Conservation Biology

Conservation Practice and Policy

Minimizing the Cost of Keeping Options Open for Conservation in a Changing Climate

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Abstract: *Policy documents advocate that managers should keep their options open while planning to protect coastal ecosystems from climate-change impacts. However, the actual costs and benefits of maintaining flexibility remain largely unexplored, and alternative approaches for decision making under uncertainty may lead to better joint outcomes for conservation and other societal goals. For example, keeping options open for coastal ecosystems incurs opportunity costs for developers. We devised a decision framework that integrates these costs and benefits with probabilistic forecasts for the extent of sea-level rise to find a balance between coastal ecosystem protection and moderate coastal development. Here, we suggest that instead of keeping their options open managers should incorporate uncertain sea-level rise predictions into a decision-making framework that evaluates the benefits and costs of conservation and development. In our example, based on plausible scenarios for sea-level rise and assuming a risk-neutral decision maker, we found that substantial development could be accommodated with negligible loss of environmental assets. Characterization of the Pareto efficiency of conservation and development outcomes provides valuable insight into the intensity of trade-offs between development and conservation. However, additional work is required to improve understanding of the consequences of alternative spatial plans and the value judgments and risk preferences of decision makers and stakeholders.*

Keywords: coastal squeeze, multiple objectives, spatial planning, uncertainty

Minimizando el Costo de Mantener Opciones Abiertas para la Conservación en un Clima Cambiante

Resumen: *Los documentos de política abogan que los administradores deben mantener sus opciones abiertas mientras planean proteger a los ecosistemas costeros de los impactos del cambio climático. Sin embargo, el beneficio de mantener la flexibilidad permanece en su mayoría sin explorar y los acercamientos alternativos para la toma de decisiones bajo incertidumbre pueden llevar a mejores resultados conjuntos para la conservación y otras metas sociales. Por ejemplo, mantener las opciones abiertas para los ecosistemas costeros incurre en costos de oportunidad para los desarrolladores. Diseñamos un marco de trabajo de decisión que integra estos costos con pronósticos de probabilidad para la extensión del aumento en el nivel del mar para encontrar un balance entre la protección del ecosistema costero y el desarrollo costero moderado. Aquí sugerimos que en lugar de mantener sus opciones abiertas, los administradores deben incorporar predicciones inciertas del aumento en el nivel del mar en el marco de toma de decisiones que evalúe los beneficios y los costos de la conservación y el desarrollo. En nuestro ejemplo, basado en escenarios plausibles del aumento del*

Paper submitted April 2, 2013; revised manuscript accepted September 26, 2013.

Conservation Biology, Volume 00, No. 0, 1–8

DOI: 10.1111/cobi.12238

nivel del mar y suponiendo que participa alguien que toma decisiones neutral al riesgo, encontramos que el desarrollo sustancial puede acomodarse con la pérdida despreciable de bienes ambientales. La caracterización de la eficiencia de Pareto de la conservación y los resultados del desarrollo proporcionaron una perspicacia valiosa para la intensidad de los equilibrios entre el desarrollo y la conservación. Sin embargo, se requiere trabajo adicional para mejorar el entendimiento de las consecuencias de los planes espaciales alternativos y los juicios de valor y las preferencias de riesgo de los tomadores de decisiones y las partes interesadas.

Palabras Clave: compresión del litoral, incertidumbre, objetivos múltiples, planeación espacial

Introduction

It is a widely held view that a wise approach to conserving biodiversity under climate change is to keep open as many future conservation options as possible (WRR 2007). When responding to the uncertainties arising from climate change, many governments, policy analysts, and organizations have advocated or adopted approaches that seek to keep future options. For example, the government of the Netherlands has given priority to keeping its options open in their climate-change policy (WRR 2007), whereas the Australian Government has been advised that priority should be given to options that address known threats and provide flexibility to follow alternative pathways in the future (Productivity Commission 2012). The city of Greater Geelong in Australia takes an approach that aims to "increase flexibility and keep options open" (CGG 2010).

