The importance of social values in the prioritization of research: a quantitative example and generalizations

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Abstract

1. Identifying critical uncertainties about ecological systems can help prioritize research efforts intended to inform management decisions. However, exclusively focusing on the ecological system neglects the objectives of natural resource managers and the associated social values tied to risks and rewards of actions.
2. I demonstrate how to prioritize research efforts for a harvested population by applying expected value of perfect information (EVPI) analysis to a matrix projection model of steelhead (*Oncorhynchus mykiss*) and an explicit utility function that models risk/reward objectives. Research priorities identified by EVPI diverge from priorities identified by matrix elasticity analyses that ignore utility. The degree of divergence depends on uncertainty in population vital rates and the particular form of the utility function used to represent risk/reward of harvest.
3. *Synthesis and applications.* EVPI analysis that includes perceived utility of different outcomes should be used by managers seeking to optimize monitoring and research spending. Collaboration between applied ecologists and social scientists that quantitatively measure peoples' values is needed in many structured decision making processes.

Keywords

decision theory, elasticity, harvest, human dimension, matrix model, social values, value of information

1 | INTRODUCTION

Applied ecologists inform decisions by reducing uncertainty about ecological systems. Reducing system uncertainty is necessary but not sufficient for good decision making. Good decision making stems from careful consideration of objectives (Keeney 1992) that will often entail tradeoffs. In natural resource management contexts, good decision making must therefore also include stakeholder perceptions of the tradeoffs between conservation risks and utilization rewards.

If decisions about natural resources neglect peoples' values, then ecological science can seem aloof or irrelevant, and the decision-making process will seem arbitrary to stakeholders. The resulting void is filled with calls for greater integration of people into environmental decisions that are often vague and disconnected from established quantitative decision-theoretic tools (e.g. translational ecology). There is broad recognition of the need for better integration of human dimensions into natural resource management, but quantitatively synthesizing ecological science, human perceptions, and decision making remains challenging.

Management of exploited populations exemplifies a social tradeoff between risk and reward. There is an obvious desire to harvest as much as possible provided that current harvest does not jeopardize future harvest. Framed this way, exploitation is purely an ecological question. A quantitative ecologist armed with a matrix population model could use elasticity analysis to "Design sampling procedures that focus on estimating the vital rates where accuracy matters most" (Caswell 2001, p. 207). Matrix elasticity analysis addresses the decision of where to direct monitoring and research efforts by focusing exclusively on the ecological system (population growth rate). How can we incorporate socially-determined values about the risks and rewards of utilization and conservation? How do research and monitoring efforts to estimate population vital rates that 'matter most' change if we include socially-determined values about harvest?

These questions can be answered with a rigorous and direct method. The method applies expected value of perfect information (EVPI, Schlaifer & Raiffa 1961) analysis to a matrix population model with continuous-scale parameters. Three algebraic models are used to model different socially-determined risk/reward tradeoffs of promulgating distinct harvest rates under distinct population growth rates. Results of monitoring and research prioritization from this analysis are compared to analogous results obtained from matrix elasticity analysis that focuses exclusively on the ecological system (population growth rate) and ignores the socially-determined risk/reward tradeoff of harvest. Using a case-simulated scenario of a harvested steelhead (*Oncorhynchus mykiss*) population and hypothetical models of the socially-determined risk/reward tradeoff of harvest, the method will expose the effect of including socially-determined values on data collection priorities without distraction by empirical caveats.

2 | EXPECTED VALUE OF PERFECT INFORMATION

The expected value of perfect information (EVPI) quantifies the benefit from resolving uncertainty prior to making a decision. It uses the perceived benefits/costs associated with taking alternative actions under alternate states of reality, and returns the value reaped from correctly assessing reality over some baseline of ignorance. EVPI can be used to prioritize research and monitoring around the uncertainties that 'matter most,' where 'mattering' is defined in terms of the utility of actions. In applied ecological contests, EVPI has been used to (1) design monitoring programs that address stakeholder conservation concerns (Runge et al. 2011), (2) identify the switch-point between monitoring and acting (Bennett 2017), (3) spatially prioritize conservation efforts (Raymond et al. 2020), and (4) quantify the species-persistence benefits of reducing the most important uncertainty- species responses to threat alleviation (Nicol et al. 2019). EVPI has also been focus of reviews (Canessa et al. 2015, Bolam et al. 2019), and analytical methods have expanded to include imperfect information (Williams & Johnson 2015, Nicol et al. 2019).

