needs to be quantified. That is, the distribution of likelihood in the continuum of which the best estimate is the centre needs to be ascertained. This distribution can often be represented by the error estimate for the central value. Once estimates are available of the magnitude of the ecosystem changes which would result from the proposed disturbance, together with their uncertainty, their importance can be assessed in the light of whatever value system is adopted, and their values and probability can be balance against the values and probability claimed for the other effects of disturbance — those for the sake of which it is proposed. The value systems used will reflect considerations outside the scientific realm — economics, aesthetics, ethics, sociology — as well as questions like irreversibility which are strictly scientific. The advantages claimed for the disturbance can then be weighed against the adverse effects expected, and an informed decision can be made. Indeed, if the disturbance itself is an continuing process, continuous monitoring of the effects can enable the original forecasts to be updated, and any limits placed on the disturbance can be relaxed or tightened as forecasts are improved.

REFERENCES

Abbot, I. and Van Heurck, P., 1985. Response of bird populations in jarrah and karri forest in Western Australia following removal of half the canopy of the jarrah forest. *Aust. For.* **48:** 227–34.

Calver, M. J., Bradley, J. S. and Wright, I. W., 1999. Towards scientific contributions in applying the precautionary principle: an example from Western Australia. *Pac. Cons. Biol.* **5:** 63–72.

David W. Goodall
Centre for Ecosystem Management
Edith Cowan University,
Joondalup WA 6027 Australia

RESPONSE

In a recent paper we suggested means for quantifying the precautionary principle and aiding resolution of disagreement in cases calling for its application. In his commentary on this paper, Goodall (1999) makes four important points: (i) that it is reasonable to ask proponents of a disturbance to demonstrate that any possible consequence will lie within specified and acceptable limits, (ii) that a null hypothesis is worth disproving only if it is credible, (iii) that one should beware of asking the wrong question when framing environmental studies, and (iv) that scientific proof as generally understood does not apply to the precautionary principle. We are in substantial agreement with all these arguments. However, as explained below, we differ in our assessment of their implications.

SPECIFIED AND ACCEPTABLE LIMITS TO BE MET BY PROPONENTS OF A DISTURBANCE

Many commentators on the precautionary principle support a shifting of the balance of proof, requiring proponents of a disturbance to demonstrate that the consequences will lie within specified limits (e.g., Peterman 1990a,b; Peterman and M'Gonigle 1992; Underwood 1997). We endorsed this position in our original paper, using logging in the jarrah forest of Western Australia and its putative impacts on jarrah forest mammals as our primary example. We noted the various measures in place to ameliorate possible impacts and argued that the value of these measures could not be assessed without measuring the response variable of changes in the population trends of selected species of jarrah forest mammals. We proposed three indicator mammal species on the basis of features of their biology and an assessment of demonstrated deleterious impacts of logging on mammal populations elsewhere in Australia and in the northern hemisphere. To address the question of logging impacts on the selected species, we suggested monitoring their population trends with a view to detecting declines of 40% over two years in the Common Brushtail Possum *Trichosurus vulpecula* and 20% over two years for the Western Ringtail Possum *Pseudocheirus occidentalis*. In deciding if these rates of decline have been exceeded, one may err by concluding that a decline of the specified magnitude has taken place when it has not (Type I error), or by concluding that such a decline has not taken place when it has (Type II error). We acknowledged these possibilities and assigned probabilities of 0.20 to each as standards that should be met in assessing if a decline of the chosen magnitude occurred. As stressed in Calver *et al.* (1999), these figures were proposed for illustration only, because choice of final values in these matters should be reached by discussions involving all stakeholders.

We believe that this approach is consistent with asking proponents of a disturbance to place possible consequences of the disturbance within specified limits. Furthermore, if the consequences of the errors can be costed, with, perhaps, a special monetary value assigned for non-economic costs such as aesthetic values, economic consequences of the error rates proposed can be assessed. We find this philosophy very similar to that presented in Goodall's final paragraph.

SCIENTIFICALLY CREDIBLE NULL HYPOTHESES

Few would argue with the contention that every action has consequences and that therefore every disturbance will have an environmental impact. The critical question, as Goodall (1999) highlights, is to assess the size and direction of the impact. Thus the "no impact" hypothesis is a rhetorical device suitable for generalization, but in a given situation it is replaced by a more specific null hypothesis with scientific credibility. Taking an example from Calver *et al.* (1999), the null hypothesis for the case of the Western Ringtail Possum, based on the figures given, would be: "Over two years the population of the Western Ringtail Possum has not declined by more than 20%". We contend that this null hypothesis is plausible, since it is scientifically valid to postulate that any mortality caused by logging is not at a level that would cause population declines of this magnitude. Moreover, the power analysis proposed by Calver *et al.* (1999) would expose any test of this hypothesis that had only a low chance of rejecting it if it was in fact false, or was so insensitive it could detect only a gross violation in excess of reasonable concern. The great strength of power analysis is that it focuses explicitly on the magnitude of the effect that one wishes to detect and quantifies the potential errors involved in deciding whether or not the effect has been found.