However, there are costs to maintaining options that must be considered and balanced against the benefits, and the most cost-effective course of action may not always be the one that maximizes flexibility. A preference for maintaining or maximizing flexibility embodies a risk-averse attitude in which losses to a primary objective weigh on the decision maker's mind more than gains in secondary objectives. Relative to risk neutrality, risk aversion incurs opportunity costs. For example, the Byron Shire Council in Australia proposed a planned retreat policy to minimize risk of erosion to development over a 100-year period and to maintain natural beach processes. Buildings within 20–50 m from the erosion escarpment were to be relocated or removed (Byron Bay Shire Council 2010). This policy was controversial and not implemented. The opportunity costs of such actions can be substantial, given the concentration of economic activity in coastal regions and the high value of coastal lands (McGranahan et al. 2007).

Although it is reasonable for policy and management decisions that address the effects of climate change not to foreclose future options and to allow flexibility to respond to unforeseen circumstances, the idea of keeping options open is not a well-defined objective. Such objectives should identify precisely how much flexibility to maintain, the economic and conservation opportunity costs of achieving this flexibility, and how to most efficiently achieve the desired flexibility.

Uncertainty around future climate change and its impacts on biodiversity are a strong motivation to ensure flexibility in conservation planning (Wintle et al. 2011). One of the most uncertain and potentially largest impacts of climate change on biodiversity is from sea-level rise (e.g., Kopp et al. 2009; Rahmstorf 2010). Sea-level rise can lead to the loss of coastal wetland communities and their dependent species (e.g., Loucks et al. 2010; Traill et al. 2011), but the degree to which wetland communities are lost depends on numerous factors (e.g., rate of inundation and existing barriers to wetland migration) (e.g., Nicholls & Cazenave 2010). The extent of sea-level rise itself depends on future climate and physical processes (e.g., increased flow of water from melting glaciers to oceans), which are themselves uncertain (e.g., Zwally et al. 2002; Raper & Braithwaite 2006).

Decisions on how, where, and when to implement conservation actions that acknowledge sea-level rise involve consideration of multiple costs, including the cost of gathering better information to inform action (Runting et al. 2013), damage costs from sea-level rise impacts (Turner et al. 1995), economic opportunity costs of not developing land (Naidoo & Iwamura 2007), and conservation opportunity costs of not investing effort and money in other conservation activities. For policies that seek flexibility for conservation in the face of sea-level rise, the greater the aspiration for flexibility the greater the opportunity costs will be because flexibility is achieved by prohibiting development on land that may be important for the future migration of an ecosystem. It is challenging to implement policies that forgo potential development because of scientific uncertainty, especially when decisions affect property rights (Hanak & Moreno 2012). Pursuing the aim of maximizing flexibility without considering exactly how flexibility contributes to the long-term objectives of biodiversity conservation, and without due consideration of other costs, is likely to result in suboptimal outcomes. We sought to devise an approach to assess the trade-offs between conservation and development benefits that considers uncertainty in sea-level rise and compare the outcomes for conservation and development, when jointly optimized, with their outcomes when maximizing flexibility.

We investigated the conservation benefits and costs of preventing coastal development with the aim of conserving habitat for coastal ecosystem migration under