Formally, the expected value of perfect information is

$$EVPI = \int \left[\max_{\psi \in \Psi} u(\psi,\theta) \right] f(\theta) d\theta - \max_{\psi \in \Psi} \left[\int u(\psi,\theta) f(\theta) d\theta \right],$$

where $u(\psi,\theta)$ is the utility of taking action ψ given state parameter θ. The first square bracket gives the maximum utility over all possible actions given the state parameter. Multiplying this into the probability of the state parameter taking on a given value, $f(\theta)$, and then integrating across all possible state parameter values yields the expected utility assuming perfect actions for the given state. The second term subtracts off the utility obtained from taking actions that give maximum utility across all parameter states. Thus EVPI is the value obtained from making rational decisions under perfect information about state parameters minus the value obtained from making rational decision that are constrained by a baseline of ignorance about potential values of the state parameter. The difference (EVPI) quantifies what can be gained by switching from rational evaluation of potential states to perfect knowledge of state.

3 | MATRIX POPULATION MODEL AND ELASTICITY

Oncorhynchus mykiss that exhibit an anadromous life history (breed in freshwater and rear in the ocean) are known as steelhead. Many steelhead populations are composed of individuals that return from the ocean between ages 3 through 6 to breed in freshwater. Most individuals die after their first breeding event (semelparity) but some will make a second trip to the ocean and back to freshwater to breed again (iteroparity). A population transition matrix, A, for such steelhead that includes freshwater harvest of adults prior to breeding is

$$A=\begin{bmatrix} 0 & 0 & s_1 b_3(1-h_3) f_3/2 & s_1 b_4(1-h_4) f_4/2 & s_1 b_5(1-h_5) f_5/2 & s_1 b_6(\\ s_2 & 0 & 0 & 0 & 0 & \\ 0 & s_3 & 0 & 0 & 0 & \\ 0 & 0 & (1-b_3) s_4 + b_3(1-h_3) r_3 z_4 & 0 & 0 & \\ 0 & 0 & 0 & (1-b_4) s_5 + (1-r_3) r_4 b_4 (1-h_4) z_5 & 0 & \\ 0 & 0 & 0 & 0 & (1-b_5) s_6 + b_5(1-h_5)(1-r_4) r_5 z_6 & \end{bmatrix}$$

where s is survival probability, b is breeding probability, h is harvest rate, f is fecundity in terms of eggs per female, r is repeat breeding (iteroparity) probability, z is survival of individuals attempting to breed a second time, and subscripts give the postbreeding age of individuals. For 3 year old steelhead to produce 1 year old offspring, the parent must return to breed as a soon-to-be 3 year old (b_3), not be harvested ($1-h_3$), deposit eggs (f_3; division by 2 for 50:50 sex ratio), and the eggs must survive to age 1 (s_1). There are two ways a 3 year old fish becomes a 4 year old fish. It may not return to freshwater to breed ($1-b_3$) and then survive its fourth year (s_4), or it may return to freshwater to breed as 3 year old (b_3), avoid harvest ($1-h_3$), attempt to breed the following year (iteroparity, r_3), and successfully survive (z_4). Survival of older fish follows a similar pattern except that steelhead attempting iteroparity cannot have subsequently tried. This prevents more than two consecutive breeding events. An example of state parameter values is given in Table 1.

The transition matrix A implies a density-independent population growth rate, λ, which is the dominant real eigenvalue of A. Since decisions about harvest rates, h, should be predicated on the magnitude of λ, it is prudent to ask which matrix entries have the largest effects on λ. These are the life history events that need to be well estimated, and thus seemingly deserve research and monitoring priority (Caswell 2001, p. 207). Elasticity analysis yields the proportional sensitivity in λ relative to proportional change in the transition matrix cell entries, α_{ij}. Matrix A contains many α_{ij} that are defined by several parameters. It is possible to perform the elasticity analysis in terms of these lower-level parameters. Decomposing the elasticity analysis into constituent parameters s, b, h, f, r, and z provides greater resolution into important population processes. Let x represent any of the constituent parameters. The elasticity of population growth rate, λ, to a lower-level parameter is

$$\frac{x}{\lambda}\frac{\partial \lambda}{\partial x}=\frac{x}{\lambda}\sum_{ij}\frac{\partial \lambda}{\partial \alpha_{ij}}\frac{\alpha_{ij}}{\partial x}.$$

