Answering the 'so what?' questions about environmental contaminants

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Abstract

Ecological risk assessment for environmental pollutants should be a probabilistic forecast of the effects of contaminants at the level of biological populations. Effects at the level of individuals, except for impacts on humans and endangered species, are often considered less important for environmental management. Although still in wide use, deterministic models cannot adequately portray the environmental stochasticity that is ubiquitous in nature. The probabilistic analysis should not be reduced to a simplistic summary based on the mean. A comprehensive assessment requires consideration of the full distribution of risks. 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 a probability distribution of the 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 bounding analysis and Monte Carlo simulation techniques.

Resumo

["Respondendo às perguntas 'e daí?' sobre contaminantes ambientais"] A avaliação de risco ecológico para poluentes ambientais deve ser uma previsão probabilística dos efeitos dos contaminantes no nível das populações biológicas. Os efeitos no nível dos indivíduos, com exceção dos impactos nos seres humanos e nas espécies ameaçadas, são frequentemente considerados menos importantes para o manejo ambiental. Embora ainda sejam amplamente utilizados, os modelos determinísticos não podem retratar adequadamente a estocticidade ambiental de natureza onipresente. A análise probabilística não deve ser reduzida a um resumo simplista com base na média. Uma avaliação abrangente requer consideração da distribuição completa dos riscos. Existem duas maneiras de visualizar uma avaliação de risco de distribuição do impacto de um produto químico em uma população. O primeiro é exibir, lado a lado, as duas distribuições de risco decorrentes de simulações separadas com e sem o impacto, mas igualmente em todos os outros aspectos. Alternativamente, pode-se exibir uma distribuição de probabilidade das diferenças entre trajetórias populacionais com e sem impacto, mas igualmente em todos os outros aspectos. Como todas as previsões científicas, uma avaliação ecológica de riscos requer propagação apropriada da incerteza. Isso pode ser feito usando uma mistura de análise de limite de intervalo e técnicas de simulação de Monte Carlo.

1. Introduction

Environmental contaminants such as leachates from mine tailings, agricultural fertilizers and pesticides, manufacturing by-products, and combustion residues adversely affect plants and animals in aquatic and terrestrial ecosystems. Effects on humans can be both direct and indirect through the ecological impacts on the many species upon which humans depend economically or ecologically. Ecological risk assessments are used to quantify the impacts and characterize the consequent risks to humans and other organisms from such contaminants.

The biological effects of chemical contaminants in the natural environment are usually characterized by toxicity assessments conducted at the level of individual organisms. In fact, generic toxicity assessments use exemplar species that are easy to culture in the laboratory such as lettuce seedlings, algae, nematodes, and daphnia water fleas, which themselves have limited ecological relevance for the impacted habitats that are actually of concern. Even after studying the toxicity and growth/reproductive effects of a contaminant, and even if current body burdens can be characterized in the receptor species of concern, analysts may still not be able to answer the most basic questions about the long-term consequences of contamination because of the biological and ecological complexity of organisms in ecosystems, including bioaccumulation and biomagnification, biodegradation, population compensation and depensation, and competitive and trophic interactions. Extrapolating the results of individual-level impacts observed in toxicology laboratories to effects at the ecosystem level may simply be beyond the current scientific capacity of ecology.

Ecological risk analysis based on toxicity assessments at the level of the individual organism or below often cannot answer basic ‘so what?’ questions. What does increased mortality in nematodes imply about the consequences for much more complex organisms? What does it mean, moreover, if some fish die because of a contaminant that otherwise would not, or their reproduction is reduced? Can a population mask or rebound from these effects? Can seemingly minor effects accumulate or cascade to create considerable damage to a population?

The US EPA, like many governments and institutions around the world, employs a multiple-tier assessment scheme (Dearfield et al. 2005; cf. Ashton et al. 2008) that uses conservative, generic values in a screening assessment in the first tier. It introduces site-specific values to the calculation in a baseline assessment in the second tier. Only in the highest third tier are fully probabilistic analyses used.

This paper argues that tenable answers to the ‘so what?’ questions require a probabilistic ecological risk analysis focusing on populations or short food chains. Such analyses form a practical compromise between relevance and tractability that can and should be employed at all assessment tiers so long as a proper accounting of uncertainty is made in both toxicological and ecological variables used in the assessment.