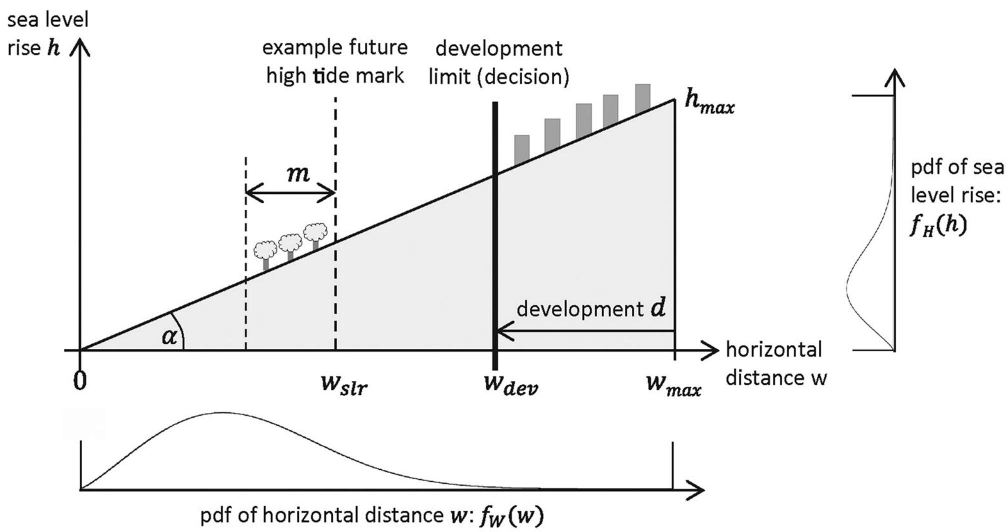

Figure 1. Coastal zone diagram and projections of sea-level rise. The wedge represents land that extends from the current high-tide mark (0,0) to the high-tide mark corresponding to the highest possible sea-level rise by 2100 (w_{max},h_{max}) and marks the current development frontier. The mangrove area extends horizontally m meters below high-tide mark. The development limit w_{dev} defines the horizontal distance over which development should occur to simultaneously provide sufficient conservation and development benefit (development is therefore allowed over a distance of $d = w_{max} - w_{dev}$). The lower graph shows the probability density $f_W(w)$ for the sea's horizontal advance (i.e., distance w based on the probability density $f_H(h)$ for sea-level rise h and the slope of the coast).

uncertain sea-level rise projections. We developed an analytical approach for trading off the benefits of future conservation options against the opportunity costs of delaying development in areas that may be important future conservation areas. We quantified the uncertainty in sea-level rise projections and assessed the consequences of alternative planning decisions on the extent of coastal development. Given data on a particular coastline, our approach can be incorporated into a decision strategy for climate-change adaptation that maintains an appropriate level of flexibility while balancing demands for land for conservation and development.

Methods

Model Description

We used a theoretical, linear coastline to assess the trade-off between conservation and development benefit in the coastal zone, given uncertainty in the extent of future sea-level rise (Fig. 1). The decision model contained 2 discrete time steps to measure the present and future benefits of a single planning decision made by a policy maker. Environmental benefit was quantified as the horizontal extent suitable for mangrove ecosystems at the second time step (the future), whereas the development benefit was measured by the horizontal extent of coastline where development is allowed (at present or with discounted value in the future). For simplicity, we assumed a constant grade α; thus, the relationship between height and horizontal distance of the inundation from the current tide line was linear (though our approach could be generalized to any profile). The current high-tide mark was our reference (horizontal distance $w_0 = 0$ and elevation $h_0 = 0$). The realized future high-tide mark, as a result of sea-level rise above h_0, was defined as h_{slr} and corresponded to a horizontal distance w_{slr} from the reference w_0. We defined h_{max} (and corresponding w_{max}) as the maximum sea rise projected under any emissions trajectory and climate model and assumed the development front (the lowest location allowed to be developed) was located at the maximum projected sea-level rise at the initial time step (the present). That is, managers keep their conservation options the most open by only allowing development above the worst case scenario for sea-level rise until the long-term extent of sea-level rise is known (i.e., all uncertainty is resolved).

Considerable uncertainty remains in projections of sea-level rise and in its regional variations (Church et al. 2011); therefore, h_{slr} (and its corresponding horizontal distance w_{slr}) was treated as a random variable. We estimated a probability density function $f_H(h)$ for global mean sea-level rise h_{slr} by the year 2100, relative to the year 2010, based on the weighted combination of model projections by Johansson et al. (2012) (Supporting Information). This is a probability density for the global mean for sea-level rise (without estimating regional variation [Supporting Information]). For tractability, we fitted a single probability density to the mixture of Weibull

