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Choosing ecosystem service investments that are robust to uncertainty across multiple parameters

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Abstract. Info-gap decision theory facilitates decision making for problems in which uncertainty is large and probability distributions of uncertain variables are unknown. The info-gap framework allows the decision maker to maximize robustness to failure in the presence of uncertainty, where uncertainty is in the parameters of the model and failure is defined as the model output falling below some minimally acceptable performance threshold. Info-gap theory has found particular application to problems in conservation biology and ecological economics. In this study, we applied info-gap theory to an ecosystem services trade-off case study in which a decision maker aiming to maximize ecosystem service investment returns must choose between two alternative land uses: native vegetation conservation or the establishment of an exotic timber plantation. The uncertain variables are the carbon price and the water price. With a "no-information" uncertainty model that assumes equal relative uncertainty across both variables, info-gap theory identifies a minimally acceptable reward threshold above which conservation is preferred, but below which plantation establishment is preferred. However, with an uncertainty model that allows the carbon price to be substantially more uncertain than the water price, conservation of native vegetation becomes an economically more robust investment option than establishing alien pine plantations. We explored the sensitivity of the results to the use of alternative uncertainty models, including asymmetric uncertainty in individual variables. We emphasize the general finding that the results of info-gap analyses can be sensitive to the choice of uncertainty model and that, therefore, future applications to ecological problems should be careful to incorporate all available qualitative and quantitative information relating to uncertainties or should at least justify the no-information uncertainty model.

Key words: asymmetric uncertainty; carbon price; Fynbos conservation; info-gap decision theory; Jonkershoek Valley, South Africa.

Introduction

Many decision-making problems in conservation biology involve choices between land-use options that provide different suites of ecosystem services (Daily 1997, Polasky et al. 2005, Polasky et al. 2008). Such decision-making problems generally involve uncertainty in one or more key parameters, such as life-history traits of species, economic parameters and environmental conditions. In some cases, uncertainty may be so severe (sensu Ben-Haim 2006) that one cannot even formulate probability distributions to describe uncertainty about model input parameters and model structures. This precludes the use of decision theory that is cast in the language of probability and creates a potential stumbling block for effective decision making. One tool for dealing with severe uncertainty outside the language of probability is info-gap decision theory (Ben-Haim 2006), which has recently found application in conservation biology, but has a longer history in engineering and other fields (e.g., Regan et al. 2005, Moilanen et al. 2006*b*).

Info-gap theory seeks to find solutions that minimize the occurrence of failure given that uncertainty exists. In a conservation biology context, failure could be defined as a population of animals falling below a minimum viable threshold under a given management regime, or as a land management strategy yielding insufficient economic revenue to justify its operation. The uncertainty referred to in info-gap theory is generally uncertainty about the value of key parameters in a model (or set of models) that underpin management or investment decisions, though the theory can also be used to explore the implications of model structural uncertainty. Based on point estimates of parameters and an uncertainty model that defines what it means to be wrong about point estimates, info-gap theory can identify the decision that allows us to be the most "wrong" without falling below the failure threshold. In

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other words, it identifies the decision that is most robust to uncertainty about key input parameters.

The key to the machinery of info-gap theory is the uncertainty model, which specifies nested subsets of parameter values to represent how estimates of parameters may deviate from the truth. In the simplest case, uncertainty expands at equal rates about point estimates of all uncertain variables in a system. Conservation biologists and ecological economists have employed this simple model in most previous applications of info-gap decision theory (e.g., Regan et al. 2005, Moilanen and Wintle 2006, Fox et al. 2007, Nicholson and Possingham 2007, Knoke 2008, Davidovitch et al. 2009, Rout et al. 2009, Burgman et al. 2010, Carrasco et al. 2010, Yemshanov et al. 2010). Info-gap theory, however, offers a much richer set of uncertainty models. Potentially, these different uncertainty models could be used in ecological economics and conservation biology to express more accurately our knowledge about a given system and to refine the decision-making process.

