Benefits of Bayesian Modelling For Conservation

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Abstract

Introduction: The challenges and needs of today's conservation science are well-suited for Bayesian data analysis

Conservation science in the 21st century seeks to address the dual crises of climate change and rapid biodiversity loss. These are problems that require urgent action globally, as loss of earth's biodiversity and its benefits are accelerating (Brondizio et al., 2019; Ripple et al., 2017; Tittensor et al., 2014). Conserving biodiversity is, of course, the primary motivation for the field of conservation biology (Williams et al., 2020) and at the heart of recent international resolutions such as the Convention on Biological Diversity's Aichi targets (UNEP CBD 2010) and of Sustainable Development Goal 15 (Assembly, 2015).

Recently, nature conservation has been integrated into global climate change mitigation assessment and efforts, as well, through the concept of âĂŸnatural climate solutionsâĂŹ (NCS). NCS are intentional human actions (or 'NCS pathways') that protect, restore, and improve management of forests, wetlands, grasslands, oceans, and agricultural lands to mitigate climate change (Griscom et al., 2017).

Though action is urgently needed, effective biodiversity conservation and durable climate change solutions should be evidence-based.

- 'best available science' often required by policy
- part of science process, though often 'ideal' data are not available
- synthesizing multiple data sources and incomplete datasets may be required

A critical part of building the evidence base is transparency and reproducibility in science.

- This includes being transparent and clear about uncertainty
- Communicating/quantifying uncertainty about climate change mitigation (e.g., principles of Natural Climate Solutions, Ellis 2023, IPCC requires uncertainty (Chap 3 from 2006))

Bayesian data analysis provides a framework and approaches that align well with these needs of conservation biology.

- Moving beyond null-hypothesis testing
- Propagation of uncertainty
- Frameworks to synthesize multiple sources of data and update as new information becomes available
- Though some fields within conservation biology and natural resource management have adopted Bayesian methods (wildlife mark and recapture models or occupancy models, fisheries), historically they have not been widely used conservation science.

Aim

We aim to help accelerate adoption of Bayesian data analytical approaches in conservation science because we believe these approaches offer features that are well-suited to the field and could enhance progress, with more widespread adoption. We describe the benefits of using Bayesian methods for conservation science questions, summarize what is required to use these methods, and provide example code and analyses relevant to current conservation problems. We also share resources and a glossary that we hope will make Bayesian tools more approachable to those who have not used them before.

Benefits for Conservation

Bayesian approaches offer powerful and flexible model that can get the job done!

Ecological data are notoriously poorly aligned with classic stastical techniques (e.g., nonnormal data, unbalanced, etc). This can result in situations where frequentist models are not possible to fit or result in inaccurate estimates (e.g.,case study 1). Bayesian modelling approaches are flexible and powerful enough to provide robust estimates under a wide range of conditions.

In addition, conservationists are often particularly interested in species with small populations, since these are often the ones most at risk of extinction, or ones that are poorly understood (Stinchcombe et al., 2002). Frequentist statistics rely on asymptotic behavior, which makes it difficult for these methods to draw useful conclusions from small sample sizes (**?**). Bayesian methods, however, do not have this same reliance, and so are better able to accommodate small sample sizes. However, these methods still require care when working with small sample sizes, because priors matter much more; yet this is also an opportunity to include the full gamut of prior knowledge from many sources that may not typically be included in quantitative analyses (McNeish, 2016).

Frameworks for integrating multiple data sources

Conservation problems are complex and addressing them, especially in the era of climate change, requires integrating social, economic, biological, and physical information to provide the evidence base upon which decisions can be made. Conservation evidence comes in many forms, including from quantitative studies, community knowledge, expert knowledge, traditional ecological knowledge, and others. Conservation decision-making requires integrating these multiple sources of information to provide an evidence base upon which decisions can be grounded (Stern and Humphries, 2022). Bayesian methods enable two fruitful avenues for such integration. First, information can be amalgamated into Bayesian Belief Networks (Marcot et al., 2001; Newton et al., 2007). Second, extant information can be used to inform prior distributions (O'Leary, 2008).

Adaptive management and comparing alternatives

Conservation scientists often need to compare outcomes from current 'business-as-usual' approaches to new alternatives. For example, conservation scientists might be interested in deciding whether an alternative practice produces the same results as current practice. The need to test new approaches, coupled with the fact that ecosystems are dynamic and often yield unexpected behaviors (Levin et al., 2012; Gross, 2013), have led to practices of adaptive management in conservation (Holling and Walters, 1978). Yet frequentist statistical frameworks rarely provide information necessary to inform adaptive management (Prato, 2005). Specifically, frequentist statistics incapacity to compare support for a variety of hypotheses (including a 'null' hypothesis) prevents this method from informing what interventions will most likely bring about conservation gains (Prato, 2005). For example, in its submission process, leading conservation journal *Conservation Biology* requires that authors recognize that, "8. ensured you have not misinterpreted statistical nonsignificance as no effect if a frequentist approach was used (absence of evidence is not evidence of absence)?" Bayesian analysis, on the other hand, can provide evidence to support a null hypothesis, e.g., that the current and alternative and current management practices produce similar results (Gallistel, 2009).