2. Variability in the natural world

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.

Fig. 1 depicts the possible futures of a hypothetical population’s abundance. Thirty different realizations are shown, any of which might be the future abundance of the population over a 25-year time window. All of these trajectories start at 100, which represents the current measured abundance, which might be in terms of number of individuals or perhaps a density per unit area. Many of the populations are decreasing over time. The declines may be due to the effect of an environmental contaminant, or it they may be due to the happenstance of weather conditions that buffet the population from year to year. Some of the trajectories are increasing, which can occur as a result of favorable environmental conditions over the years. This tangle of trajectories constitutes the prediction of the population’s future.

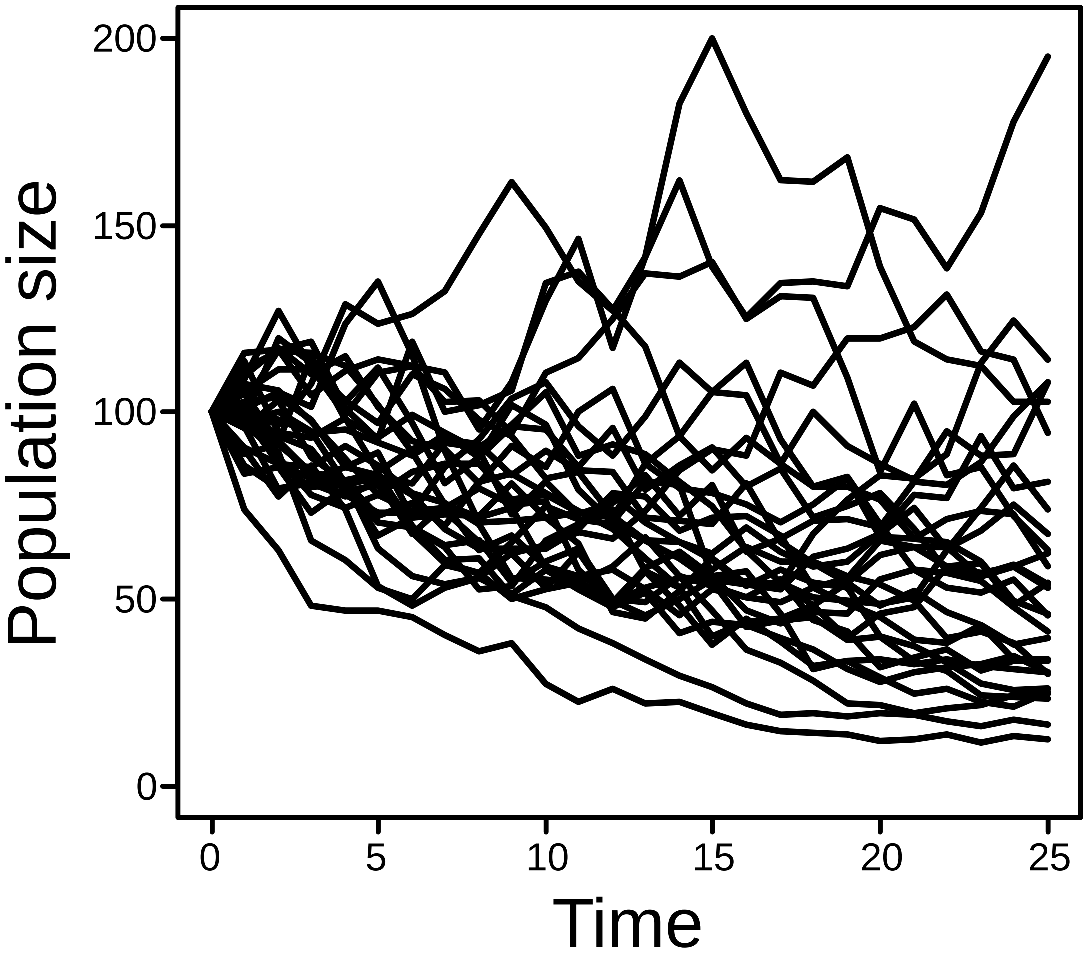

Fig. 1.