A straightforward extension of the simple uncertainty model described in the previous paragraph is the expanding-boxes (Ben-Haim 2006:23) or uniform-bound model (Yemshanov et al. 2010). In this model, the rates of expansion of uncertainty about different parameters are different but proportional to one another. The expanding-boxes model effectively defines the "wrongness" of any parameter combination as the maximum deviation from the best guess about any one of the parameters. One previous environmental management problem has employed the expanding-boxes model with different expansion rates for each variable (McCarthy and Lindenmayer 2007). The expanding-boxes model is more sophisticated than the simple uncertainty model described in the previous paragraph, but it still conflicts with the intuition that, in defining "wrongness," deviations across multiple parameters should be added or combined in some other way. A more flexible uncertainty model that addresses this problem is defined by the Minkowski norm (Ben-Haim 2006), which effectively allows one to create uncertainty models such as "expanding ellipsoid" models (e.g., McDonald-Madden et al. 2008) and models in which deviations from best guesses are measured along axes corresponding to linear combinations of different parameters.

One assumption of all of the uncertainty models discussed thus far is that uncertainty envelopes expand at the same rate in the positive and negative direction around one parameter. In many cases, this assumption may not best represent our information about the system. Drawing on the ecosystem services case study from the next section, suppose that we are operating under the assumption of a carbon price at US$20 per Mg (ton). According to the expanding-boxes model and even the general Minkowski norm model, a value of $40 is "as wrong as" a value of $0, whereas an asymmetric model of uncertainty may be more realistic. Exploring how to incorporate such asymmetric uncertainty into analyses in conservation biology and ecological economics is, therefore, an additional priority.

Here we applied info-gap theory to a case study of ecosystem services in the South African Fynbos biome. This case study was previously analyzed using the classical decision–theory approach of maximizing net present value, which in this case equals the net present economic value of one hectare of land in terms of water, carbon, and timber values (Chisholm 2010). In the current analysis we aimed to expand upon the 2010 study by (1) providing a demonstration of the application of info-gap theory to address uncertainty around ecosystem service investment decisions, (2) demonstrating how decisions made using info-gap theory may be sensitive to the chosen uncertainty model, and (3) providing advice on how uncertainty about which uncertainty model to use might be addressed in practice. In our case study, we employed a general uncertainty model that included the uncertainty models of all previous info-gap applications to ecological problems (expanding-boxes with equal relative uncertainty, expanding-boxes with unequal relative uncertainty, expanding ellipsoids) as special cases. We demonstrate that decisions can be sensitive to the choice of uncertainty model. We discuss strategies for choosing between uncertainty models in the context of the case study and provide recommendations for future studies of this kind.

Methods

Ecosystem services case study

The Fynbos biome covers 46 000 km^2 of the mediterranean-climate region in southwest South Africa (Cowling 1992). Fynbos vegetation is characteristically speciose, shrubby, and fire-prone. The study site is a water catchment in the Jonkershoek Valley about 50 km from Cape Town (described in detail in van Wilgen et al. 1992, Chisholm 2010). Two dominant land uses in this catchment are native vegetation conservation (1700 ha) and pine-based forestry (*Pinus radiata*; 760 ha). Ecosystem services associated with native vegetation include water supply (Turpie et al. 2008), tourism, and biodiversity values. Ecosystem services associated with pine plantations include timber supply and carbon sequestration (the biomass of pine trees is substantially greater than that of the native vegetation) (see Plate 1).

Our analysis is based on a previous treatment of this problem (Chisholm 2010) that used a coupled ecological-economic model to estimate the net present value of one hectare of land under the two alternative land-use scenarios (conservation vs. plantation). The original ecological model is a discrete-time dynamical system based on a six-pool carbon-flux model, parameterized with published data and modified to include fire and harvesting (details in Chisholm 2010). The original economic model produced estimates of net present land value based on parameter values derived from published biomass–streamflow estimates (le Maitre et al. 1996), current local water prices, current international carbon prices, accounting methods for certified emissions reductions (Dutschke et al. 2004, Olschewski and Benitez 2005), and raw data from the local timber industry (details in Chisholm 2010).