The first term inside the summation is the sensitivity of λ to a given projection matrix cell entry, α_{ij}. These sensitivities are then multiplied into the partial derivative of α_{ij} with respect to the constituent parameter x, summed across all cells and then scaled by the magnitude of x relative to λ. Calculating the elasticity of λ with respect to b_3 thus begins by finding the partial derivative of λ with respect to b_3 for cell α_{13}

$$\frac{\partial \lambda}{\partial b_3}=\frac{f_3\left(1-h_3\right)s_1}{2}$$

and the other cell in which b_3 appears, cell α_{43}

$$\frac{\partial \lambda}{\partial b_3}=z_4\left(r_3-h_3 r_3\right)-s_4.$$

These partial derivatives are summed and then multiplied by the quotient, $\frac{b_3}{\lambda}$.

4 | INCORPORATING SOCIAL VALUES

The foregoing elasticity analysis will identify critical parameters in the ecological system. This could be used to focus research and monitoring on the most important parameters with respect to λ, but it neglects the socially-determined objectives of managers. Managers may reap greater reward with increasing harvest rate provided that post-harvest population growth rate is positive. The reward is negative (penalty) for promulgating harvest rates that cause negative population growth. Thus there is a precarious motivation to harvest up to, but not exceed, rates that permit positive population growth. Three such utility functions are given below and in Figure 1.

$$u_1 \propto \begin{cases} -1, \mathit{if}\ \lambda < 1 \\ h, \mathit{if}\ \lambda > 1 \end{cases}$$
$$u_2 \propto \begin{cases} -2 + 2\lambda, \mathit{if}\ \lambda < 1 \\ h, \mathit{if}\ \lambda > 1 \end{cases}$$
$$u_3 \propto \begin{cases} -4 + 4\lambda, \mathit{if}\ \lambda < 1 \\ 5h^2, \mathit{if}\ \lambda > 1 \end{cases}$$

Each utility function u_1, u_2, and u_3 gives the utility of harvest at level *h* (*h* is the action we can take, which can be any number on the interval [0, 1]) given the effect this action has on λ. Using some set of values for state parameters $\theta \equiv (s, b, f, r, z)$ we can calculate the utility of harvest at level *h* by doing the Eigen analysis of matrix *A* to get λ and then using the result to evaluate the function u. Thus EVPI can be calculated for all state parameters and utility functions. A probability density function $f(\theta)$ is required to model plausible state parameter values. This is derived from the same data used to generate point estimates of the state parameters θ. If data do not exist, then $f(\theta)$ is a prior distribution arising from professional opinion and literature review.

4 | UNCERTAINTY AND EVPI

The state parameter for survival-at-age, *s*, is a number on the interval [0, 1]. The beta distribution is thus a suitable probability density function, $f(\theta)$, to model plausible values of *s*. The Beta distribution was reparameterized in terms of mean μ and variance σ^2:

$$f(s)=\frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}$$

where Γ is the gamma function, Γ(X+1) = X!, and by method of moments

$$a=\mu\left(\frac{\mu(1-\mu)}{\sigma^2}-1\right)$$

$$b=(1-\mu)\left(\frac{\mu(1-\mu)}{\sigma^2}-1\right).$$

It is thus possible to 'center' $f(s)$ on values given in Table 1 while entertaining scenarios of relatively low and high certainty. Two level of certainty in fecundity-at-age, *f*, were modeled with the normal distribution, which is parametrized by mean and standard deviation (Table 1).

The harvest action ψ is one of nine rates Ψ={0.1, 0.2, . . ., 0.9}. This discretization is likely fine-scale relative to degree the management control over harvest rate (Eriksen et al. 2018). For simplicity, matrix elasticity and EVPI are compared only for state parameters *s*, and *f*.

5 | DIFFERENCE BETWEEN EVPI AND ELASTICITY

Elasticity analysis shows that survivals to ages 1, 2, and 3 (s_1, s_2, s_3) are equal to one another and more important to know than any other parameter ($s_4, s_5, s_6, f_3, f_4, f_5, f_6$; Figure 2). However, the EVPI analysis shows that s_1 is most important if the third utility function is used for both levels of certainty. EVPI analysis further shows that s_2 is slightly more important than s_1 if the first utility function is used and certainty is low. Increasing certainty causes this to flip so that s_1 is once again most important. Both elasticity and EVPI analyses indicate declining importance of survival beyond age 3. Under low certainty, EVPI for s_6 is zero (for all three utility functions) because optimal harvest decision will always be made without perfect information. Under high certainty, EVPI is zero for s_6 and s_5. More generally, increasing the prior certainty decreases EVPI.

