Ecological risk assessment based on extinction distributions

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Abstract

Many researchers now agree that an ecological risk assessment should be a probabilistic forecast of effects at the level of the population. The emerging consensus has two essential themes: (i) individual-level effects are less important for ecological management, and (ii) deterministic models cannot adequately portray the environmental stochasticity that is ubiquitous in nature. It is important to resist the temptation to reduce a probabilistic analysis to a scalar summary based on the mean. An assessment of the full distribution of risks will be the most comprehensive and flexible endpoint. There are two ways to visualize a distributional risk assessment of a chemical's impact on a population. The first is to display, side by side, the two risk distributions arising from separate simulations with and without the impact but alike in every other respect. Alternatively, one can display the risk of differences between population trajectories with and without impact but alike in every other respect. Like all scientific forecasts, an ecological risk assessment requires appropriate uncertainty propagation. This can be accomplished by using a mixture of interval analysis and Monte Carlo simulation techniques.

1. Introduction

Perhaps the most salient feature of the dynamics of ecological systems is their variability. The abundance of natural populations and the behavior of ecosystems fluctuate from place to place across space. If these populations and systems are monitored through time, there is always considerable variation observed in any given place as a result of the vagaries of climate and local happenstance. These fluctuations are partially due to interactions we understand, but a substantial portion is due to various factors such as weather that we cannot foresee. Consequently, no matter how good our ecological models become, they will not be able to forecast the weather with reliable precision. The resulting variability of ecological patterns and processes, as well as our residual uncertainty about them, prevent us from making precise, deterministic estimates of the effects of environmental impacts. Because of this, comprehensive impact assessment requires a *language of risk* which recognizes natural variability, yet permits quantitative statements of what can be predicted.

Not all ecologists sense that a risk-based approach is required. Many have suggested using changes in the asymptotic growth rate as a measure of the impact (e.g., Pesch et al. 1987; Caswell 1995; Munns et al. 1997; cf. Walthall and Stark 1997). Ferson et al. (1996) criticized this measure for its insensitivity to initial conditions and its inability to model environmental stochasticity, density dependence and other critical aspects of demography. Since the seminal paper by Ginzburg et al. (1982), many authors have come to agree that an ecological risk assessment should be a probabilistic forecast of population-level effects. There were two themes present in that paper that have become consensus views. The first is that, apart from humans and endangered species which enjoy special protections, effective ecological management is based on assessments above the level of the individual organism. The second is that a probabilistic analysis that incorporates variability and recognizes uncertainty is crucial for an ecological engineering that can provide practical answers to the questions about the magnitude and severity of impacts of chemicals. The emergence of this risk language has been an important development in applied ecology over the last two decades because it allows impacts to be placed in the context of natural variability.

2. Distribution of cumulative risk

In this language of risk, we characterize not the future abundance of a population, but a distribution from which the future abundance is expected to be drawn (Fig. 1). The probability that the population reaches a certain size or lower within some time horizon is called the risk of (quasi-)extinction (Ginzburg et al. 1982). The amount of times it takes a population to reach some threshold size is characterized by a distribution called the time to (quasi-) extinction. Our risk analysis admits that we do not know future vital rates that govern population growth, but it presumes that we can statistically characterize the *distributions* of these rates. We estimate these distributions from observations of the past values of the relevant vital rates. This approach usually assumes that the distributions are stationary, but this is much more reasonable than the assumptions of a deterministic analysis.

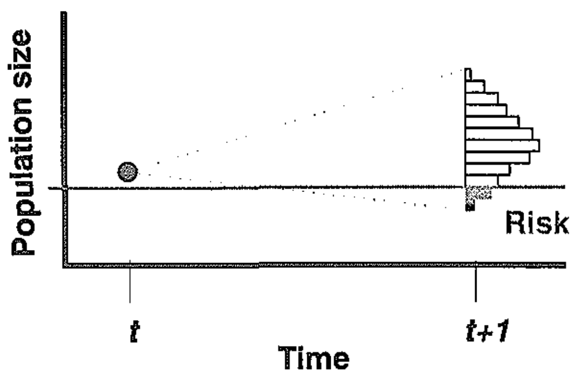

Fig. 1.