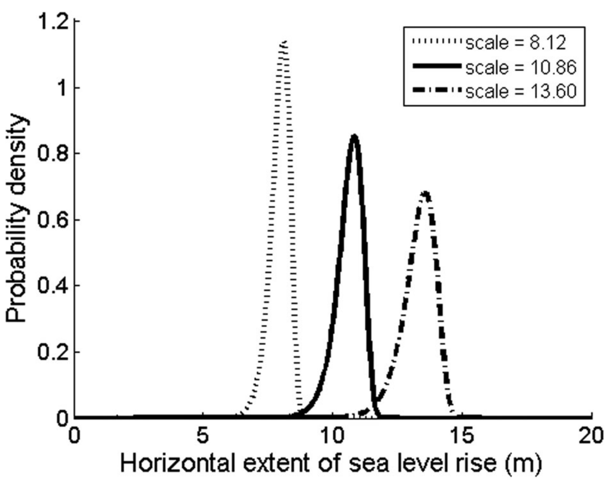

Figure 2. Probability density function used to describe sea-level rise based on Johansson et al. (2012). The resulting Weibull distribution had shape parameter 2.2 and scale parameter 10.86 and is used as our baseline.

distributions estimated by Johansson et al. (2012) and adjusted for observed sea-level rise to 2010. The resulting Weibull distribution had shape parameter 2.2 and scale parameter 10.86 (Fig. 2). The scale parameter of 10.86 represents a mean horizontal change in sea level of 10.86 m, which results from a mean vertical sea-level rise of 0.95 m. To demonstrate the effect of uncertainty in the estimate of the mean vertical sea-level rise on our 2 benefits, we also considered scale parameters with values smaller and larger than our best estimate of 10.86. That is, to assess the uncertainty around the mean sea-level rise we used 3 mean sea-level rise scenarios: 0.7, 0.95, and 1.2 m (representing corresponding horizontal extents of sea level change of 8.12, 10.86, and 13.60 m). All scenarios are within the 26–155 cm range of global mean sea-level rise suggested by Johansson et al. (2012). Varying the scale parameter with a constant shape parameter suggests one knows the general shape of the distribution, but mean sea-level rise is uncertain.

Assuming a constant slope of the coast, $\tan(\alpha)$, where α is the coastal slope angle, we translated a sea-level rise of h into a new high-tide mark that was at a horizontal distance $w = h/\tan(\alpha)$ from the current high-tide level. The probability density function of the horizontal change in the hide-tide mark, $f_W(w)$, was thereby derived from $f_H(h)$ and was also a Weibull distribution with scale $\lambda = \lambda_h/\tan(\alpha)$ and shape $k = k_h/\tan(\alpha)$:

$$f_W(w) = \begin{cases} \frac{k}{\lambda}\left(\frac{w}{\lambda}\right)^{k-1} e^{-\left(\frac{w}{\lambda}\right)^k}, w \geq 0 \\ 0, w < 0 \end{cases}. \quad (1)$$

We assumed a coastal slope of 5° (for the effect of varying the coastal slope angle, α, Supporting Information). The shape parameter of the probability distribution of sea level change in the horizontal direction was 2.2/tan (5°) = 25.15.

The area suitable for mangroves was located immediately below the high-tide level. For simplicity we assumed it was a band of constant horizontal width m, unless constrained by development (m = 0.2 wmax). The area suitable for mangroves therefore moved inland as the high-tide mark rose. We assumed there was no temporal lag in mangrove migration and no accretion of sediments counteracting sea-level rise (i.e., increase in potential mangrove ecosystem), though these assumptions could be relaxed by applying probability distributions for these variables.

A single planning decision was made at time zero, choosing a development limit w_{dev} that constrained how far development could proceed from its current position toward the sea. Land beyond that was reserved for conservation. Development was therefore allowed to proceed immediately a horizontal distance $d = w_{\max} - w_{\mathrm{dev}}$ from its original position. We assumed developers used as much of the coastline as permitted by the planning decision at time zero. If sea-level rise did not reach this development limit, the mangrove ecosystem below the new high-tide mark was unaffected. Conversely, if sea-level rise was higher than the development limit, the mangrove ecosystem was reduced. We assumed the full extent of long-term sea-level rise would be known with greater accuracy by 2030, the time of the second decision (Supporting Information). If projected sea-level rise was lower than w_{dev}, then any untapped development potential was used at the second time step.