Ability to quantify and propagate uncertainty

Bayesian analyses are particularly useful for decision-making because they not only include a range of information types, but also include associated uncertainty (Stern and Humphries, 2022). The integration of multiple datasets required by many conservation problems in turn necessitates quantifying and sometimes propoagating uncertainty across multiple sources and/or multiple modeling steps. Bayesian approaches enable straightforward quantification and propagation of uncertainty, including for some conservation problems that can require analyses for which frequentist statistics are unable to compute the associated uncertainties (Bolker et al., 2009; Bates, 2006). Frequentist statistics produce metrics like confidence intervals and p-values, which have very specific interpretations (Fornacon-Wood et al., 2021). However, these metrics are often misinterpreted. Bayesian statistics, in contrast, produces credible intervals, for which the intuitive interpretation matches the technical definition, yielding much more easily interpretable results, particularly for non-statistician colleagues and decision-makers (Fornacon-Wood, 2021).

Moreover, Bayesian methods enable uncertainty to be propagated through multiple analyses, ensuring that end results represent the full uncertainty of the process under study. (Draper, 1995; Gilbert et al., 2023; Eyster et al., 2022; Saunders et al., 2019). For example, using Bayesian methods, one can calculate the abundance of birds in different types of management landscapes such as traditional agriculture and perennial polycultures, and then propagate the uncertainty associated with those abundances into a downstream analysis to test whether the bird communities in the alternative perennial polyculture landscape are maintained simply as an ecological sink (Eyster et al., 2022).

Conservation often requires making easily-interpretable wildlife status categories to inform decision making (Brooks, 2008). For example, conservation might be prioritized for species declining 'rapidly' versus 'moderately.' These discrete categories require information about when a species' population has passed a particular threshold (Brooks, 2008). Bayesian models make it possible to assess the evidence for whether a species has surpassed a given threshold (Brooks, 2008).

Case Studies

Robust estimates; bird example (Deirdre, Mao)

- Extinction example referenced in (Wade, 2000). Compare frequentist (Maximum likelihood) to Bayesian analysis to get at population trend and extinction risk
- simulate data

Propagating uncertainty; NCS example (Ailene)

- Mitigation= flux X extent
- uncertainty propogation using posterior
- compare to boot-strapping

A future with more widespread use of Bayesian modelling in Conservation

- Implementing Bayesian modelling is easier than ever before! Computational resources (add some details)- are getting easier and should continue getting easier to develop, test, and refine models that represent focal systems and are able to address relevant questions)

- Urgency and complexity of problems and systems requires flexible, powerful modelling appraoches
- We envision a future in which conservation and ecology students (undegraduate and graduate levels) recieve statistical training to provide strong foundations in Bayesian statistics. Currently the focus of many introductory statistics classes is frequentist methods, which are not appropriate for most ecological data. It doesn't have to be this way!
- IPCC and other global institutions should include guidelines for Bayesian approaches increasibly used by ecologists (Fig. 1), as NCS gets integrated into the climate/biophysical analyses that dominated early IPCC work.