Population abundance, time and risk (i.e., probability) are the three underlying dimensions in a population-level risk assessment. In summarizing an assessment, it is common to focus on the population abundance at some time, or the time to reach some abundance. In either case, however, there is an entire distribution to be considered. It is important to resist the temptation to reduce a probabilistic analysis to a scalar summary based on the mean. It is generally not a good idea to summarize the distribution of abundance at some point in time by a simple mean abundance. Likewise, it is not a good idea to summarize the distribution of times to cross some threshold abundance with the mean time (cf. Iwasa 1998). Means are overly sensitive to outliers. Because the abundance and time distributions are usually highly skewed, the mean is a poor summary of the distribution. The median might be a better scalar estimate, but we prefer to display the entire distribution if possible. An assessment of the full distribution of risks will be the most comprehensive and flexible summary of an assessment. There are two ways to visualize the risk assessment

Fig. 2 depicts such a distribution from a hypothetical assessment. The ordinate is the chance that the population goes extinct, or more generally, falls below some threshold abundance (goes 'quasi-extinct') by the time given on the abscissa. This risk is expressed as a curve over all possible time intervals. The curve is monotonically increasing and can be identified as the distribution of the time to quasi-extinction. The scale is not given for this hypothetical result, but it should be emphasized that these kinds of distributions are often highly skewed. The threshold abundance is specified in advance, and there is such a curve for every possible threshold abundance. Of course, there is no reason to think that true extinction (for which the threshold is zero) is the most relevant threshold abundance for all species in all situations. Popular anger would surely be great if a commercially important species declined by, say, 50%. For such species, it may make sense to use a different threshold. In fact, risk assessments often display risk as a function of the threshold abundance (with a fixed time horizon) in addition to results like Fig. 2.

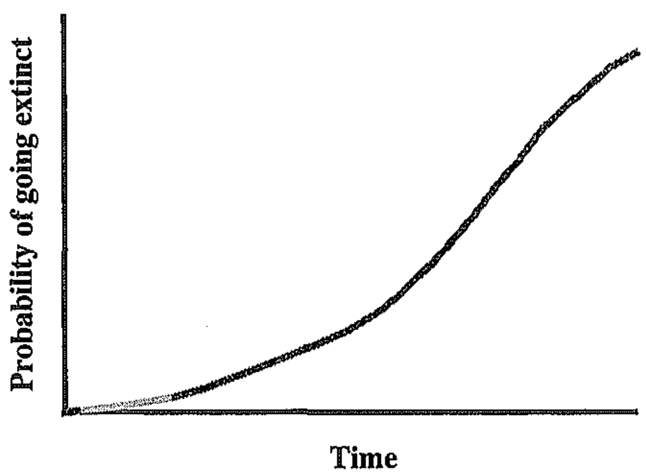

Fig. 2.

In practice, the curve in Fig. 2 can be estimated with a variety of different kinds of analyses, ranging from screening assessments with minimal data requirements (Ginzburg 1982; Iwasa 1998; Tanaka 1998; Matsuda 1998) to comprehensive assessments based on extensive empirical information. Examples of the latter include assessments with detailed internal structure of age or stage classes within a population (e.g., Lande and Orzack 1988; Ferson et al. 1989; Bridges et al. 1996; Moore et al. 1997), spatial structure of metapopulations (e.g., Akçakaya and Atwood 1997), and trophic structure including bioaccumulation (e.g., Spencer et al. 1997; 1999). A fully probabilistic assessment at the population level can be conducted with any level of detail and complexity considered appropriate by the assessor.