Calculating the Benefits of Conservation and Development

We assumed planners desired to keep the mangrove ecosystem as habitat for coastal species and for storm protection (Barbier et al. 2011). We defined a conservation benefit of 1 if the mangrove ecosystem of width m was unconstrained by development. If the high-tide mark after sea-level rise, w_{slr}, was above the development limit, the available width for mangrove ecosystem was restricted. The reduction in conservation benefit was proportional to the width suitable for mangrove ecosystem (conservation benefit decreased to zero at the point where all potential mangrove ecosystem was in the development zone).

For a given realized sea-level rise w_{slr}, the conservation benefit (B_C) was defined as a piecewise linear function:

$$B_C(w_{\mathrm{slr}}) = \begin{cases} 1 & \text{if } w_{\mathrm{slr}} < w_{\mathrm{dev}} \\ \frac{m - (w_{\mathrm{slr}} - w_{\mathrm{dev}})}{m} & \text{if } w_{\mathrm{dev}} \leq w_{\mathrm{slr}} < w_{\mathrm{dev}} + m \\ 0 & \text{if } w_{\mathrm{slr}} \geq w_{\mathrm{dev}} + m \end{cases} \quad (2)$$

Development benefits accrued in the present and future, depending on the present development allowed by the initial planning decision and the future developments possible at the end of the planning time frame in the case $w_{slr} < w_{dev}$. Each horizontal unit developed provided a development benefit b (we set $b = 1$). After a planning decision was made, development was assumed to proceed to the limit w_{dev} allowed by the planning decision. This resulted in an immediate development benefit $b(w_{max} - w_{dev})$. If the long-term high-tide mark, w_{slr}, was below the development distance, w_{dev}, then the remaining land (between the former limit and the high-tide mark w_{slr}) would be released for development at the end of the time frame. This land would also be developed, but given that the benefits are obtained in the future, we applied time discounting to calculate the total net present value of the immediate and delayed developments. We assumed that if sea level rose beyond the planned development distance, then the benefit of development was still realized due to coastal protection measures, such as levees. However, this problem could be extended to include an associated cost for this option or other alternatives. For a given sea-level rise, w_{slr}, the total development benefit B_D was defined as

$$B_D(w_{slr}) = b\big[(w_{max} - w_{dev}) + \max(w_{dev} - w_{slr}, 0)(1 - r)^t\big], \quad (3)$$

where r is the discount rate ($0 \leq r \leq 1$). In a real project, the appropriate discount rate would depend on the rate of return that could be obtained from investing an equivalent capital expenditure into an alternative development. Here, we assumed $r = 0.05$. We assumed $t = 20$ years (i.e., long-term extent of sea-level rise would be known with certainty at $t = 20$). For a chosen development distance w_{dev}, the expected benefits of conservation and development, $E[B_C]$ and $E[B_D]$, respectively, were then computed with

$$E[B_C] = \int_0^{w_{max}} B_C(w_{slr}) f_W(w_{slr})\, dw_{slr}, \quad (4)$$

$$E[B_D] = \int_0^{w_{max}} B_D(w_{slr}) f_W(w_{slr})\, dw_{slr}. \quad (5)$$

We used the integrals $E[B_C]$ and $E[B_D]$ to compute the expected benefits of conservation and development, respectively, across all possible horizontal distances w by weighting the benefit obtained at distance w by the probability that the sea level rises to that distance. These integrals could not be calculated exactly, so we used the rectangle method to estimate them (values of w_{slr} in meters from 0 to w_{max} in steps of 0.025).

To compare the trade-offs between achieving conservation and development goals with the outcomes of maximizing flexibility, we plotted a trade-off curve (Pareto front) of conservation benefits against development benefits for all possible development limits. We used the trade-off curve to identify the relative benefits of allowing no current development to ensure maximum conservation benefits (i.e., keeping all future options open by withholding development until the extent of sea-level rise was realized or known) and setting intermediate development limits that allow a trade-off between conservation and development benefits.

