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Nanson's Paradox *see* Group Decision

Natural Resource Management

Risk assessment for natural resource management (NRM) deals with the *uncertainty* of our *impact* on the natural environment. Economic growth, development, and individual prosperity generally occur at the expense of environmental conservation and protection. The world's population is about 6.5 billion [1] and at its present rate of growth, will hit 10 billion by 2040. This will create unprecedented pressures on an already stressed environment. The realization that rates of consumption of even so-called renewable resources outstrip rates of production has been slow in coming. Actions to halt or reverse the trend have been even slower. The Central Intelligence Agency (CIA) [1] identifies rapid depletion of nonrenewable mineral resources, depletion of forests and wetlands, plant and animal extinctions, and the deterioration of air and water quality as among the most serious long-term environmental problems (*see* **Air Pollution Risk**; **Water Pollution Risk**). Human-induced climate change ranks as perhaps the single most pressing issue confronting mankind (*see* **Global Warming**). While degrading the environment, we simultaneously seek continuity of "ecosystem services" from it. Our list is long. We want clean air, rivers, streams, oceans, estuaries lakes, coasts, aquifers, and soil. We want safe, reliable, and clean supplies of drinking water and food. And we want our human, industrial, and household wastes to be disposed of safely (but "not in my backyard") while ensuring habitat and species conservation, environmental restoration, long-term sustainability, no adverse impacts on human health, and a full and comprehensive assessment of risks (*see* **Hazardous Waste Site(s)**; **What are Hazardous Materials?**). Clearly, there are trade-offs that need to be acknowledged and balances that need to be struck.

Strategies that aim to reconcile economic growth and development with sustainability and environmental impact are characterized by risk. There are a number of facets to the risk equation: (a) uncertainty in all its forms (epistemic, linguistic, model); (b) model incertitude – how do we formulate and calibrate models to describe events that have never occurred and for which no data are available? – and (c) natural variability. Furthermore, as with any modeling approach, risk assessments may be compromised by an inability or reluctance to enumerate all possible consequences (e.g., the effects of smoking on humans was known by tobacco companies, but not revealed, while the effect of polychlorinated biphenyls (PCBs) in the environment only became evident years after they were first used). Other issues also arise, such as how to assess the quality of different risk assessors and different estimates and predictions (e.g., in 1968 Paul Ehrlich claimed millions of people would starve to death because of overpopulation [2], while Galtung [3] concluded that "experts . . . were remarkably wrong" in their predictions) and the difficulty in answering the question "how well did we do" after adopting a risk-based approach to environmental decision making.

To manage natural resources and assets is to manage risk. For example, we build dams to guarantee water supply, but do so at the risk of decreasing biodiversity, altering in-stream species composition, and affecting riparian vegetation further downstream. The omnipotent threat of climate change and climate variability only serves to increase uncertainties and exacerbate consequences. Thus, in countries such as Australia where climate change has resulted in prolonged droughts, the level of uncertainty in water resource management is extraordinarily high. The accurate quantification of natural resources is central to a risk-based approach to NRM, as is the provision of reliable estimates of variability and uncertainty in these estimates. This, it is acknowledged, is easier said than done because reliable quantification, estimation, and prediction for natural resource management is rendered particularly difficult by virtue of two important characteristics of natural systems: complexity and uncertainty. Complexity arises from highly nonlinear relationships, feedback loops, hysteresis, multiple causes and effects, and timescales ranging from fractions of a second to millions of years. On the other hand, uncertainty in natural systems is often the result of one or more of the following factors: an event whose consequences are predictable (e.g., flood, drought, earthquake), but whose timing and magnitude are not; a discontinuity in an otherwise smooth trend (e.g., rapid change in pH when the buffering capacity of a water body is exceeded); or, as we have already noted, unanticipated consequences of deliberate actions.

Traditional compliance-based approaches to pollution control focus on setting environmental standards whereby "safe" concentrations, loads, or exposure levels were identified and used as a not to be exceeded, regulatory limit. The approach focused on limiting public exposure to specific pollutants and did very little to identify pollution prevention measures that prohibit whole families of dangerous pollutants from being produced in the first place [4]. As noted by Fox [5], this resulted in data rich–information poor environment protection agencies that were ill equipped to make more comprehensive and holistic assessments of the environment. During the 1980s, risk-based approaches to NRM became increasingly popular, although as noted elsewhere in this encyclopedia (*see* **Ecological Risk Assessment**), these approaches were hampered by a lack of agreement as to what actually constituted a risk assessment, imprecise language, and inconsistent modes of analysis and application of risk methodologies.