3. Assessing the consequences of impacts as delta risk

Ecological management decisions should be based on the assessment of cumulative attributable risk. For environmental regulation to be fair, it should focus on the change in risk due to a particular impact. The risks suffered by a natural population can be substantial, whether or not it is impacted by anthropogenic activity. Only the potential change in risk, not the risk itself, should be attributed to the impact. On the other hand, for environmental protection to be effective, regulation must be expressed in terms of cumulative risks suffered by a population from impacts and from all the various agents involved, cumulated through time. An impact assessment typically requires an analyst to conduct parallel risk analyses, one modeling the background conditions, and the other modeling the impact conditions. The background case should not represent pristine conditions. It should be a reference against which make a comparison. The vital rates used as parameters in the in the background case are generally derived from empirical information, but may also be established by regulatory fiat. The vital rates used in the impact case are the same as those of the background case except where evidence or suspicion dictates to the contrary. For instance, in assessing chemicals known to disrupt reproductive function, fecundity rates or maturation time might be reduced. Sometimes the estimation of the vital rates for the impact case involve comprehensive toxicity studies and elaborate exposure models, but sometimes they are simply worst-case estimates. For a new chemical introduction, the vital rates to be used for the impact case can be estimated from knowledge of the effects of structurally related chemicals. At Applied Biomathematics, we have used population-level risk assessments to assess the effects of chemical contamination, harvest, thermal effects, entrainment and impingement, habitat loss, and disruption of migration and dispersal patterns. Moreover, all manner of impacts can be integrated within a single analysis so that interacting or cumulative

Fig. 3 depicts a hypothetical assessment that estimates the cumulative attributable risk to a population. The lower, dotted line represents the background risk of going extinct (or reaching some critical threshold) before a given time. This risk is expressed as a curve over all possible time intervals. The natural variability experienced by the population determines the position and character of this curve. Increasing the level of environmental stochasticity causes the curve to be higher and further to the right. Its location represents the *background risk* that the population experiences even without the anthropogenic impact. All natural systems exhibit variability whether or not there are anthropogenic impacts. This background level of risk provides a scale against which risks under impacts should be compared.

The upper, solid curve in Fig. 3 represents the risk of extinction when there is an impact. The difference between the two curves is that part of the risk that can be attributed to the presence of the impact. The degree to which the solid curve is above or to the left of dotted curve is an assessment of the population-level effect of the impact. The difference between the two curves might be quantified by the maximal vertical distance between them, or perhaps by the area between the curves. However it is measured, it is the difference between the two curves that is the attributable risk. Only this attributable risk can be fairly blamed on the agent of the impact, and removing the impact completely can only relieve the attributable risk. This way of displaying the results of an assessment emphasizes the irremovability of background risks.

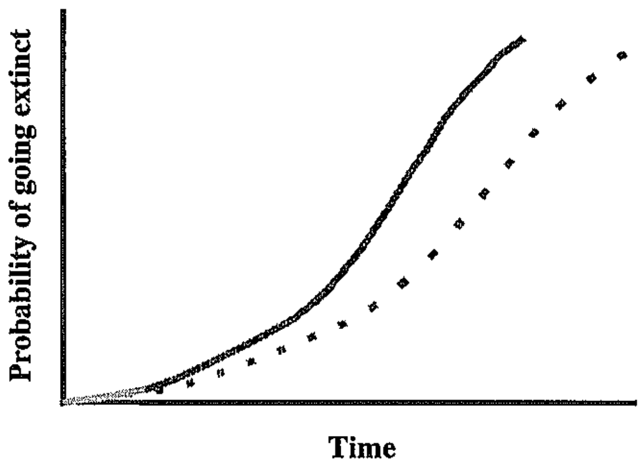

Fig. 3.

There is another way to assess the effect of an impact on the population that is somewhat more direct in that it asks how big a difference suffering an impact would make for a particular population. Fig. 4 shows such a result. The abscissa is the change in the time at which a population goes extinct or first crosses its threshold. The ordinate is again probability, and tells how likely it is that a decrease in the time of a given size will occur. Thus, Fig. 4 is the risk of a decrease in time to quasi-extinction attributable to the impact. It is again a probability distribution, displayed now as a complemented cumulative distribution function. It can be thought of as the risk of early extinction due to the impact. Any nonzero values are attributable to the impact, and positive values are adverse as they represent how much sooner a population could go extinct or decline to its threshold. More serious impacts are characterized by curves that are higher or further to the right.