Excellent examples of the development of scientifically credible null hypotheses and their use in achieving conservation goals are given in the case of the Spotted Owl *Strix occidentalis* from the United States (see the detailed review of Noon and McKelvey 1996). The authors highlighted the extreme difficulty of conducting meaningful experimental designs in the ecosystems involved to resolve the question of putative forestry impacts on the long-term viability of owl populations. However, they also noted that management plans have properties that can be stated as falsifiable hypotheses and tested with empirical data. Three important hypotheses tested during the Spotted Owl work were:

1. The finite rate of population change (λ) of owls is ≥ 1.0 (i.e., the population is not decreasing).
2. Spotted Owls do not differentiate among habitats on the basis of forest age or structure.
3. No decline has occurred in the areal extent of habitat type selected by Spotted Owls for foraging, roosting or nesting.

Assessing λ at long-term study sites tested the first hypothesis. It was significantly less than 1.0 at two sites for the Northern Spotted Owl, but not for two sites involving the Californian Spotted Owl. However, the tests on the Californian sub-species had low statistical power and the point estimates were less than one, so a conclusion that the populations were stable or growing was not justified. Observational work, based either on field studies or maps, tested the second and third hypotheses. These examples show how a power analysis approach to testing scientifically credible hypotheses is making significant contributions to conservation goals, although not all hypotheses are amenable to such an analysis. If there is wide consultation among stakeholders in selecting hypotheses, choosing the magnitude of effects to be detected and agreeing on the acceptable probabilities for different types of error, the problems identified by Goodall (1999) can be avoided and convincing, agreed standards emplaced for conservation goals. Our point is that power analysis links many of these aims.

ASKING THE WRONG QUESTION

Goodall (1999) is right in pointing out that no amount of statistical finesse can compensate for poor choice of a research hypothesis or question. If one makes a poor choice in pure research, the consequence is likely to be unpublishable findings and possibly a damaged career, but almost certainly not social or environmental dislocation. A wrong choice in a matter of environmental interest could conceivably have far-reaching consequences, especially when decisions are based on data not scrutinized by peer-review.

However, it is not always easy to select the best research question. Consequently, we argued for measuring response variables to environmental disturbance rather than implementing amelioration without any quantitative assessment of its success, and proposed that measurements of response variables should consider the magnitude of change one hoped to detect and the probabilities of the statistical errors associated with the measurements. Our argument for involving stakeholders in setting effect sizes and probabilities of error could be extended into seeking their assistance in formulating the research hypothesis in the first place. This could aid in identifying relevant questions. We make quantitative suggestions for framing questions (standards) for investigation on Pp. 67–68 of Calver *et al.* (1999).

SCIENTIFIC PROOF AS GENERALLY UNDERSTOOD DOES NOT APPLY TO THE PRECAUTIONARY PRINCIPLE

While Calver *et al.* (1999) was in press, Santillo *et al.* (1998) addressed this point. While they whole-heartedly endorsed the need for more scientific research into environmental issues, they stressed that the choice between inaction and precaution when confronted by scientific uncertainty over a planned disturbance was essentially a political decision. They saw the precautionary principle, without any quantitative scientific definition, as the appropriate guide to such policy decisions and expressed concern that scientific definitions of the precautionary principle were a power play to re-establish science as a force in environmental politics.

There are impressive successes of the precautionary principle when used as part of the political process. For example, Santillo *et al.* (1998) document the general resolve of the relevant governments to end emissions into the North Sea within a generation. Many aspects of this position can be seen in the statements concerning the precautionary principle cited in Goodall (1999). A second case concerned deciding whether mining for heavy minerals, followed by rehabilitation, should be permitted on the eastern shores of St Lucia, South Africa. The results of a detailed environmental impact assessment were submitted to a panel of eminent lay people, who considered them and then recommended to the South African government that mining not proceed, invoking the precautionary principle in justification of their decision (Kruger *et al.* 1997). Sadly, the reverse is also true and there are cases in which the principle was advocated but not upheld in practice (Francis 1996).