Fecundity is generally much less important than survival using elasticity analysis (note different scales on the two elasticity panels). The same is true for EVPI analysis, except that f_4 is quite important under low certainty and the third utility function. Similarly, the elasticity analysis finds decreasing importance of fecundity with increasing age, which is also found by EVPI analysis except for the first and second utility functions under low certainty.

6 | DISCUSSION

There is a rich literature on population harvest that stresses the importance of density-dependent population regulation (Ricker 1954, Sutherland 2001). The steelhead matrix model used here does not address density-dependence. In this model, harvest occurs immediately before breeding so density-dependent harvest effects would occur in egg and juvenile stages of the next generation. Density-dependent optimal harvest can be studied with analyses of maximum sustained yield, but problems of such analyses are well known (Larkin 1977). Questions about harvest almost always lead to questions about data availability, analysis, and robustness of operating models (policy) to uncertainty. This is now formalized with management strategy evaluation (Butterworth 2007, Punt et al. 2014). Management strategy evaluation is sufficiently broad to include socially-determined values, and would address the effect of resolving uncertainty using simulation (Mäntyniemi et al. 2009). The mathematics deployed here compare two methods of determining critical uncertainties.

Applied ecology is idiomatic without formal tools for translating quantitative results to decisions. The elaboration and dissemination of such tools (Conroy & Peterson 2013) is needed to overcome the cognitive biases associated with informal decision making (Tversky & Kahneman 1974) and implement cost-optimizations that 'do more with less' (Falcy 2018). An impediment to robust optimization of environmental decision making is the time and expertise needed to construct appropriate models. Even the mere decision to calculate EVPI entails a human resource cost that stands outside the eventual EVPI calculus. Thus, there is a start-up cost attached to the business of prudent decision-making, and it is reasonable to ask whether this business is viable when running at different scales. Indeed, intuition is free and fast while modeling is neither. There is an emerging awareness and suspicion for human proclivity to favor free and fast intuition (Kahneman 2011).

This analysis demonstrates that research and monitoring priorities depend on whether the prioritization is derived from matrix elasticity analyses or EVPI analysis. Only the latter incorporates socially-determined utilities representing the rewards and risks of harvest, and should be used if decision-makers want to incorporate stakeholder values. In this analysis, the utility function provides the critical link to the ecological system. Since priorities can be sensitive to the form of the utility function, it is important that utility functions are appropriately formulated. Social scientist can help formulate utility functions by designing and analyzing "stated preference" studies of stakeholders (Johnston et al. 2017). Components of stated preference studies relevant to natural resource management include choice experiments and the "subjective well-being" associated with non-market ecosystem services (Lindberg et al. 2020). However, these methods are not free of controversy (see Johnston et al. 2017), and cannot be known with perfection. Thus, like the decision to calculate EVPI in the first place, sensitivity to different utility functions is meta-decisional, requiring an additional tier of consideration and analysis.

It should be no surprise that what people want affects what needs to be known. Quantifying the effect of including social values into decisions using rigorous analytical methods is nonetheless rare. This commentary describes one small component of formal, quantitative decision making methods for integrating people into environmental decisions. Applied ecology will benefit from more examples of quantitative tools that integrate social values into decision making, lest our science seem aloof or irrelevant to the people it intends to serve.

7 | CODE

R computer code for recreating this analysis and extending it into other state parameters is given in Supplement 1.

DATA ACCESSIBILITY STATEMENT

This paper does not use empirical data. Supplement 1 contains computer code for generating all numerical analyses.

REFERENCES

Bennett JR, Maxwell SL, Martin AE, Chadès I, Fahrig L, Gilbert B. 2018. When to monitor and when to act: Value of information theory for multiple management units and limited budgets. Journal of Applied Ecology 55:2101-2113.

Bolam FC, Grainger MJ, Mengersen KL, Steward GB, Sutherland WJ, Runge MC, McGowan PJK. 2019. Using the value of information to improve conservation decision making. Biological Reviews 94:629-647.

Butterworth DS. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science 64:613-617.

Canessa S, Guillera-Arroita G, Lahoz-Monfort JJ, Southwell DM, Armstrong DP, Chadès I, Lacy RC, Converse SJ. 2015. When do we need more data? A primer on calculating the value of information for applied ecologists. Methods in Ecology and Evolution 6:1219-1228.