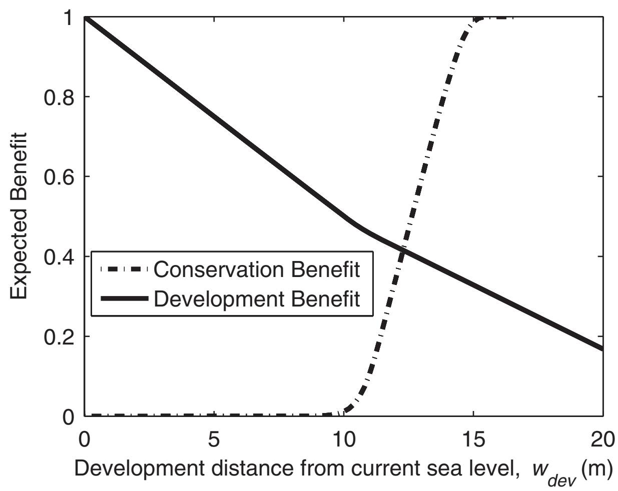

Figure 3. Expected benefits of conservation and development after 20 years as a function of the initial development limit (i.e., the horizontal distance over which development should occur to simultaneously provide sufficient conservation and development benefit) (Weibull scale parameter = 10.86).

Results

Model

As the distance between the development limit and the current high-tide mark (w_{dev}) increased the expected conservation benefit increased, but the expected development benefit decreased (Fig. 3). Sea level was expected to encroach land by roughly 10–11 m (Fig. 2). When the development limit was set within 10 m of the current high-tide mark, high development benefits were achieved but there was no conservation benefit because the tide line was directly adjacent to the development. No penalty was enforced on development because we assumed coastal protection was implemented to protect development, and this cost was not incorporated in our hypothetical example. When the development limit was set slightly above the predicted extent of sea-level rise (10–14 m; Fig. 3), the increased width of the protected zone achieved quick conservation benefits with only moderate costs to development. When the development limit was restricted beyond the predicted extent of sea-level rise (>15 m horizontal extent of sea-level rise in

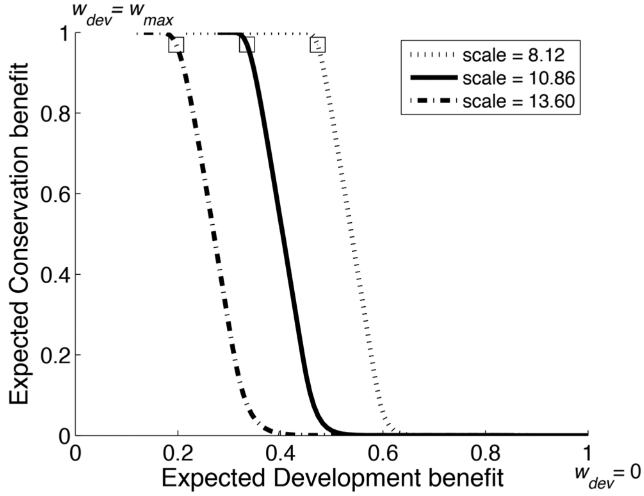

Figure 4. The trade-off curve (Pareto front) of conservation benefits against development benefits for all possible development limits. Each point along the curve represents a decision to allow development to extend a fixed distance from its current location toward the sea (distance $d = w_{max} - w_{dev}$). The location of a point along each curve illustrates expected conservation benefit (i.e., proportion of the mangrove area conserved) and the expected development benefit (i.e., proportion of the distance of maximal potential development). The square markers on each curve illustrate the development benefits achievable when conservation benefit equals 98% of the total possible conservation benefit. If we have low uncertainty about sea-level rise (Weibull scale parameters = 8.12), we achieve higher combined conservation and development benefits than when uncertainty is high (Weibull scale parameters = 13.60).

this example), continued restriction of the development limit produced development loses with no increase in conservation benefit.

These trade-offs were more apparent in the plot of the 2 performance measures used to characterize the Pareto frontier (Fig. 4). The relationship between conservation and development benefits was nonlinear, so a change in the extent of development had a disproportionate effect on the conservation benefit obtained. This effect was most pronounced when conservation benefits were very high and development benefits were low, and vice versa.