Following Chisholm (2010), our model includes three ecosystem services: water, carbon, and timber. Biodiversity values and tourism are excluded, because current per-hectare economic valuations of these services at the study site are negligible (Chisholm 2010). For tractability we restricted ourselves to considering the uncertainty in the economic values of water and carbon (arguably the two greatest economic uncertainties). We assumed that the value of timber is equal to its present value, and that plantation is managed to exclude fire (i.e., fire frequency is 30 years; see Chisholm 2010 for a full sensitivity analysis of these parameters in a more classical decision-theory framework).

We refer to the two alternative land-use decisions as q_N (conservation of native vegetation) and q_P (establishment of a pine plantation). To define the reward functions for the two decisions, we derived the following linear equations by ordinary least-squares regression from the output of numerical simulations of the original ecological-economic model (Chisholm 2010):

$$R(q_N, u_w, u_c) = k_{Nw}u_w \tag{1}$$

$$R(q_P, u_w, u_c) = k_{Pw}u_w + k_{Pc}u_c + k_P. \tag{2}$$

Here, u_w is the unit value of water (US\$/m^3), u_c is the unit value of carbon (US/Mg CO_2), and R is net present value of the land (US\$/ha). The k_i are regression coefficients with our fitted values of $k_{Nw} = 266\,000$, $k_{Pw} = 225\,000$, $k_{Pc} = 93.5$, and $k_P = 952$. The linear Eqs. 1 and 2 with these fitted values explain over 99% of the variance in the outputs of the original model (Chisholm 2010) for our fixed timber price and mean fire frequency and over the range of water and carbon values considered in the original study, justifying our linearization of the system for the present study.

Note that the net present value of carbon ($k_{Pc}u_c$) in the plantation in Eq. 2 represents only carbon stored above the baseline carbon storage in Fynbos, and that the value of the carbon in Fynbos in Eq. 1 is zero (Chisholm 2010). Formulated in this way, the model reflects the additionality principle of carbon offset markets, whereby only carbon stored above some business-as-usual baseline (preservation of Fynbos in this case) is eligible for credits (IPCC 2001). The net present value of water ($k_{Nw}u_w$ and $k_{Pw}u_w$) in Eqs. 1 and 2 is the net present value of water that falls on the hectare of land under consideration and is ultimately usable by humans. It excludes water that is used by the vegetation, because this water is not available for human consumption. Because the pine plantation uses more water than Fynbos (le Maitre et al. 1996), the total value of water is lower under the former scenario (i.e., $k_{Pw}u_w < k_{Nw}u_w$).

Based on the methodology and data sources from Chisholm (2010), our point estimate for the value of carbon ($\tilde{u}_c$) is \$20/t CO_2 and that for water ($\tilde{u}_w$) is \$0.10/m^3. With these point estimates, the net present value of native vegetation (\$26 600/ha) is slightly higher than that of a pine plantation (\$25 322/ha). These values may be a reasonable representation of current economic conditions, but which land-use decision is most robust to uncertainty in these values? In the terminology of info-gap, we asked the following question: Under which decision can we be the most wrong and still be guaranteed of getting at least some minimally acceptable reward? The minimally acceptable reward (R_c, measured in US\$/ha) is a threshold value of the net present value function (Eqs. 1 and 2). Net present values below R_c are considered failure. In the extreme case of $R_c = \$26\,600$/ha, it is clear that we prefer the conservation option, because the plantation fails to give us that reward even if our point estimates of economic values are exactly right. In the other extreme case of $R_c = \$1$/ha, it is clear that we prefer the plantation option, because it never gives us less than \$952 (at least under the model as stated, in which timber values are assumed constant). For intermediate values of R_c, the decision-making process requires deeper analysis.