3. Distribution of cumulative risk

In a language of risk, we do not try to characterize the precise future abundance of a population, but rather only a distribution from which the future abundance is expected to be drawn. Fig. 2 depicts the distribution of possible population sizes predicted for the hypothetical population at the end of the 25-year time horizon. The lower tail of this distribution—highlighted in red—represents the chance that the population declines to an abundance of 60 or lower. The probability that the population reaches such a threshold abundance 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 such a 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 still much more reasonable than the assumptions of a deterministic analysis.

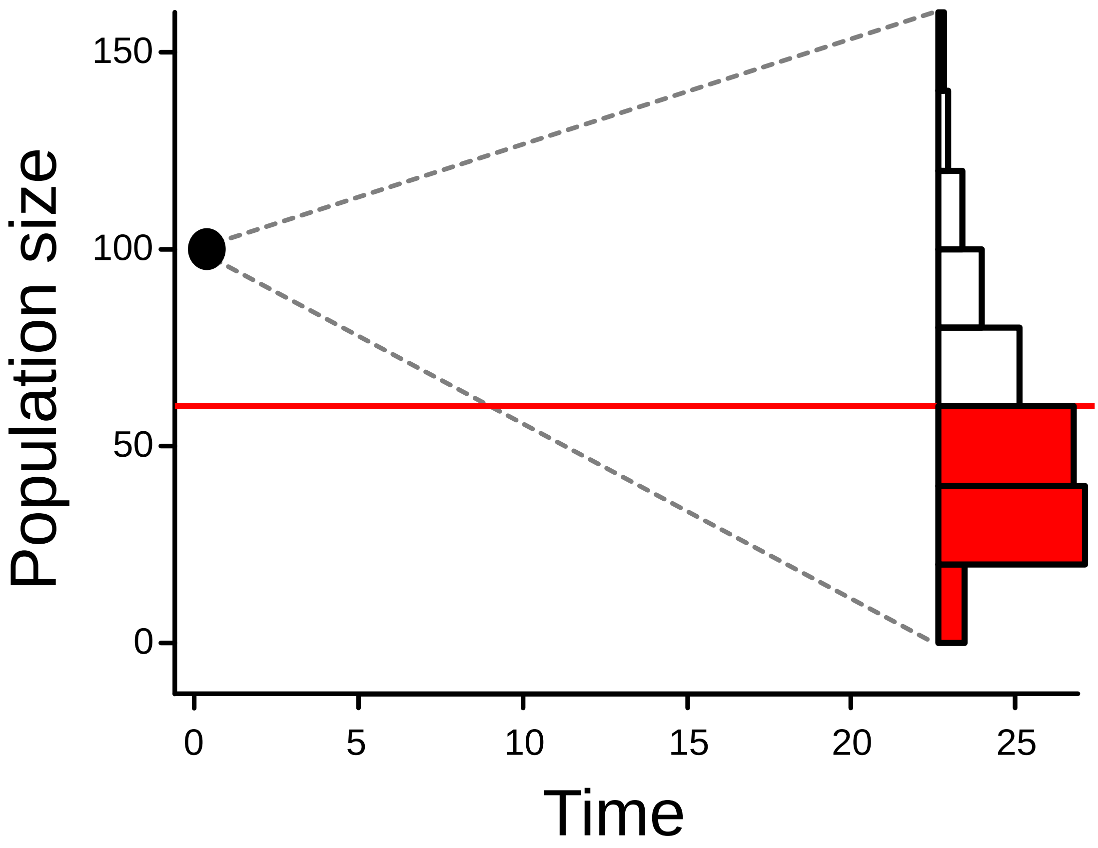

Fig. 2.

There are several ways to visualize the results of a population-level risk assessment. One way is to show the distribution of what statisticians call “first-passage times”, which are the times at which a population could go extinct or decline below some important threshold. The abscissa of its graph is time, and the ordinate is the chance that the population falls below the threshold abundance (goes ‘quasi-extinct’) by the time given on the abscissa. The threshold is set by the analyst to represent an outcome that would create concern for economic or ecological reasons. Fig. 3 depicts the distribution of possible times at which the population in our hypothetical assessment might decline to 40% of its initial abundance, that is, to a population size of 60. This graph corresponds to the hypothetical population characterized in the previous figures, with the steps arising from annual censusing in the 25-year time window.

