynx lynx*; Devineau et al. 2010). Working towards linking individual-based monitoring and management decisions (Lyons et al. 2008; Robinson et al. 2018) motivated by clear objectives offers significant value in protecting and recovering such species.

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Declarations

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