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POLICY PERSPECTIVE

Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level

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Abstract

Among the biggest global challenges for policymakers is the development of land use policies robust to climate change impacts. While diverse fields can inform adaptation, integrated social-ecological assessment of the multiple adaptation options are rare and cannot be easily applied. Here, we build on past studies by undertaking an integrated fine scale and strategic allocation of sea level rise (SLR) adaptation options that can direct policy making. We use models of probabilistic SLR inundation, urban growth, and sub- and intertidal ecosystem migration, to investigate the impacts of different SLR adaptation strategies, and how these can be allocated to best achieve both development and conservation goals. Coastal adaptation will involve trade-offs among development and conservation objectives and these will vary based on the extent to which sea levels rise. There will be trade-offs between conservation objectives regardless of the adaptation options chosen, however, retreat does provide opportunities for enabling the expansion of coastal ecosystems inland. Local governments can save billions of dollars and minimize political conflict between conservation and development goals through integrated strategic spatial planning. Our planning approach both informs policy and is transferable to other coastal regions faced with a rising sea.

Introduction

Developing robust adaptation strategies to sea level rise (SLR) poses a serious challenge to policy makers globally (Nicholls & Cazenave 2010), and knowledge from diverse fields can be harnessed to inform adaptation options. SLR will increase the risk of permanent flooding of low-lying coastal land (Nicholls 2004), resulting in the forced migration of tens of millions of people this century (Nicholls *et al.* 2011). SLR will also change the distribution of vulnerable coastal ecosystems, such as mangroves and saltmarsh, and their provision of ecosystem goods and services (e.g., Arkema *et al.* 2013). Although progress has been made in developing SLR adaptation policies, assessments rarely include an integrated social-ecological assessment of the multiple adaptation options (Fankhauser 1995; Ng & Mendelsohn 2005; Nicholls & Tol 2006) and none show how such assessments can be applied in practice.

Resolving the trade-off between development and conservation goals is challenging in the context of SLR

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as adaptation strategies can mitigate or exacerbate SLR impacts (e.g., loss of coastal ecosystems; Nicholls & Tol 2006). Driven by the desire to protect existing infrastructure, coastal armoring through levees and seawalls (hereafter called "defend") has historically been the main response to an encroaching sea. This strategy typically prevents the spread of ecosystems, such as saltmarsh or mangrove inland (Nicholls & Cazenave 2010) resulting in "coastal squeeze." Coastal squeeze is defined as the loss of intertidal habitat "due to the high water mark being fixed by a defense or structure ... and the low water mark migrating landwards in response to SLR" (Pontee 2013). Alternately, managed realignment of the shore (hereafter called "retreat") is adopted in some regions such as the United Kingdom and Germany (Rupp-Armstrong & Nicholls 2007). Deciding which strategy to choose is driven by a mix of economic and environmental goals, including the maintenance of coastal wetlands, sustainable flood defenses and the creation of new intertidal habitats (Turbott 2006; Rupp-Armstrong & Nicholls 2007).

Scientists from different fields have developed state-of-the-art, spatially explicit models that predict inundation, urban growth and the ecosystem dynamics, all of which can inform SLR adaptation. SLR inundation models now include probabilistic estimates of the likelihood of inundation and can be integrated with the probability distribution of SLR (Leon *et al.* 2014; Mills *et al.* 2014). Meanwhile, models of urban growth and ecosystems migration have been used to inform land-use planning decisions in the context of SLR for development and conservation, respectively (Huong & Pathirana 2011; Runting *et al.* 2013). To date, these modeling approaches have not been integrated to resolve the growing conflict between development and conservation interests in the coastal zone (Table S1for review of existing literature).

We use systematic spatial planning to assess the optimal configuration and trade-offs involved in SLR adaptation, incorporating spatial models of inundation by SLR, urban growth (Liu 2012), and ecosystem migration (Figure 1, SI 2, Craft *et al.* 2009; Saunders *et al.* 2013). The analysis is based on costs of adaptation strategies and their contributions to development and conservation goals, translated to quantitative area-based objectives. Here, we assess the impacts of SLR on urban growth and coastal ecosystems and how the implementation of two adaptation strategies influence these impacts: (1) "defend," where areas subject to flooding are defended by building levees protecting existing housing development and (2) "retreat," where areas subject to flooding are purchased to permit inland migration of coastal ecosystems. We also assess how adaptation strategies can be strategically combined to provide a compromise between development and conservation objectives. The development and biodiversity conservation objectives were to allow for all coastal ecosystems and urban areas to reach their maximum projected extent.