This monotonically increasing curve is the distribution of the time to population decline to the threshold (quasi-extinction). The threshold is specified in advance, and there is such a curve for every possible threshold. Because the population is stochastically buffeted by environmental conditions, the risk of falling to the threshold necessarily increases with time. These kinds of distributions are often highly skewed. In this example, the distribution is censored because the analysis was only run for 25 time steps and many population trajectories never fell below the threshold over this period.

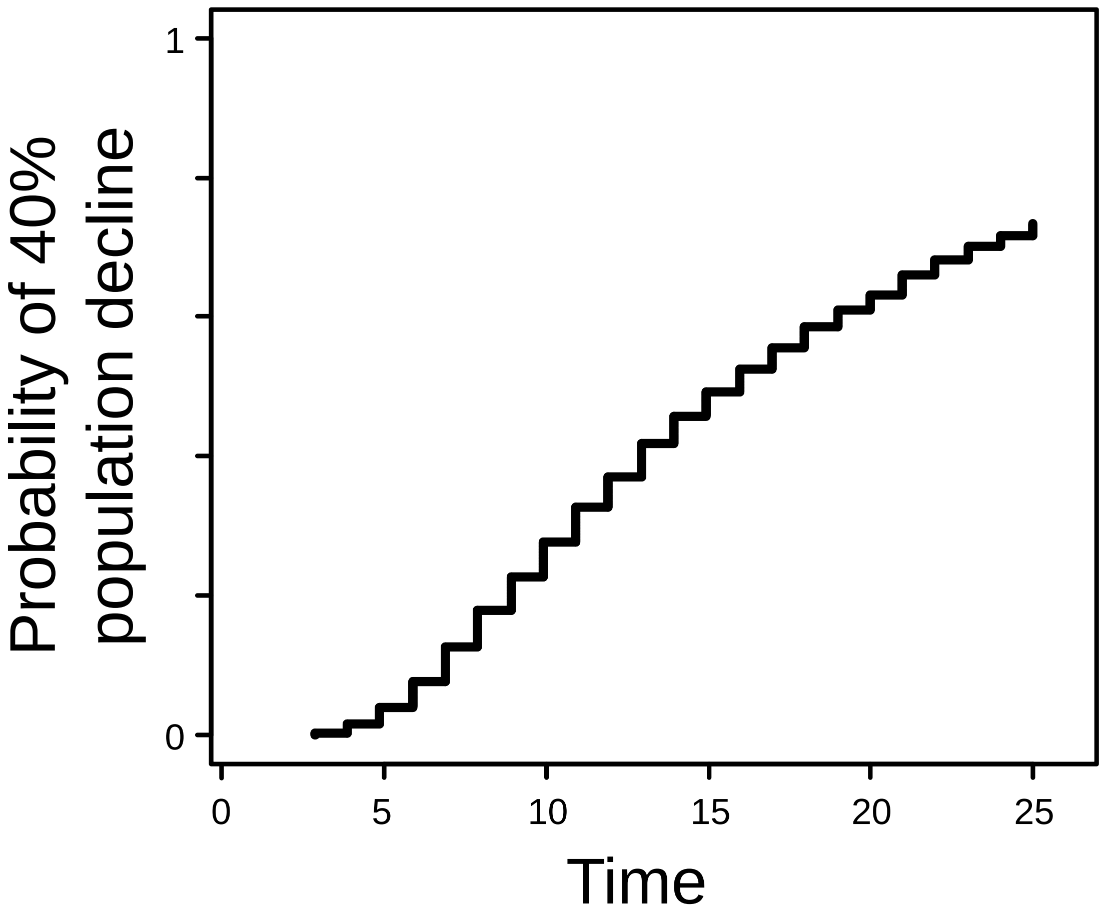

Fig. 3.

An alternative way to visualize risk assessments, in addition to results like Fig. 3, is to fix the time horizon and depict risk as a function of the threshold abundance. This allows us to characterize the probability of decline, which is considered a critical statistic in ecological risk assessment (Roast et al. 2007, page 17). Fig. 4 shows two examples of probability of decline for our hypothetical population. These graphs are not equivalent; they reveal different things about the population. The graphs differ in two ways. The left graph shows the risk of population decline *at any time step during* the 25-step simulation period, displayed as a *percentage decline* from the initial population. The right graph displays the risk of population decline *at the end* of the 25-step simulation period, displayed against *population size*. The right graph depicts the same distribution shown in Fig. 2, but in cumulative form. It is the distribution of population size at the end of the simulation window.