Caswell H. 2001. *Matrix Population Models: Construction, analysis, and interpretation*. Second Edition. Sinauer Associates.

Conroy MJ, Peterson JT. 2013. Decision Making in Natural Resource Management: A Structured, Adaptive Approach. Wiley-Blackwell.

Eriksen LF, Moa PF, Nilsen EB. 2018. Quantifying risk of overharvest when implementation is uncertain. Journal of Applied Ecology 55:482-493.

Falcy MR. 2018. A cost-optimization framework for planning applied environmental science. Bioscience 68:912-922.

Johnston RJ, Boyle KJ, Adamowicz W, Bennett J, Brouwer R, Cameron TA, Hanemann WM, Hanley N, Ryan M, Scarpa R, Tourangeau R, Vossler CA. 2017. Contemporary guidance for stated preference studies. Journal of the Association of Environmental and Resource Economists 4: 319-405.

Kahneman D. 2011. Thinking fast and slow. Farrar, Straus, and Giroux.

Keeney RL. 1992. Value-focused thinking: A path to creative decisionmaking. Harvard University Press.

Larkin PA. 1977. An epitaph for the concept of maximum sustained yield. Transactions of the American Fisheries Society 106:1-11.

Lindberg K, Swearingen T, White EM. 2020. Parallel subjective well-being and choice experiment evaluation of ecosystem services: marine and forest reserves in Coastal Oregon, USA. Social Indicators Research 149:347-374.

Mäntyniemi S, Kuikka S, Rahikainen M, Kell LT, Kaitala V. 2009. The value of information in fisheries management: North Sea herring as an example. ICES Journal of Marine Science, 66:2278-2283.

Nicol S, Brazill-Boast J, Gorrod E, McSorley A, Peyrard N, Chadès I. 2019. Quantifying the importance of uncertainty on threat management for biodiversity. Nature Communications 10, 3570.

Raymond CV, McCune JL, Rosner-Katz H, Chadès I, Schuster S, Gilbert B, Bennett JR. 2020. Combining species distribution models and value of information analysis for spatial allocation of conservation resources. Journal of Applied Ecology 57:819-830.

Ricker WE. 1954. Stock and recruitment. Journal of the Fisheries Research Board of Canada 11:559-623.

Runge MC, Converse SJ, Lyons JE. 2011. Which uncertainty? Using expert elicitation and expected value of perfect information to design an adaptive program. Biological Conservation 144:1214-1223.

Punt AE, Butterworth DS, de Moor CL, De Oliveira JAA, Haddon M. 2014. Management strategy evaluation: best practices. Fish and Fisheries 17:303-334.

Schlaifer R. Raiffa H. 1961. Applied statistical decision theory. Clinton Press Inc.

Sutherland WJ. 2001. Sustainable exploitation: A review of principles and methods. Wildlife Biology 7:131-140

Tversky A, Kahneman D. 1974. Judgement under uncertainty: Heuristics and biases. Science 185:1124-1131.

Williams BK, Johnson FA. 2015. Value of information in natural resource management: technical developments and application to pink-footed geese. Ecology and Evolution 5:466-474.

Tables

Table1. Parameter values of the population projection matrix *A* (top). Variance and standard deviation used for scenarios of low and high certainty (square brackets) in calculations of expected value of perfect information (bottom).

Parameter	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
s	0.02	0.2	0.8	0.8	0.8	0.8
b			0.4	0.5	0.9	1
f			2000	2500	3000	3000
r			0.4	0.2	0.2	0
z				0.2	0.2	0.2
σ_s^2	[0.01, 0.02]	[0.05, 0.1]	[0.05, 0.1]	[0.05, 0.1]	[0.05, 0.1]	[0.05, 0.1]
$\sigma_f^{\square}$			[200, 500]	[200, 500]	[200, 500]	[200, 500]