Methods

We conduct our investigation in the coastal region of Moreton Bay Regional Council, Queensland, Australia (Figure S1); seaward of the metropolis of Brisbane, the fastest growing "mature" city in the world (Lasalle 2012), and landward of the coastal embayment of Moreton Bay. Marine and coastal ecosystems within Moreton Bay support significant populations of the International Union for Conservation of Nature Red-listed marine species (e.g., dugongs, turtles, and shorebirds), commercial fisheries, and high biodiversity (Chilvers *et al.* 2005). Our study region consisted of the area in Moreton Bay Regional Council with >5% probability of inundation (total area of 193 km^2).

We combined four spatially explicit models, at a 30 by 30 m resolution, to quantify the impacts of different coastal adaptation options to inundation by SLR and storm surge. We focus on impacts of adaptation on urban areas and the distribution and abundance of coastal ecosystems (Figure 1) and consider predicted changes of the extent of urban areas and migration of subtidal (seagrass) and intertidal (e.g., mangroves and tidal marsh) ecosystems by 2100. We estimated changes in the extent of "developed" areas to 2031, which includes urban and rural residential land, industrial and commercial land using a cellular automata-based urban growth model (Text S1, Liu 2012). Future distributions of coastal wetlands were modeled using the Sea-Level Affecting Marshes Model (SLAMM, Text S2, Craft *et al.* 2009) and the future distribution of seagrass was based on a local Moreton Bay model (Saunders *et al.* 2013, Text S3). The probability of coastal inundation due to SLR and storm surge from a 100-year storm was determined using a novel probabilistic approach combining uncertainties from errors in mapped elevation (Leon *et al.* 2014) and the probability distribution function for global SLR (Johansson *et al.* 2014; Mills *et al.* 2014; Figure 2, Text S4). Future SLR scenarios were based on likely SLR scenarios (66% probability of occurrence, in line with the Intergovernmental Panel on Climate Change (IPCC) standard for communicating uncertainty) and encompass the IPCC likely range for SLR for Representative Concentration Pathway scenarios 4.5, 6.0, and 8.5 (Stocker *et al.* 2013; Figure 3). Models predicted 27 km^2 of urban development (a 51% increase since 2011) and 72–102 km^2

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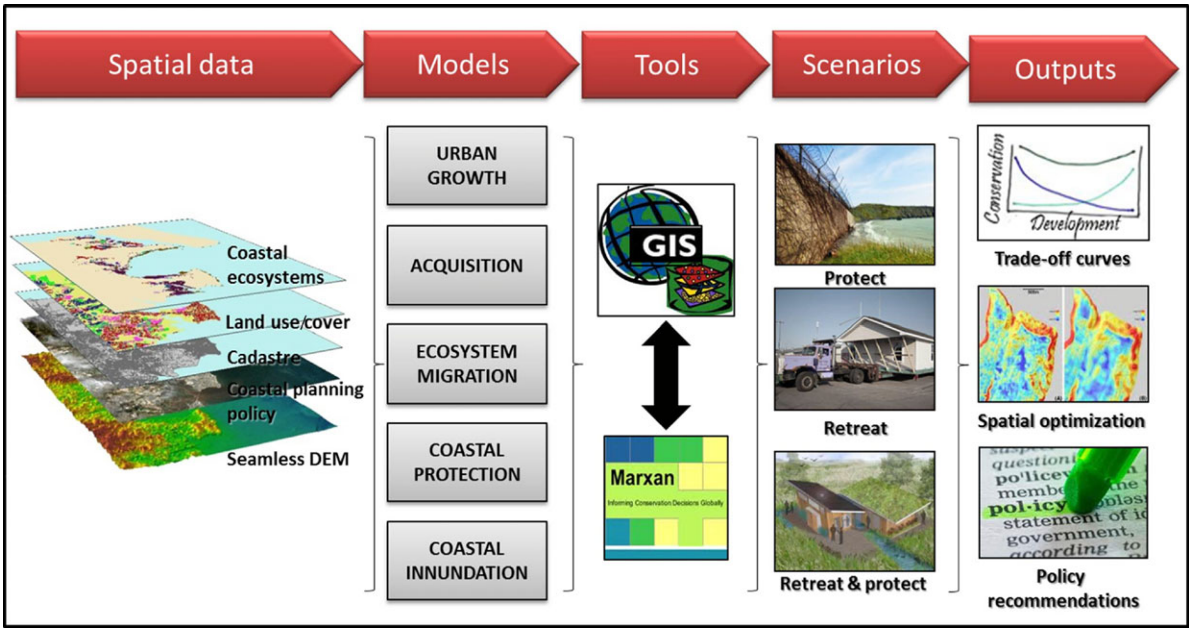

Figure 1 Flow chart of the process undertaken to plan for SLR.
Initially the spatial data were collected and models were processed independently. Impacts and trade-offs between different SLR adaptation strategies were assessed by combining models using geographic information system and systematic planning software. Finally, recommendations were provided of how policy should be adapted based on the results of this study.

of coastal ecosystems within the inundated region, 14% and 37–53% of the area with over 5% probability of inundation, respectively.