The left and right graphs differ in terms of the scale used for the abscissa, but also in terms of what risk they consider. If they were displayed on the same abscissa, the risk of decline at any time step during the simulation period would not be smaller than the risk of that decline at the end. In both graphs, increasing risk represents higher chances of falling to lower abundances. In the left graph, the risk gets worse as the curve moves up or to the right. In the right graph, the risk gets worse as the curve moves up or to the left. In our hypothetical example, we see that almost all trajectories fall below the initial population size of 100. More than half fall below the population size of 60 (40% population decline).

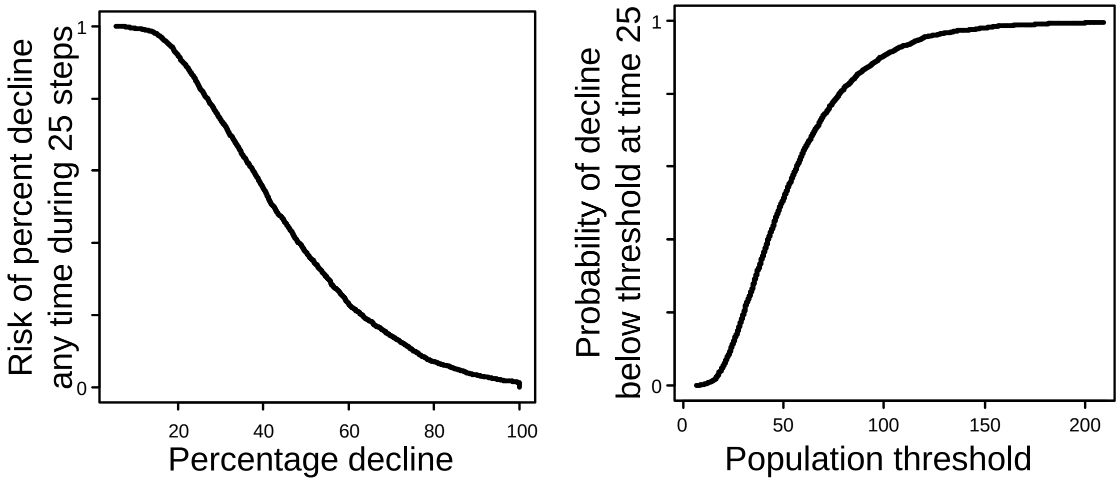

Fig. 4.

In practice, the risk-analytic summaries exemplified in Figs. 3 and 4 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; Roast et al. 2007; Ashton et al. 2008; Bartell 2008; Pastorok et al. 2019) 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.

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.

4. 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. Population-level risk assessments have been used to characterize the effects of chemical contamination, harvests, thermal effects, entrainment and impingement, habitat loss, and disruption of migration and dispersal patterns. Moreover, all manner of impacts can be combined within a single analysis so that interacting or cumulative effects can be properly accounted for and integrated.

Fig. 5 depicts a hypothetical assessment that estimates the cumulative attributable risk to a population. The lower, gray line represents the background risk of going extinct (or reaching some critical threshold) before a given time. This risk is expressed as a line over all times. The natural variability experienced by the population determines the position and character of this line. Increasing the level of environmental stochasticity causes the curve to be higher and further to the left. 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, black line in Fig. 5 represents the risk of extinction when there is an impact. The difference between the two lines is that part of the risk that can be attributed to the presence of the impact. The degree to which the black line is above or to the left of the gray line is an assessment of the population-level effect of the impact. The difference between the two lines might be quantified by the maximal vertical distance between them, or perhaps by the area between the lines. However it is measured, it is the difference between the two lines 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 this attributed risk. This way of displaying the results of an assessment emphasizes the irremovability of background risks.