General info-gap uncertainty model

An info-gap analysis requires the definition of an info-gap uncertainty model. In this study, we utilized a general info-gap uncertainty model that subsumes the "expanding-box" uncertainty model that has been used most widely in conservation biology and ecological economics applications, and which can also be generalized to represent an ellipsoid parameter uncertainty space. We then investigated the sensitivity of the decision to changes in the parameters defining the uncertainty model. Consider the following info-gap uncertainty model (Ben-Haim 2006), which defines the set of water and carbon prices that are within a horizon of uncertainty α:

$$\mathcal{U}(\alpha, \tilde{u}_w, \tilde{u}_c) = \left\{ (u_w, u_c) \colon \left(\left| \frac{(u_w - \tilde{u}_w)}{\psi_w \tilde{u}_w} \right|^p + \left| \frac{(u_c - \tilde{u}_c)}{\psi_c \tilde{u}_c} \right|^p \right)^{\frac{1}{p}} \le \alpha, u_w, u_c \ge 0 \right\} \quad \alpha \ge 0 \tag{3}$$

where ψ_i defines the relative uncertainty in variable i (a larger value of ψ_i means that variable i is more uncertain; the case $\psi_w = \psi_c$ corresponds to the default assumption of equal relative uncertainty in all variables), p defines the shape of the envelope, and the other parameters are defined in the previous subsection. Values of p of specific interest are $p = 1$, which corresponds to linearly additive uncertainties and an "expanding diamonds" model, $p = 2$, which corresponds to an ellipsoid uncertainty model, and $p \to \infty$, which corresponds to the basic expanding-boxes uncertainty model. Intermediate values of p in the range $(2, \infty)$ correspond to shapes that are intermediate between ellipsoids and boxes (i.e., intermediate between ellipses and rectangles in two dimensions).

Applying the uncertainty model (Eq. 3) to the reward functions (Eqs. 1 and 2) of the ecosystem services case study gives the robustness of the native vegetation decision (see Appendix A for derivation) as

$$\alpha_N = \frac{k_{Nw}\tilde{u}_w - R_c}{\psi_w k_{Nw}\tilde{u}_w}$$

and the robustness of the plantation decision (see Appendix A for derivation) as

$$\alpha_p = \frac{k_{Pw}\tilde{u}_w + k_{Pc}\tilde{u}_c + k_P - R_c}{\left((k_{Pw}\psi_w\tilde{u}_w)^{\frac{p}{p-1}} + (k_{Pc}\psi_c\tilde{u}_c)^{\frac{p}{p-1}}\right)^{\frac{p-1}{p}}}.$$

Accordingly, for any given R_c, we would make decision q_N (i.e., in favor of conservation of the native vegetation), if $\alpha_N > \alpha_P$. From this, we can derive a condition that governs our decision:

$$\left((k_{Pw}\psi_w\tilde{u}_w)^{\frac{p}{p-1}} + (k_{Pc}\psi_c\tilde{u}_c)^{\frac{p}{p-1}}\right)^{\frac{p-1}{p}} < k_{Nw}\psi_w\tilde{u}_w. \quad (4)$$

Specifically, if this condition is met, then we choose q_N if $R_c > R^*$, and if this condition fails, then we choose q_N if $R_c < R^*$, where R^* is given by

$$R^* = \left[(k_{Pw}\tilde{u}_w + k_{Pc}\tilde{u}_c + k_P)\psi_w - \left((k_{Pw}\psi_w\tilde{u}_w)^{\frac{p}{p-1}} + (k_{Pc}\psi_c\tilde{u}_c)^{\frac{p}{p-1}}\right)^{\frac{p-1}{p}}\right] \div \left[\psi_w - \frac{1}{k_{Nw}\tilde{u}_w}\left((k_{Pw}\psi_w\tilde{u}_w)^{\frac{p}{p-1}} + (k_{Pc}\psi_c\tilde{u}_c)^{\frac{p}{p-1}}\right)^{\frac{p-1}{p}}\right]. \quad (5)$$