Setting Environmental Standards for NRM

NRM encompasses environment protection, but has a broader scope. It is about balancing competing risks and demands, while ensuring the long-term sustainability of the biosphere or some part of it. The duality between *management* and *protection* has resulted in the establishment of environmental standards. The "fixed lines in the sand" that characterized the command-and-control approach to environmental regulation in some areas of NRM have given way to more flexible "standards", "guidelines", and "trigger values". This has been necessary because high levels of complexity, uncertainty, and background variation mean that transgressions of fixed lines will occur even in the absence of anthropogenic influences. For example, storm events often result in exceedingly high concentrations and loads of sediments and nutrients in rivers and streams; upwelling in oceans may be responsible for abnormally high chlorophyll levels at the surface; while complex population dynamics may result in uncharacteristic abundances of some (nuisance) species that are unrelated to human impact. The important feature of a standard, guideline, or trigger value is that it is not so much the "violation" of the numerical target that is important, but rather the *frequency* with which such violations occur. This notion immediately moves us away from prosaic "in compliance–out of compliance" assessments and more into the realm of *risk*. As noted by Barnett and O'Hagan [6], management standards need to be set in the context of an understanding of the processes involved and not the result of a somewhat arbitrary scaling of a result adapted from elsewhere. For example, prior to the release of revised water quality guidelines [7], many threshold values for pollutants and toxicants in marine and freshwaters were established using the "assessment factor" technique. Using this procedure, an endpoint (i.e., some outcome of a toxicity experiment) concentration for an organism or animal was scaled by a "factor" – typically orders of magnitude (10, 100, 1000 etc.) – so as to provide a margin of safety for humans. Notwithstanding the arbitrariness associated with the choice of the numerical factor value, no consideration was given to how relevant, meaningful, or achievable the resulting concentration was (*see* **Cumulative Risk Assessment for Environmental Hazards**). Nor did it provide any quantification of the level of protection afforded to humans and other species. In recognition of these deficiencies, the Australian guidelines adapted the risk-based approach of Aldenberg and Slob [8]. The idea was to use a theoretical distribution fitted to a sample of no observable effect concentrations (*NOEC s*). This is the smallest concentration at which an "effect" (in terms of a designated endpoint) is observed from which a small percentile (typically 5%) was estimated. The resulting figure is referred to as a *trigger value* since an exceedance does not result in punitive action but rather it triggers a next-level investigation to explain why such a result was observed. A distinguishing feature of the trigger value is its attempt to tie the concentration to an effect in the population. The underlying assumption that a trigger value obtained as the pth percentile from the *NOEC* distribution will be protective of $p\%$ of all species in the environment is, nevertheless, contentious [9].

NRM, the Precautionary Principle, Neyman–Pearson Hypothesis Testing and Statistical Power

Countries around the world have, to varying degrees, embraced the *Precautionary Principle* (PP) as a guiding philosophy for risk-based NRM. A number of variants of the PP exist; however, the basic tenet is that it seeks to avert or limit the risk of serious or irreversible harm to humans or the environment in the absence of full scientific certainty about that harm [10]. The critical issue is not whether we should be precautionary, but how precautionary we need to be on a case-by-case basis [11]. Poor risk management arises not only from insufficient levels of precaution, but equally from the pursuit of excessively high and unwarranted levels of precaution [11]. As we have seen in earlier sections of this article, uncertainty is a hallmark of NRM. The PP is one approach to dealing with uncertainty. A number of others exist such as prudent reduction, principle of prevention, best available techniques not entailing excessive cost (BATNEEC), best practicable environmental option (BPEO), and as low as reasonably achievable (ALARA). A distinguishing (and contentious) feature of the PP is that it shifts the onus of proof. Under the PP, proponents of a proposed activity (e.g., construction of a dam, erection of a mobile phone tower, deepening of a shipping channel, logging of a forest, construction of a housing estate) may be required to demonstrate that the activity has no serious or unacceptable environmental or human-health implications. Historically, the burden of proof has required those *opposing* the proposed activity to demonstrate that the activity is harmful. It is at this juncture, that risk assessments are usually produced in support of diametrically opposed conclusions. Statistical models can assist, although the use of different data and different modes of analysis are just two reasons behind the confusion and controversy that often accompanies a formal quantitative risk assessment (QRA). Conventional statistical hypothesis testing (or *null hypothesis testing* (*NHT*), as it is sometimes referred to), commences with a pair of hypotheses. The *null hypothesis* ("null" because it is meant to assume nothing or status quo conditions) is initially assumed to be true; the *alternative hypothesis* is generally the compliment or negation of the null hypothesis and will only be adopted if the evidence (in the form of data) provides extremely low support for the null hypothesis. This level of support is embodied in the ubiquitous (and widely misunderstood and abused) *p value*. The declaration of a "statistically significant result" occurs when a statistical test procedure returns a "small" *p value*. In the context of NRM, many of these features of hypothesis testing are troublesome. For a start, how small is small when it comes to *p values* and who decides? why is the minimization of a Type I error (the probability that the test incorrectly rejects a true null hypothesis) seen to be overridingly more important than the minimization of a Type II error (the probability that a false null hypothesis is accepted)? is it sensible to adopt the convention of couching a null hypothesis in terms of "no effect" when applied to NRM? and finally, is the binary view of the world that the hypothesis testing framework imposes on us the best way to assess environmental condition? Notwithstanding these issues, the PP imposes a role reversal on the null and alternative hypotheses. A precautionary approach to hypothesis testing would commence with an hypothesis that asserts that the proposed action has deleterious consequences. The alternative hypothesis then states that the consequences are not deleterious. As with the PP, this hypothesis testing schism has no clear-cut solution or recommendations although Fox [12] provided details of a hybrid approach. Equally problematic is the issue of "ecological significance" – that is, quantifying the magnitude of a change in condition that would be ecologically important. Environmental scientists and natural resource managers often struggle with the specification of an ecologically important effect size, but this is mandatory if, as is increasingly being demanded by natural resource management agencies, the issue of *statistical power* is to be investigated.