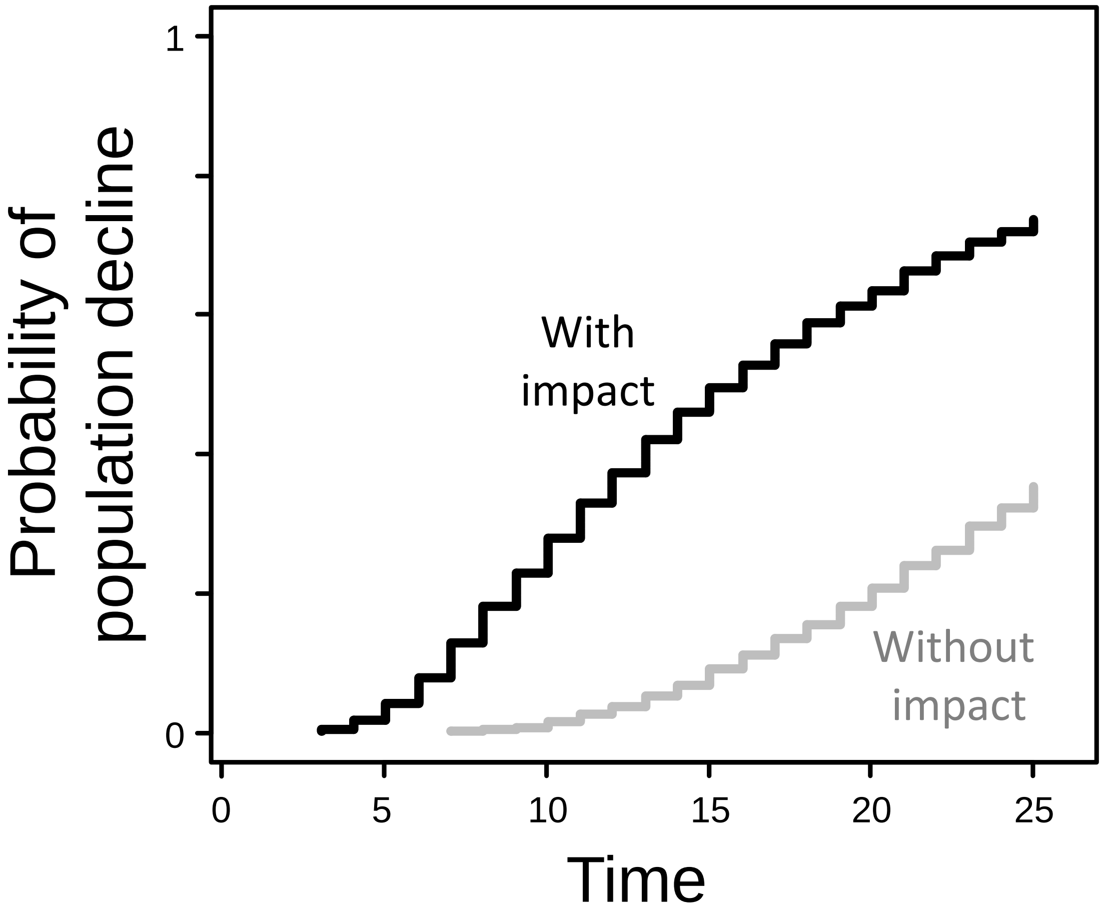

Fig. 5.

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. 6 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. 6 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 or population decline due to the impact, or the risk that the impact will steal so much time from the population's longevity. Any nonzero values are directly 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. 5 is insufficient to estimate Fig. 6. These two summaries communicate different aspects of the assessment. Fig. 5 shows the difference of risks, whereas Fig. 6 shows the risk of differences.