This assessment can easily be implemented in a Monte Carlo simulation in which two copies of each population trajectory are maintained. The first population does not experience the impact, but is subject to the normal buffeting of environmental variability. The second population is exactly identical to the first in every way except that it experiences the impact and its vital rates are discounted accordingly. The pairing of dual populations in the Monte Carlo simulation is crucial so that the same random deviates are used for both the impacted and unimpacted populations. Otherwise, it is impossible to compute the difference because the essential correlation information will be lost. This means, for instance, that the information in Fig. 3 is insufficient to estimate Fig. 4. These two summaries communicate different aspects of the assessment. Fig. 3 shows the difference of risks, whereas Fig. 4 shows the risk of differences.

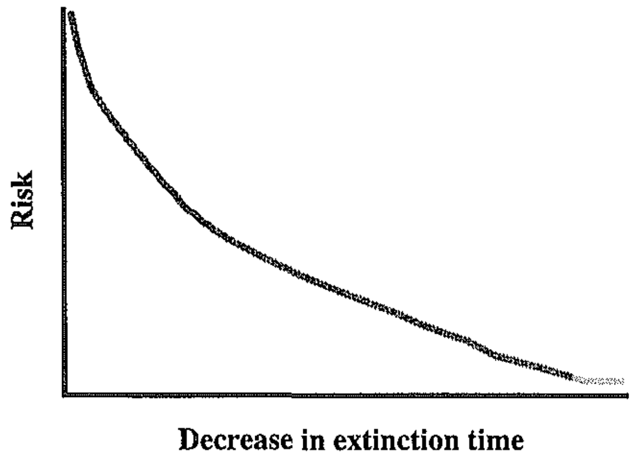

Fig. 4.

4. Uncertainty propagation is needed when data are scarce

One important advantage of summarizing the assessment in terms of the risk of early extinction is that it is easy to display the uncertainty about the estimate. Fig. 5 depicts intervals bounds around the distribution shown in Fig. 4. This depiction conveys the incertitude (i.e., partial lack of knowledge) about the result that arises from measurement error in the input parameters.

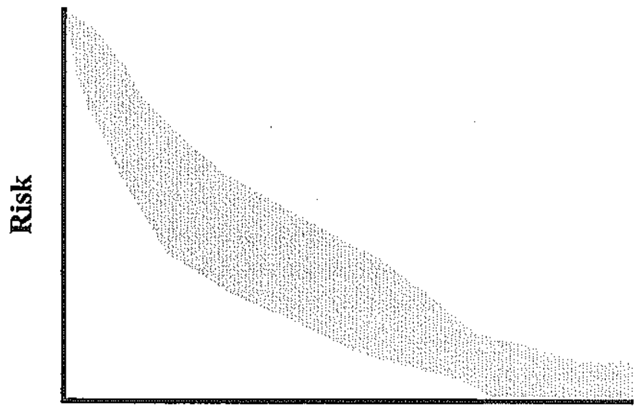

Fig. 5.

A properly constructed risk assessment distinguishes between incertitude and variability (Ferson and Ginzburg 1996). Of course, the conclusions possible in the face of great incertitude are weaker than they might have been if there were there no measurement error or gaps in scientific understanding. For instance, as measurement error becomes larger, the gray region in Fig. 5 would grow wider and we would have less surety about what the risks actually are. But making a useful decision does not require perfect precision. A reliable picture may emerge from an assessment even though empirical information is very limited. In this context, the artful use of conservative assumptions can be very important. For example, Ginzburg et al. (1990) explain how a conservative assumption can replace ignorance about the nature of density dependence in a species and allow a risk assessment to obtain reliable results that may turn out to be good enough for management or regulatory decisions. Assessments that employ probabilistic risk analysis to take account of the ubiquitous variability of ecological processes in nature, should also use uncertainty propagation techniques to be honest about our uncertainty arising from measurement error and incomplete scientific understanding.

5. Acknowledgments

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6. References

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