Results

Simple uncertainty model

We first present our results for the simple minimal-information uncertainty model characteristic of most of the models used in conservation biology and ecological economics. This corresponds to the special case $p \to \infty$, $\psi_w = \psi_c$, of the general uncertainty model described above. In this case, Condition 4 becomes

$$k_{Pw}\tilde{u}_w + k_{Pc}\tilde{u}_c < k_{Nw}\tilde{u}_w$$

which is true for the parameterization of the present case study. Accordingly, we make decision q_N if our minimal reward threshold (R_c) satisfies the following condition:

$$R_c > R^* = \frac{k_P k_{Nw}\tilde{u}_w}{k_{Nw}\tilde{u}_w - (k_{Pw}\tilde{u}_w + k_{Pc}\tilde{u}_c)} = \$11\,355.70$$

and we make decision q_P otherwise.

Expanding-boxes uncertainty model

We next considered a somewhat more sophisticated uncertainty model according to which the uncertainty of the price of water may be less than the uncertainty in the price of carbon. This is an expanding-boxes model and represents a special case of the general uncertainty model with $p \to \infty$, $\psi_w \le \psi_c$. In this case, Condition 4 becomes

$$k_{Pw}\psi_w\tilde{u}_w + k_{Pc}\psi_c\tilde{u}_c < k_{Nw}\psi_w\tilde{u}_w.$$

For the parameterization of the present case study, this condition holds if

$$\frac{\psi_w}{\psi_c} > \frac{\tilde{u}_c}{\tilde{u}_w}\frac{k_{Pc}}{k_{Nw} - k_{Pw}} = 0.456.$$

We can also derive the critical reward threshold (R^*) as follows:

$$R^* = \frac{k_P\psi_w + k_{Pc}(\psi_w - \psi_c)\tilde{u}_c}{\psi_w - \frac{1}{k_{Nw}\tilde{u}_w}(k_{Pw}\psi_w\tilde{u}_w + k_{Pc}\psi_c\tilde{u}_c)}.$$

Suppose that the price of carbon is twice as uncertain as the price of water, so $\psi_w/\psi_c = 0.5$, in which case Condition 4 is met and we make decision q_N if $R_c > R^* = -\$67\,830$, i.e., we always choose conservation of native vegetation over the pine plantation. If the price of carbon is three times as uncertain as the price of water, then $\psi_w/\psi_c = 1/3$, in which case Condition 4 is not met and we make decision q_N if $R_c < R^* = \$49\,113.11$, which exceeds the value of the reward functions at the point estimates, and thus, should certainly be true for any nontrivial decision problem. In fact, it is possible to show that we always make decision q_N if $\psi_w/\psi_c < 0.663$ (i.e., if the uncertainty in the price of carbon is roughly 50% greater than the uncertainty in the price of water) regardless of the value of R_c (still assuming here that $p \to \infty$, so we are using the expanding-boxes model). We explore a broader range of values of ψ_w/ψ_c in Fig. 1.

Ellipsoid uncertainty model with equal relative uncertainty

Our third uncertainty model is an ellipsoid model with equal relative uncertainty, which corresponds to a special case of the general uncertainty model with $p = 2$ and $\psi_c = \psi_w$. Condition 4 becomes

$$(k_{Pw}\tilde{u}_w)^2 + (k_{Pc}\tilde{u}_c)^2 < (k_{Nw}\tilde{u}_w)^2$$

which is true for the parameterization of the present case study. From this and from Eq. 5, we find that we choose q_N if

$$R_c > R^* = \frac{(k_{Pw}\tilde{u}_w + k_{Pc}\tilde{u}_c + k_P) - \left((k_{Pw}\tilde{u}_w)^2 + (k_{Pc}\tilde{u}_c)^2\right)^{\frac{1}{2}}}{1 - \frac{1}{k_{Nw}\tilde{u}_w}\left((k_{Pw}\tilde{u}_w)^2 + (k_{Pc}\tilde{u}_c)^2\right)^{\frac{1}{2}}}$$