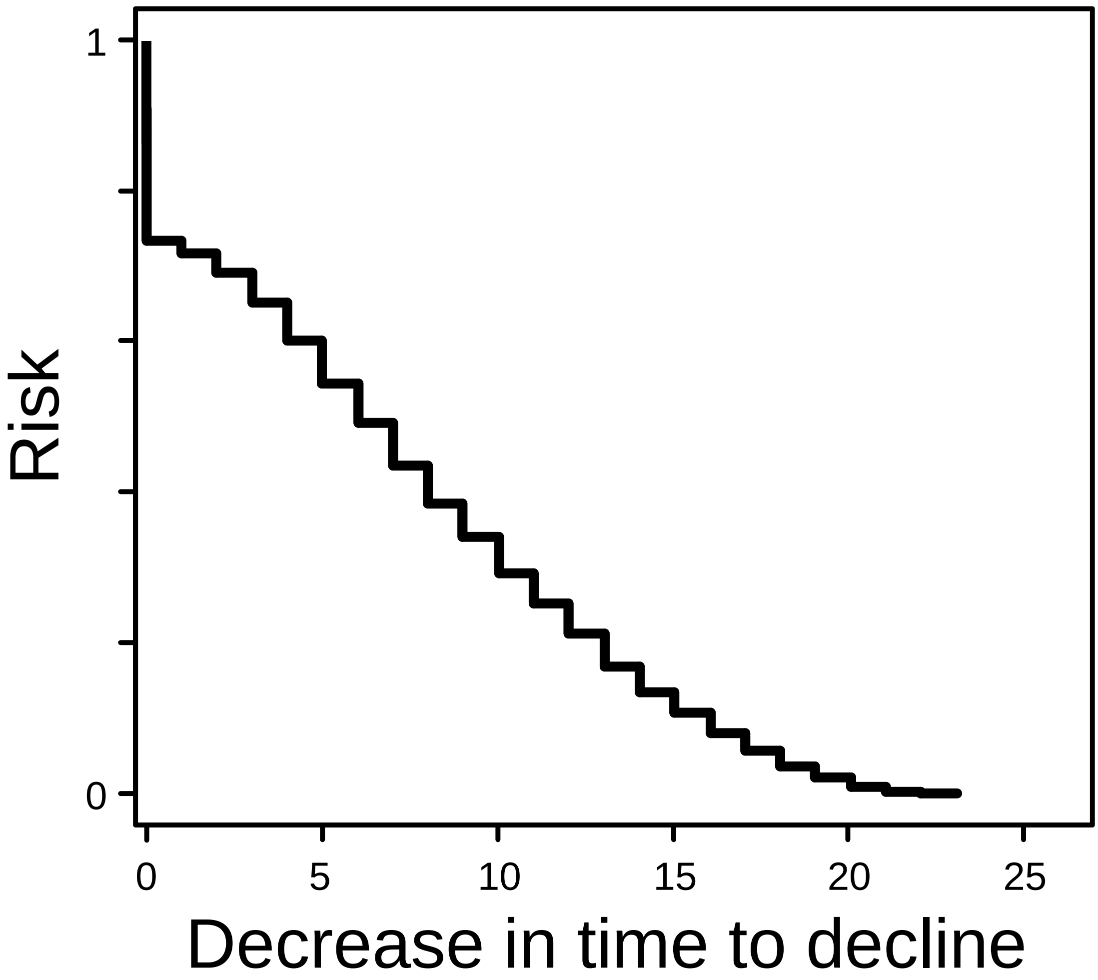

Fig. 6.

5. 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. 7 depicts intervals bounds around the distribution shown in Fig. 6. This depiction conveys the incertitude (i.e., partial lack of knowledge) about the result that arises from measurement error in the input parameters.