The benefits of keeping options open for conservation (i.e., selecting a relatively small value for w_{dev}) increased as sea-level rise increased (i.e., most benefit obtained with 1.2 m rise in sea level). The smallest sea-level rise scenario (0.7 m) provided a greater subset of development decisions that accommodated some development without compromising conservation benefits (flat portion at top of Fig. 4). For this subset of options, we considered only the option that yielded the highest development benefit (i.e., right-most point in the subset) because very little additional conservation benefit was gained by limiting development. Similarly, there was a subset of development decisions for which there were no conservation benefits. For this subset, we considered the option that yielded the highest development benefit (i.e., point farthest to the right in Fig. 4). The width of the Pareto curve was much broader when sea-level rise was high (1.2 m); hence, there was a greater range of development decisions that invoked a trade-off, whereby a gain in development came at a cost to conservation, or vice versa.

With a constant slope ($\alpha = 5°$) and a mangrove band of m=$0.2w_{\mathrm{max}}$, 98% of the expected conservation benefit was obtained and development benefits of 47%, 33%, and 20% were achieved for sea-level rise of 0.7, 0.95, and 1.2 m, respectively (squares on curves in Fig. 4). Allowing no development until sea-level rise is known (i.e., all options open for conservation) returned relatively low development benefits of 22%, 16%, and 12% for sea-level rise scenario of 0.7, 0.95, and 1.2 m, respectively. This loss in development was interpreted as the cost of keeping options open for conservation. Therefore, quantifying the uncertainty in sea-level rise resulted in a 119%, 99%, and 64% increase in development benefit (percent increase of 100% was equivalent to doubling the benefit) and <2% loss in total conservation benefit when compared with keeping all options open for sea-level rise of 0.7, 0.95, and 1.2 m, respectively. At the other extreme, when no conservation benefits were retained (i.e., <1% of conservation benefits, Supporting Information), there was a 3-fold (approximately 200%) improvement in development benefit as a result of considering uncertainty. This improvement occurred because development was allowed to proceed sooner rather than after observing sea-level rise over 20 years; thus, the present value rather than the discounted value of the development benefit was realized. The slopes of the trade-off curves were steep for all 3 values of the scale parameter (Fig. 4). Thus, for small decreases in development benefit there were large increases in conservation benefit. For example, foregoing 12%, 13%, or 14% of total development benefits for sea-level rise of 0.7, 0.95, and 1.2 m, respectively, resulted in conservation benefit increasing from 10% to 98% of total conservation benefits.

The extent to which there are decisions that benefit both conservation and development was determined by a combination of factors: shape parameters of the sea-level rise distribution, planning horizon, beach slope, and discount rate applied to development (Supporting Information). Uncertainty in the shape parameter made little difference to our results, over the range of values we explored (Supporting Information). Steeper beach slopes had Pareto fronts that shifted to the right; thus, more development benefit was achieved for a given conservation benefit. This was because areas with steeper slopes had less inundation for a fixed rise in sea level (Supporting Information). Increasing the discount rate applied to the development benefit shifted the Pareto frontier to the left; this meant less development benefit was achieved for a given conservation benefit. The discount rate affected the expected development benefit, not the conservation benefit (Supporting Information).

Discussion

By incorporating uncertainty into planning decisions, less costly climate-change adaptation can be achieved than by aiming to keep all options open (Fig. 4). Our model showed opportunities for economic development without forgoing future conservation options and that maximizing future options is unlikely always to be the preferred response to uncertainty. While the extent of the trade-off between development and conservation benefits depended on model parameters, directly integrating uncertainty of sea-level rise in predictions of conservation and development costs allowed identification of options that achieved greater conservation or development benefits at no cost to the other objective. It also eliminated options that unnecessarily reduced one benefit for no gain in the other. Maintaining all options under uncertainty may lead to decisions that are unnecessarily costly from perspectives other than that of conservation. That is, the decision to cease development when it could have been allowed may result in foregone development benefits. Explicitly incorporating uncertainty into decision making and evaluating trade-offs between different competing goals makes for better decisions.