$$= \$18\,148.68$$

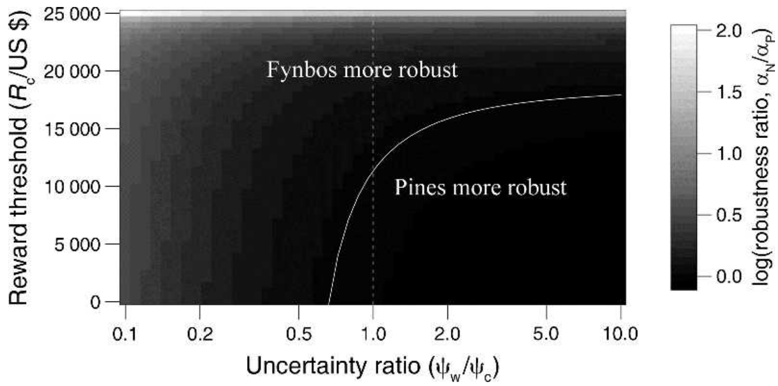

FIG. 1. Log ratio of the robustness values for the two land-use decisions, Fynbos conservation and pine plantation establishment, for the standard expanding-boxes info-gap uncertainty model. The horizontal axis corresponds to variation in the relative uncertainties of the two key variables: the water price (ψ_w) and the carbon price (ψ_c). The white vertical dashed line shows the usual default assumption of equal relative uncertainty. The vertical axis represents the minimum reward threshold (R_c). Along the solid white curve ($R_c = R^*$), the robustness of the two decisions is equal; below the curve, the pine decision is more robust; above the curve, the Fynbos decision is more robust.

which is a stronger condition than that for the expanding-boxes model ($p = \infty$).

Ellipsoid uncertainty model with unequal relative uncertainty

Our final uncertainty model is an ellipsoid model ($p = 2$) with unequal relative uncertainty ($\psi_w < \psi_c$). In this case, it can be shown that we always choose decision q_N regardless of the value of R_c if $\psi_w/\psi_c < 0.161$, i.e., if the price of carbon is about six times more uncertain than the price of water. For larger values of ψ_w/ψ_c, the decision depends on the value of the critical reward threshold, R_c (Fig. 2).

Asymmetric uncertainty

A possible extension to the general info-gap uncertainty model defined by Eq. 3 would be to allow asymmetric uncertainty in the parameters to express, for example, the notion that there is greater uncertainty in the positive direction than in the negative direction (given a nominal estimated water price of \$0.10/m^3, we may consider a water price of \$0.20/m^3 more likely than a water price of \$0.00/m^3). One way to achieve this is to replace the uncertain parameters by their logarithms. In the present case study, this transformation actually has no effect on the results, because the reward functions are monotonically increasing in the uncertain variables and only uncertainty in the negative direction matters. In the terminology of info-gap theory, the uncertainty model based on the untransformed parameters and the uncertainty model based on the log-transformed parameters are expansion equivalent. However, it is quite easy to conceive of simple decision problems in which the two uncertainty models are not expansion equivalent (see Appendix B). The potential importance of this issue is explained in the *Discussion*.