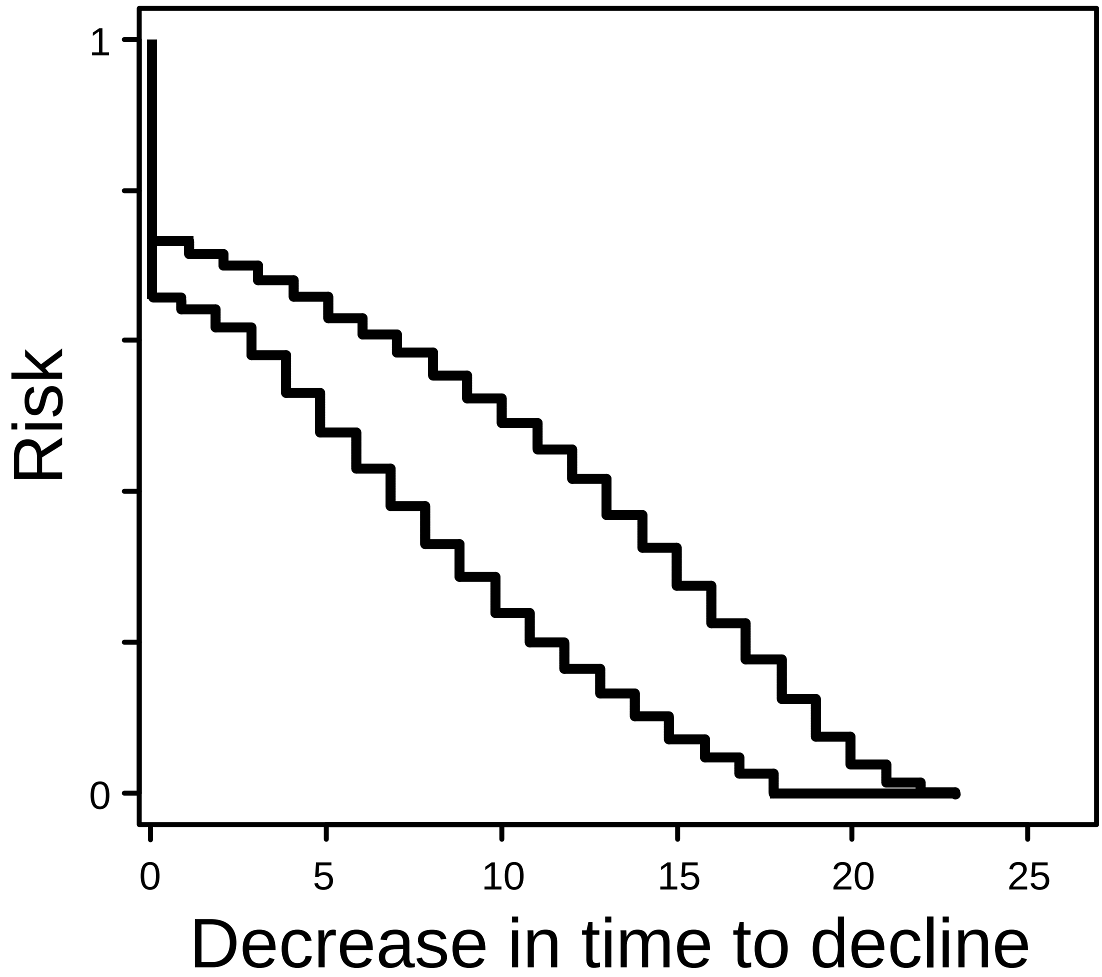

Fig. 7.

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 enclosed region in Fig. 7 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.

6. Conclusions

In aquatic and terrestrial ecosystems, contaminants such as leachates from mine tailings, manufacturing by-products, combustion residues, agricultural fertilizers and pesticides adversely affect plants and animals. The population-level consequences of these effects are determined by natural ecological processes which are inherently complex. These processes can mask the effects of an impact or greatly magnify it, depending on the life histories of the biological species involved. This complexity can also delay the consequence of an impact or alter its expression in other ways. Moreover, natural biological systems fluctuate in time and space, often due to factors such as weather that we cannot predict. Our scientific understanding of ecosystem ecology is itself very limited, and quantitative predictions for such systems would require vastly more data and mechanistic knowledge than are usually available. So the complexity and variability of these natural systems and our lack of knowledge about them prevent us from making precise estimates.

Extrapolating the results of individual-level impacts observed in toxicology laboratories to effects at the ecosystem level may simply be beyond the current scientific capacity of ecology. Thus, toxicity assessments at the level of the individual organism or below cannot answer basic “so what?” questions such as what consequences limited mortality or reduced reproduction will have on a population. Could the natural resilience of a population allow it to rebound? Can we be sure there will be any noticeable impact at all on the population as a whole from effects measurable in the toxicology laboratory? Can we be sure that seemingly minor growth or reproductive effects of a contaminant will not be magnified by a species’ sensitivity to create a substantial population-level impact? These questions can only be answered in a probabilistic risk assessment based on a stochastic population model. As a practical matter, ecological risk analysis must focus on single-species populations and short food chains as a useful compromise between relevance and tractability. Such assessments can form the basis of a regulatory framework designed to protect environmental resources, and likewise inform polluting industries about how they should provision for uncertainties in their consideration of remediation strategies. Although often restricted to higher-tier assessments, these probabilistic population-level assessments are also valuable in lower-tier, generic or even screening assessments.

7. Acknowledgments

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