META-ANALYSIS OF CORAL REEF BIODIVERSITY: MANAGING A GLOBAL CRISIS THROUGH IMPROVED METHODS FOR COMBINING DISPARATE INFORMATION TYPES

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Problem Description

Coral reefs are under threat from a variety of agents, such as coastal development, overfishing, and climate change. Reefs are widely believed to have degraded substantially over the course of the last century, and to be further threatened by the increasingly rapidly changing climate. However, the information that is available to inform coral reef managers about the magnitude of the coral reef crisis, and about ways to help reefs resist further degradation or to recover, is limited. In particular, our picture of what has happened to reefs in the past half-century is based largely on attempts to summarize evidence obtained by studies of reef dynamics by small research teams, typically working in particular locations and often for short bursts of time, using a range of different methods designed to address research questions idiosyncratic to those research groups. Nevertheless, data from many thousands of individual surveys are now available from a broad range of locations around the globe, and there is a strong need to leverage this information in a rigorous way for management. However, attempts to synthesize this information to date have often drawn mutually inconsistent conclusions. For example, analyses of coral cover in the Caribbean have yielded estimates of a gradual, geometric decline in coral cover since the mid-1970s (Gardner et al. 2003), but also an abrupt step change in 1981 with little systematic trend before or after this event (Schutte et al. 2010). The narrow confidence limits reported in these studies imply markedly different histories for the same region. Clearly, new ways are needed to combine these data in ways that can provide a more consistent view of the status and changes in coral reef biodiversity; one in which the uncertainty associated with the synthesis of data from individual studies is more comprehensively represented.

Our MISG study group was tasked with developing meta-analytical methods to estimate changes in the abundances of reef organisms through time, by taking rigorous account of the spatial, temporal, and methodological heterogeneities associated with the available data. The sample data we had to work with came from the Long-term Monitoring Program (LTMP) of the Australian Institute of Marine Science (AIMS). AIMS has monitored aspects of the biodiversity of the Great Barrier reef over many decades and very large spatial scales using consistent and calibrated methods. The logic of beginning with these data was that any new methods developed could first be applied to “well-behaved” data collected in consistent ways over space and through time, but that was extensive enough that it could be degraded in strategic ways to investigate the robustness of new meta-analytical methods to the pathologies characteristic of attempts to synthesize data from different research programs.

Project Activities

Preliminary work by the moderators indicated that a variety of approaches to meta-analysis had been applied to this particular problem, but also, that a range of promising statistical methods for analysing long-term ecological trends in abundance had not. Therefore, the first activity of the group was to review and critically evaluate the strengths and weaknesses of both existing meta-analytical approaches, and standard approaches. The group's second activity was to conduct some exploratory analyses of the AIMS LTMP data, focusing in the first instance on overall coral cover. Finally, we considered some possible model specifications, initially for the LTMP data in particular, but also with an eye to approaches that could potentially be applied to the more general meta-analysis problem.

Literature Review. Our literature review identified several key papers on the meta-analysis of trends in abundances of coral reef organisms. These were mostly focused on the Caribbean, which has been the most extensively studied region, and has also suffered conspicuous degradation over the time period during which coral reef scientists have been collecting systematic data (Gardner et al. 2003, Cote et al. 2005, Schutte et al. 2010, Zychaluk et al. 2012). These papers differed in various ways. Gardner et al. (2003) weighted the contributions of studies according to sample size, Cote et al. (2005) according to the areal extent of studies. Schutte et al. (2010) did not weight studies at all. One key feature of all of these studies was that, in their analyses of Caribbean-wide trends, the geographical distribution of studies was not explicitly considered: thus, ten studies from the same bay in Jamaica were implicitly assumed to provide the same information about trends in the whole of the Caribbean as if those ten studies had been spread more broadly throughout the region. This, coupled with differential approaches to weighting and some differences in which studies were included in the various meta-analyses, were likely reasons for the inconsistencies in results between the different meta-analyses.

Secondly, we identified papers that analysed trends in coral reef data from individual data sets, but which had not been applied in a meta-analysis context. Much of this work has been conducted using AIMS LTMP data. These include a range of "standard" regression-type approaches including linear mixed-effects models with temporal autocorrelation (e.g. (Sweatman et al. 2011), analysis with semi-parametric smoothed regressions (e.g., De'ath et al. 2012); and nonlinear least-squares fitting (e.g., Osborne et al. 2011). These approaches tended to account for more features of the data structure than the meta-analyses did (e.g., temporal autocorrelation in Sweatman et al 2011, or nonlinearities expected from density-dependent growth in Osborne et al. 2011).

Finally, we noted that "best practice" analysis of population time series in ecology was increasingly combining the direct fitting of density-dependent population models to data (as in Osborne et al. 2011), but also explicitly accounting for both observation error and process noise. In autoregressive processes, such as population growth, these two sources of variability in data have fundamentally different effects: observation error does not propagate through time, but process noise does. Most commonly, this approach is applied using the Gompertz population model, which is a linear autoregressive process when abundance is expressed on a logarithmic scale. No studies of coral reefs have explicitly adopted this observation error-process noise approach, although Thibaut et al. (2012) seek to approximate it by exploiting the hierarchical structure of the LTMP.

Exploratory Analyses. To become more familiar with the LTMP data, the group undertook some exploratory investigations of the data. One group investigated the behaviour of the proportional change in abundance over time (logarithm of the ratio of observed coral cover at successive time intervals). Another investigated the strength of correlations at different levels of the sampling hierarchy (i.e., the correlation of time series between transects within sites, between sites within reefs, and between reefs within shelf position scales). A third approach was to seek to identify potential factors and nonlinearities in the data with a Classification and Regression Tree (CART) analysis. These analyses indicated that most of the variation in the data was between reefs rather than between sites or between transects. Indeed, correlations between reefs appeared remarkably low. Group members also classified the time series into three groups: time series lacking notable trends, but exhibiting substantial stochastic variability, those exhibiting a longer-term trend and less interannual variability, and those with abrupt decreases, indicative of a catastrophic disturbance.

Possible Modelling Approaches. Several potential modelling approaches were outlined and discussed by Workshop participants. One was a spline model currently under development by PhD student, Julie Vercelloni, as part of the broader QUT-AIMS collaboration. It is a Bayesian semi-parametric regression approach that captures how variability at one scale is related to variations at another scale, with uncertainty for each level (sector, reef, habitat, site). An alternative was an hierarchically-structured Gompertz state-space model, with random effects of spatial scale and year. This is less flexible in functional form than the spline approach, but has the advantage of parameter values that are more biologically directly interpretable. Some early progress was made in coding this model for fitting in WinBUGS, but this process was not completed by the close of the workshop. A variant of the Gompertz approach, suitable if coral cover is not exhibiting density-dependent dynamics, would be a (density-independent) geometric growth model. Finally, although simple linear mixed effects models of coral cover have already been applied to the AIMS LTMP data, this approach might be a suitable first pass for meta-analysis, given its comparative ease of fitting. Within this framework, “study” could be treated as a random effect.

These initial investigations into new approaches to the meta-analysis of “ill-behaved” ecological data, while still largely preliminary, have served as a catalyst for a new collaboration that the Industry partner and moderators will pursue. In the meantime, a review article reporting on the above achievements on a broader context of meta-analysis is planned. It will be led by Mengersen with participation open to all members of this working group.

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