DISCUSSION

This analysis demonstrates that optimal ecosystem service investments can be sensitive to assumptions

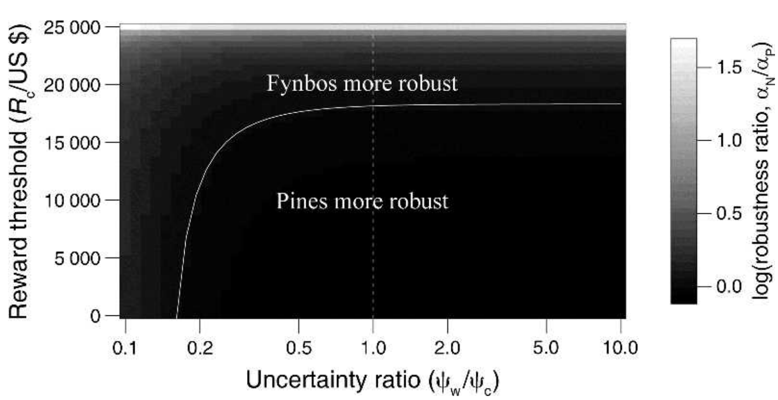

FIG. 2. Log ratio of the robustness values for the two land-use decisions, as for Fig. 1, but with an ellipsoid info-gap uncertainty model.

PLATE 1. Fynbos shrublands on a fire break in the Jonkershoek Valley, South Africa, with pine plantations (right) and more mature Fynbos (left) also visible in the background. Photo credit: R. A. Chisholm.

about uncertainty. For our case study in the South African Fynbos, conservation of native vegetation is more favored than establishment of a pine plantation when the uncertainty in the future carbon price is substantially greater than uncertainty in the future water price. Conservation is also more favored under info-gap theory's standard expanding-boxes uncertainty model, which treats uncertainties in different variables independently, than under the alternative ellipsoid uncertainty model, which considers combinations of uncertainties in different variables and is arguably more realistic.

It is apparent from the results that the relative uncertainties of the future prices of water and carbon are key to making robust decisions in this case study. In principle, info-gap uncertainty models can be refined if quantitative information about the uncertainty (e.g., standard errors) is available (Davidovitch et al. 2009, Yemshanov et al. 2010). In the absence of such information, the default "no-information" assumption is usually that relative uncertainty is equal across all uncertain variables. With regards to the present case study, quantitative information on the future prices of water and carbon is difficult to obtain. However, we do know that, in October 2010, the price of carbon on the European Union market was \$21/t CO_2 (Thomson Reuters Point Carbon, *available online*)[5] and that the price dropped from roughly 50% more than this to roughly 50% less than this in a four-month period around the end of 2008. Furthermore, there is uncertainty as to whether an afforestation project that eliminated native vegetation would be eligible for carbon credits at all (i.e., there may be 100% uncertainty in the carbon price). In contrast, there is obviously a permanent market for water in South Africa, which assures the future price of water to some degree. Thus, an uncertainty model with greater relative uncertainty in the carbon price (i.e., towards the left of Figs. 1 and 2) seems more consistent with the available information, and such an uncertainty model tends to favor the conservation option. At the very least, this analysis highlights the fact that an understanding of the relative volatility of carbon and water prices is essential for sensible land-use decision making in the Fynbos region. The more general point here is that sensitivity analyses on info-gap uncertainty models can clarify the decision-making process even if quantitative information on uncertainties is not available. The default assumption of equal relative uncertainty in most info-gap analyses in conservation biology and ecological economics may sometimes be a sensible no-information assumption. Often, however, the consideration of even qualitative estimates of relative uncertainty can refine the uncertainty model and, as shown here, lead to qualitatively different decisions.

Another aspect of info-gap uncertainty models that requires careful consideration is the rate at which uncertainty envelopes expand in the positive vs. the negative directions. In the Fynbos case study, for example, a water price of \$0.20/m^3 may be considered more likely than a water price of \$0.00/m^3, even though they are equidistant from the point estimate of \$0.10/m^3. Many applications of info-gap theory to problems in conservation biology and ecological economics, including the present one, avoid this problem of asymmetric uncertainty because their reward functions are mono-

[5] http://www.pointcarbon.com/

tonic with respect to the uncertain variables and/or because they are only concerned about being wrong in one direction (e.g., Moilanen et al. 2006*a*, *b*, Nicholson and Possingham 2007). However, it is quite easy to devise biologically plausible info-gap problems whose output is not robust to asymmetric uncertainty (e.g., Appendix B). In principle, there are many ways to address this problem by incorporating the asymmetry into the uncertainty model. One particular approach of relevance to ecological examples is to log-transform uncertain variables where appropriate prior to analysis. The log-transformation model may be particularly applicable to quantities whose errors are expected to compound multiplicatively rather than additively (e.g., population sizes; see Appendix B).