Our results were based on existing development being above the maximum projected rise in sea level. However, in many coastal areas, development has already closed many conservation options (Schlacher et al. 2007; Schmidt et al. 2012). Within these areas it is important to communicate that keeping options open is not possible anymore; the focus can then shift to minimizing loss of conservation values (Fig. 4).

In our simplified example, we assumed linear marginal value functions for conservation and development proportional to area (Barbier et al. 2008). But the real consequences for a 1 km^2 loss in biodiversity value or development value may depend in complex ways on variation in the particular land area and its spatial context. For example, a loss of 1 km^2 of mangrove could be a loss in an area of critical importance for an endangered or endemic species (e.g., tigers, Loucks et al. 2010) or a decrease in the land available for strategic development of critical infrastructure. Therefore, when applying this trade-off to real case studies, it is important to consider spatial variation and context when assessing the consequences of loss for development and conservation.

For the sake of comparison to a strategy that seeks to keep options for conservation open, we assumed the preference was to maximize development gains and tolerate a small (not $>2\%$) loss in conservation value. However, individuals vary in the value judgments that inform notions of acceptable trade-offs between conservation and development (Heath et al. 1999) and the degree to which they can tolerate risk for either of the objectives. Different stakeholders may assign quite different importance to the 2 objectives. Even if stakeholders can agree on an appropriate trade-off point under uncertainty, conservation and development interests may differ on how to handle risk. Eliciting the preferences and the risk attitudes of decision makers and stakeholders will help to elucidate the underlying value judgments at the heart of the decision (Keeney 2002).

One could also develop a dynamic model where decisions are made at more than one point, rather than a single decision in a 2-step model. A multiple decision-point model allows for adaptive management (McCarthy & Possingham 2007). Further, a dynamic model could also allow the option of removing development (with associated costs). Such a model might also have to anticipate the economic and political costs of regulatory decisions that change frequently.

Under some circumstances, gains in one objective could be made with relatively little cost to another objective. Nonlinear patterns in the response variables or in the value preferences of the decision makers can give rise to these opportunities because there are places in the decision space where the trade-offs are attenuated. We suspect these opportunities are considerably more common than political rhetoric suggests because nonlinear dynamics are more common than we admit. Nonlinear (e.g., threshold) responses are increasingly cited by scientists (Martin et al. 2009), and nonlinear preference structures (risk averse or risk-seeking) are more likely the norm than risk-neutral ones (Keeney 2002). The way to find solutions that benefit conservation and development is to be explicit about the decision structure, the expected system dynamics, and the values preferences.

We have characterized the uncertainty about sea-level rise as a "known unknown," this means we do not know what the extent of sea-level rise will be, but we are aware of our uncertainty and can characterize it probabilistically. We used a multicriteria risk analysis to understand the nature of the decision and to handle uncertainty appropriately. But the arguments for keeping options open may be grounded more in the fear of surprises that cannot be anticipated and, therefore, cannot be described with a probability density function. We demonstrated that there are costs to keeping options open, and these costs hold regardless of the nature of the degree of uncertainty. What is challenging about the situation is the difficulty in knowing whether those costs are warranted. We suggest that the best course of action is to articulate as many known unknowns as possible and subject them to the kind of decision analysis we used.

Balancing the conflict between the natural processes of wetland migration resulting from climate change and the maintenance of existing development in the coastal zone is one of the key challenges for coastal managers (Caldwell & Segall 2007), especially because uncertainties surrounding sea-level rise accentuate the existing trade-offs between development and conservation goals (e.g., Hanak & Moreno 2012). We devised a transparent way of determining the portion of the landscape on which approvals for development should be delayed given uncertainty about future sea levels and the economic costs incurred by delaying decisions. This approach is superior to simply keeping options open because economic benefits could be attained without forgoing future conservation options. We found a defensible balance between flexibility of future conservation options and economic development that affects future conservation options.

Acknowledgment

H.P., M.B., and M.M. acknowledge the Australian Research Council for funding support. J.J.L.M. was supported by the National Environment Research Program Decisions Hub.

Supporting Information

Details on the estimated probability of sea-level rise (Appendix S1), result of quantifying uncertainty (Appendix S2), and sensitivity analysis for our model (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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