Statistical power and sample size analyses are useful adjuncts in the *planning* stage of any investigation or study. An *a priori* power analysis requires the investigator to nominate an ecologically significant effect size, a measure of intrinsic variation in the parameter under study (usually a mean response), a sample size and a level of significance (the Type I error rate). Armed with this information, it is a fairly straightforward task to compute the probability that the hypothesis-test procedure will correctly reject a false null hypothesis. This probability is referred to as the *power* of the statistical test. Obviously, a test with high power is preferred over a low-powered test. Unfortunately, further confusion exists about how to calculate and interpret the results of a power analysis. This is hardly surprising, given the lack of consensus in the literature and the publication of flawed advice [13, 14]. In fact, Hoenig and Heisey [15] identified 19 independent articles published between 1983 and 1997 advocating the use of *postexperiment* power analysis. Postexperiment power analysis often involves the computation of "observed power" – a flawed quantity which will invariably "explain away" a nonsignificant statistical result as an outcome of a low-powered statistical design.

Modes of Analysis: Frequentist or Bayesian

Until recently, quantitative risk analyses were underpinned by "conventional" modes of statistical analysis. Frequentist statistical inference makes up the bulk of all statistical methodology and undergraduate statistics courses devote considerable time to it. Neyman–Pearson hypothesis testing and regression techniques are the mainstays of environmental assessments that support natural resource management decisions. There is nothing intrinsically wrong with these methods. Provided the attendant assumptions are satisfied, conventional *t-tests* and analysis of variance (ANOVA) techniques are optimal (uniformly most powerful) – in other words, one can essentially do no better with the available resources. Unfortunately, although diagnostic analyses are available to help assess the adequacy of the statistical method employed, these are oftentimes overlooked or ignored. This is seen as a major shortcoming of current NRM risk analyses. The inappropriate use of statistical models can result in fatally flawed natural resource management decisions.

Frustrated with actual and perceived limitations of the frequentist dogma, many environmental scientists are turning to information theory [16] and *Bayesian statistics* [17] (*see* **Bayesian Statistics in Quantitative Risk Assessment**) as alternative paradigms that are more aligned with the goals of risk-based NRM. Bayesian methods are seen as attractive if for no other reason than an explicit recognition of the legitimacy of "subjective" probability in the form of a *prior* probability distribution. In the context of NRM, a prior probability distribution might, in fact, represent the diversity of (personal) belief about some proposition that is held by a range of stakeholders. Although this does not necessarily mean that a Bayesian approach is necessarily superior to other competing methodologies, it does have a certain appeal, inasmuch as it provides a transparent means of elicitation and incorporation of personal belief and/or expert opinion. To this extent, Bayesian methods are useful and are being increasingly used as part of a risk-based approach to NRM decision making.

As noted by Schipper and Meelis [18], data used to underpin decisions about environmental condition are invariably collected successively in time and so it makes sense to analyze those data sequentially. Apart from their own work, relatively little seems to have been done along these lines.

Future Directions

An examination of the literature identifies follow-up monitoring as a significant gap in risk-based approaches to NRM. Thus, while we argue over the merits of the precautionary principle and the commensurate shift toward prudent foresight, we spend comparatively little time on asking "how well did we do" [19, 20]. As noted by Suter [21], "a common criticism of risk-based environmental management is that we do not know whether it is effective". Further research is required to develop companion tools and techniques that allow risk assessors to gauge the effectiveness of individual risk-based NRM programs.

As noted in this article, Bayesian methods for risk-based NRM are becoming increasingly popular. Protocols for the elicitation of "expert opinion" require further development and refinement as do methods for ranking those opinions. This may require closer collaboration between psychologists and statisticians to develop methods for reliably extracting opinions to improve the quality of the risk analysis and increase stakeholder trust in the process.

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