The results of this study were also sensitive to the choice of the elliptic uncertainty model over the expanding-boxes model (compare Figs. 1 and 2). We suggest that the elliptic model more accurately represents an intuitive view of the world, because the expanding-boxes model effectively asserts that being in error by 50% about the carbon price but exactly right about the water price is "as wrong as" being in error by 50% for both prices, which is counterintuitive. However, this does not resolve the more general problem about which value of p to select for the model defined by Eq. 3 (i.e., the elliptic model corresponds to $p = 2$, but any other positive value of p could be plausible). One general insight is that the expanding-boxes model tends to favor scenarios that involve fewer uncertain variables (native vegetation conservation in our study), whereas the ellipsoid and other uncertainty models treat scenarios with different numbers of uncertain variables more equitably.

The methodological lessons from our study are broadly relevant to other ecosystem service decision problems. The most similar previous study to ours was an application to an Australian land-use decision problem in which managers faced a choice between native revegetation and establishment of a *Pinus radiata* plantation (McCarthy and Lindenmayer 2007). Because the Australian study did not rely on the standard equal relative uncertainty assumption of most info-gap models, and because each land-use scenario therein has apparently only one uncertain variable, it appears that the main result of that paper is robust (i.e., native revegetation is more robust as long as the cost of establishment is sufficiently small). However, it is not clear whether the same is true of other info-gap studies in conservation biology, the majority of which rely on the simple info-gap uncertainty model and have multiple uncertain variables (e.g., Regan et al. 2005, Moilanen et al. 2006*b*).

One limitation of our analysis is that we did not consider uncertainty in variables other than the values of water and carbon. In particular, we ignored uncertainty in the timber price, the fire return interval, or water yields under future climates (Chisholm 2010). The robustness of the conservation option is independent of the timber price, so accounting for that uncertainty would tend to move the optimal decision towards conservation. Likewise, the conservation option is more robust to uncertainty in the fire return interval, because fire reduces biomass and leads to increased water yields (although possibly decreased water quality in the short term) (le Maitre et al. 1996), but can completely destroy a timber resource and associated carbon values in plantations (Chisholm 2010). The issue of uncertain water yields under future climate change scenarios is more complex and deserves a separate analysis: Global climate change models predict lower rainfall for the Fynbos biome (IPCC 2007), which will make both Fynbos and plantations less economically valuable because lower rainfall means lower water supply and slower tree growth. Another broader limitation of this study is that it considers only utility from timber, water, and carbon values. Extending the utility function to include tourism, biodiversity, and existence values would again move the optimal decision towards conservation, as there is little evidence that alien pines provide such benefits.

The main conclusion of this paper is that ecosystem service investment decisions can be sensitive to our assumptions about uncertainty. In our case study, which uses the info-gap decision theory framework, afforestation of native Fynbos with pine plantations in South Africa appears to be a poor decision if we assume that the future carbon price is much more uncertain than the water price, but this result is sensitive to other assumptions about how the uncertainty horizon expands. We make the general recommendation that future ecological applications of info-gap theory should not rely only on the default expanding-boxes uncertainty model, but should ensure that uncertainty models accurately reflect available information, even if this information consists only of qualitative or rough quantitative estimates of relative uncertainty.

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Supplemental Material

Appendix A

Derivation of info-gap robustness formulae for the ecosystem services case study (*Ecological Archives* A022-039-A1).

Appendix B

Bacterial growth problem demonstrating the potential importance of asymmetric uncertainty in info-gap models (*Ecological Archives* A022-039-A2).