Figures

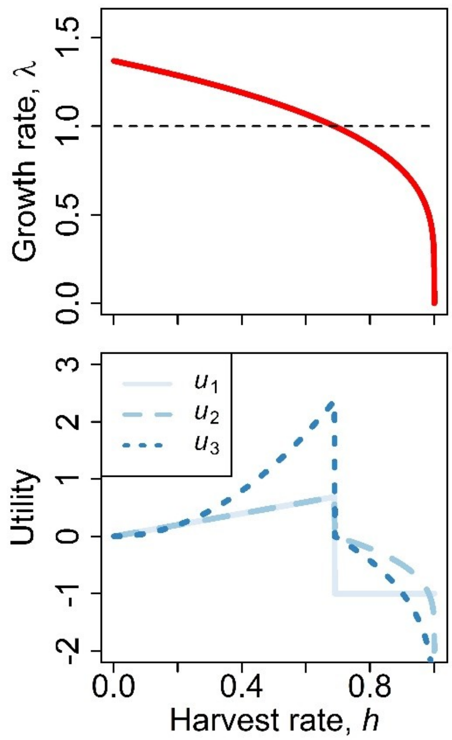

Figure 1. Population growth rate computed from the population transition matrix *A* parameterized with values given in Table 1 (top). Horizontal dashed line references population replacement. Three utility functions increase with harvest rate until population growth rate becomes negative (bottom).

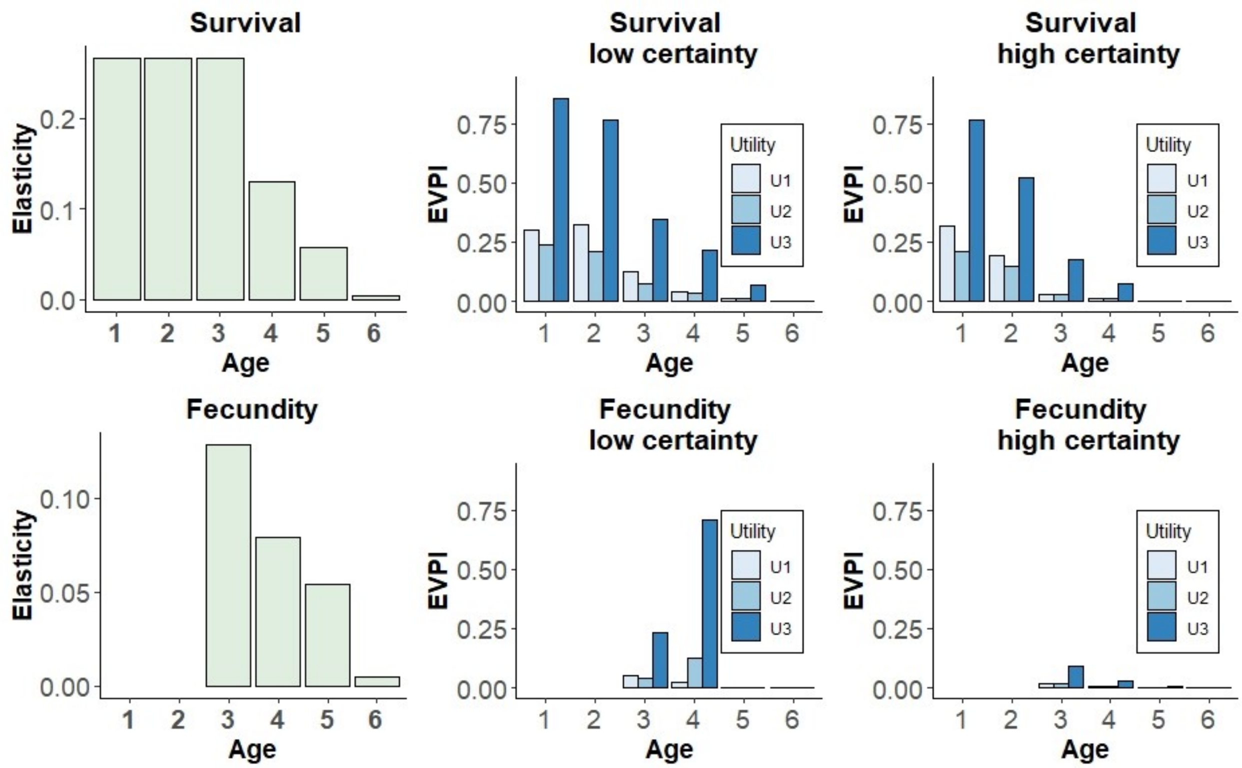

Figure 2. Comparison of matrix elasticity analysis (green) and expected value of perfect information analysis (EVPI, blue) for survival-at-age (top row) and fecundity-at-age (bottom row). Bar height is proportional to importance of survival or fecundity-at-age. EVPI panels contain results for three utility functions and two levels of uncertainty. Units of elasticity and EVPI are not directly comparable. EVPI analysis includes the effect of the socially-determined utility, whereas elasticity analysis focuses exclusively on the ecological system (population growth rate).