Box 1: Defining Bayesian Analysis

Box 2: Resources to Get Started

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Figures

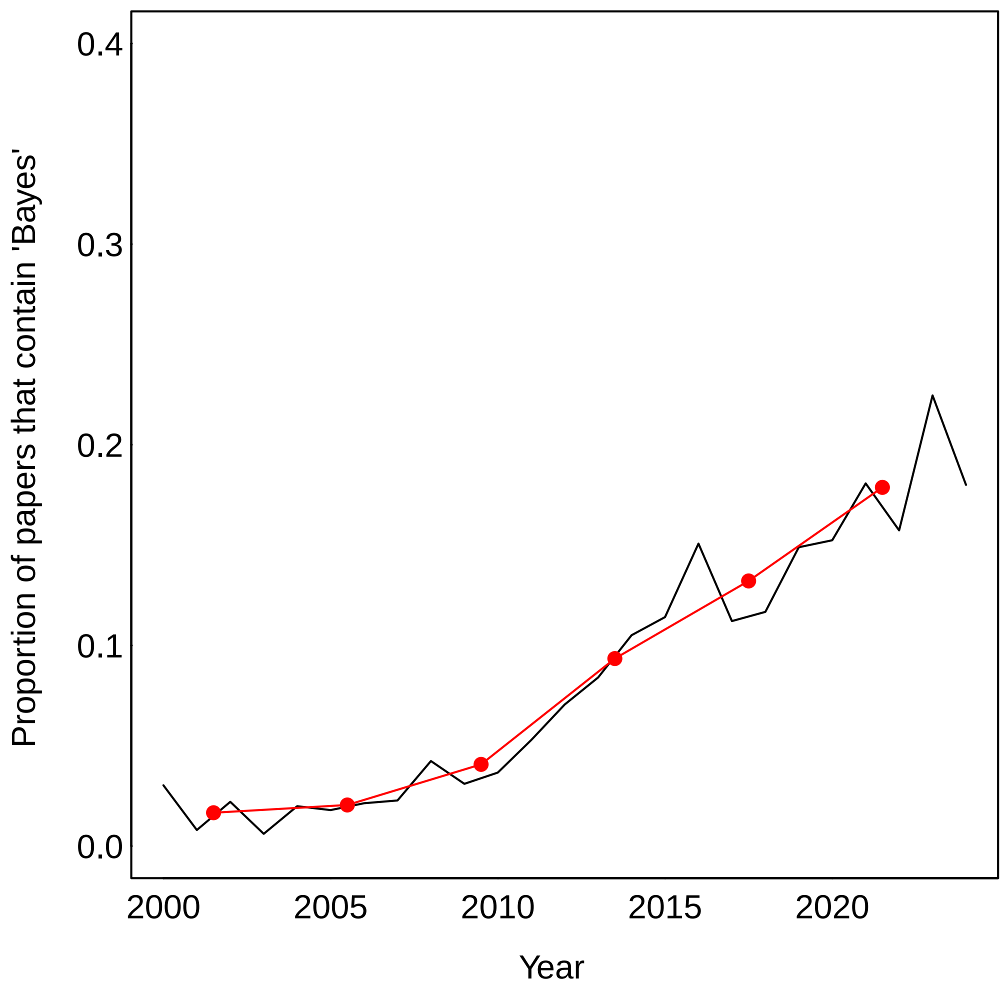

Figure 1: **Proportion papers using Bayes in XX major conservation journals since 2000**

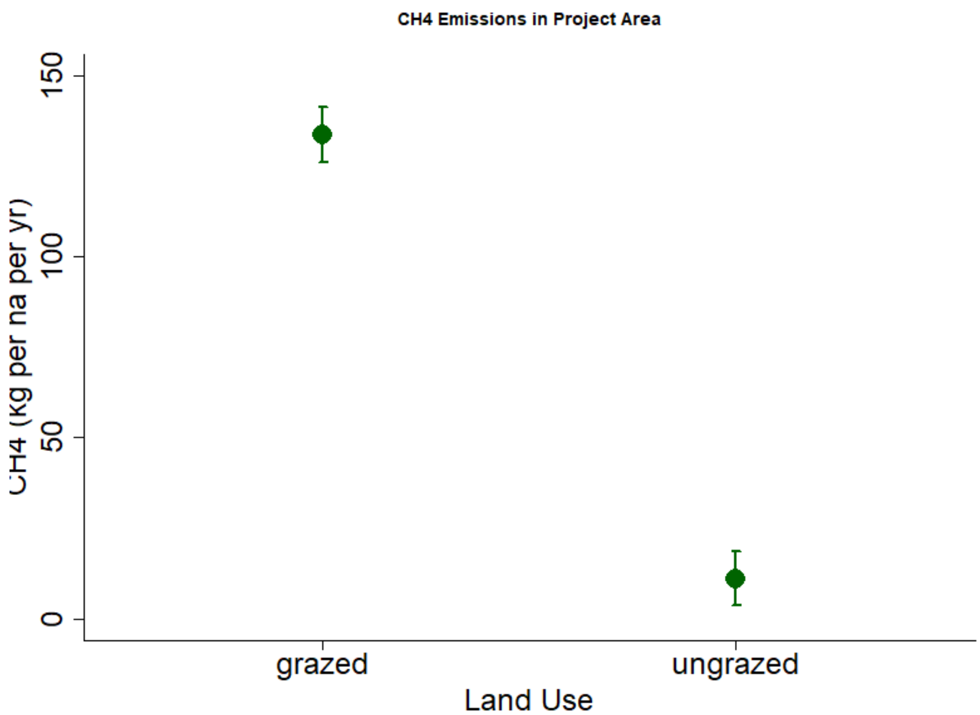

Figure 2: **NCS Example: Uncertainty propagation**