It is significant that the successes in applying the precautionary principle as a political process took place in an atmosphere of accord regarding goals. In other circumstances, such as the cases discussed by Francis (1996) and Calver *et al.* (1999), applications of the precautionary principle have been contested politically or in the courts and judgement has been complicated by the lack of clear, quantitative definitions. We pointed out that this was a driving force in the development of both legal and scientific definitions of the principle (e.g., O'Riordan and Jordan 1995) and that, in this context, several authors had linked the precautionary principle to statistical power analysis. Recently, Rogers *et al.* (1997) and Varis and Kuikka (1997) have proposed alternative quantitative approaches to the precautionary principle, based on risk analysis paradigms and Bayesian statistics respectively. Furthermore, Buhl-Mortensen and Welin (1998) have reaffirmed the role of statistical power analysis in evaluating research results in the light of the precautionary principle.

We believe that quantitative definitions of the precautionary principle are necessary to phrase clear legislation less vulnerable to legal challenge. Perhaps the true role of quantitative approaches will come in monitoring activities permitted under the precautionary principle, subject to the condition that they will be monitored and halted before any serious or irreversible damage occurs (Deville and Harding 1997). Such a position gives primacy to the political process in initial applications of the precautionary principle and uses science and statistics effectively in placing unambiguous quantitative guidelines on the standards expected of any activity permitted.

CONCLUDING REMARKS

We believe that we are in substantial agreement with the major points raised in Goodall (1999), although we differ in believing that the implication of these points is that quantitative environmental standards are necessary to resolve disagreements in wildlife management issues. In our opinion, quantitative definitions of the precautionary principle will help reduce legal uncertainty regarding contentious applications of the principle and give an unambiguous and valuable position to science in the political process. The need to involve all stakeholders in developing quantitative aspects of the precautionary principle to apply to a given situation is a great strength of this approach. The quantitative definitions should also lead to clearer exposition of research hypotheses and to explicit statements of the limits of change within which proponents of disturbance must operate. Goodall (1999) is a timely reminder of the importance of these issues.

REFERENCES

Buhl-Mortensen, L. and Welin, S., 1998. The ethics of doing policy relevant science: the precautionary principle and the significance of non-significant results. *Science Eng. Ethics* **4**: 401–12.

Calver, M. C., Bradley, J. S. and Wright, I. W., 1999. Towards scientific contributions in applying the precautionary principle: an example from Western Australia. *Pac. Cons. Biol.* **5**: 63–72.

Deville, A. and Harding, R., 1997. Applying the precautionary principle. The Federation Press, Sydney.

Francis, J. M., 1996. Nature conservation and the precautionary principle. *Environ. Values* **5**: 257–64.

Goodall, D., 1999. Environmental management: the precautionary principle and null hypotheses. *Pac. Cons. Biol.* **5**: 78–80.

Kruger, F. J., van Wilgen, B. W., Weaver, A. v. B. and Greyling, T., 1997. Sustainable development and the environment: lessons from the St Lucia environmental impact assessment. *S. Afr. J. Sci.* **93**: 23–33.

Noon, B. R. and McKelvey, K. S., 1996. Management of the Spotted Owl — A case history in conservation biology. *Ann. Rev. Ecol. Syst.* **27**: 135–62.

O'Riordan, T. and Jordan, A., 1995. The precautionary principle in contemporary environmental politics. *Environ. Values* **4**: 191–212.

Peterman, R. M., 1990a. Statistical power analysis can improve fisheries research and management. *Can. J. Fish. Aqu. Sci.* **47**: 2–15.

Peterman, R. M., 1990b. The importance of reporting statistical power: the forest decline and acidic deposition example. *Ecology* **71**: 2024–027.

Peterman, R. M. and M'Gonigle, M., 1992. Statistical power analysis and the precautionary principle. *Mar. Poll. Bull.* **24**: 231–34.

Rogers, M. F., Sinden, J. A. and De Lacy, T., 1997. The precautionary principle for environmental management: a defensive-expenditure application. *J. Env. Manage.* **51**: 343–60.

Santillo, D., Stringer, R. L., Johnson, P. A. and Tickner, J., 1998. The precautionary principle: protecting against failures of scientific method and risk assessment. *Mar. Poll. Bull.* **36**: 939–50.

Underwood, A. J., 1997. Environmental decision-making and the precautionary principle: what does the principle mean in environmental sampling practice? *Landsc. Urban Plan.* **37**: 137–46.

Varis, O. and Kuikka, S., 1997. Joint use of multiple environmental assessment models by a Bayesian meta-model — the Baltic salmon case. *Ecol. Mod.* **102**: 341–51.

M. C. Calver
School of Biological Sciences and Biotechnology,
Murdoch University,
Murdoch WA 6150

J. S. Bradley
School of Biological Sciences and Biotechnology,
Murdoch University,
Murdoch WA 6150

I. W. Wright
School of Mathematics and Statistics,
Curtin University,
Bentley WA 6102