The time frame used for the urban growth model (2011–2031) was shorter than that used for the SLR and coastal ecosystem migration models (2011–2100) because of uncertainties in predicting urban growth accurately past existing infrastructure plans, which would hinder our ability to provide insight into different coastal adaptation policy options. We opted to assess the likelihood of potential coastal squeeze using a realistic scenario of urban growth to 2031 as opposed to a less realistic scenario that ran to 2100 given that the more defined model is likely to improve our policy recommendations. Given that the average life of a building is 75 years (Conti 2007), urban development existing in 2031 will be impacted by and interact with other SLR impacts in 2100. We modeled SLR to 2100 because the impacts of SLR become more apparent over longer time frames. The mismatch in model time frames results in a likely underestimate of the potential impact of SLR on urban development, and of urban development on ecosystems.

We used the systematic planning software Marxan to allocate the two common SLR adaptation strategies (Titus 1991). Marxan allows users to identify the location of multiple "zones" (i.e., adaptation strategies) and minimize the cost involved subject to the constraint that all objectives are achieved (Watts *et al.* 2009). Marxan uses a simulated annealing algorithm to identify near-optimal spatial configurations of adaptation.

Adaptation strategies were assessed individually and then in combination, providing a trade-off curve between the conservation and development benefits. The SLR adaptation strategies considered were: (1) Defense: where reinforced levees were built to defend existing and projected development. The cost associated with defense was estimated to be between AU$4,000–10,000 per meter of levee (pers. comm. Dr. Ian Teakle, BMT WBM; SI 6.1), and the length of levee required was calculated as that needed to surround the inundated edge of land parcels. For simplicity, we assumed the levee would be built using the most direct routes across the coastline where development (existing or future) had to be defended. We assumed that coastal ecosystems could no longer exist within land parcels that were defended by levees. (2) Retreat: this strategy refers to "managed realignment" of the shoreline, where the migration of ecosystems is facilitated though the purchase of land. For simplicity, we assumed that an adaptation strategy would be selected for groups of land parcels (hereafter termed planning units, $n = 306$) that would be collectively flooded because of their hydrological connectivity (based on topography and geographic proximity; Figure S1). Only a single adaptation strategy, defense or retreat,

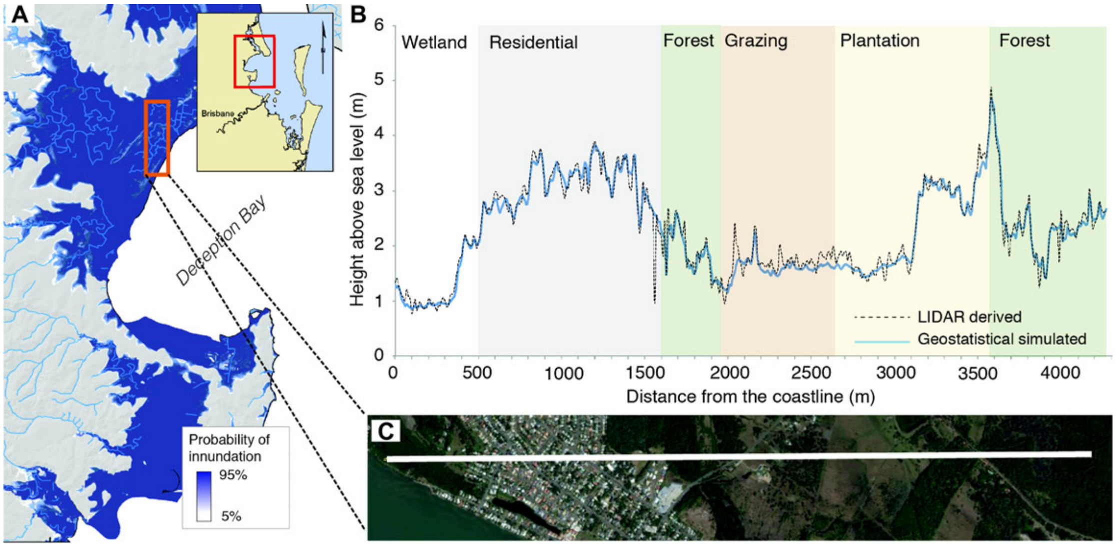

Figure 2 (A) Probability of inundation modeled in our study region, based on uncertainty of the digital elevation model combined with the probability distribution function representing global mean SLR (Weibull distribution scale 0.95 and shape 2.2). (B) Transect (white line in [c]), across a subset of the study region, indicating the different land covers encountered. The uncertainty in the digital elevation model varies across the transect and is influenced by land cover, as shown in (C). In (C), the difference between the LiDAR derived and the geostatistical simulated digital elevation model demonstrates the uncertainty in information on surface elevation.

could be allocated to a given planning unit. The cost associated with retreat was the current acquisition cost (improved or unimproved) of land parcels (Text S5). We assumed that development was no longer allowed in these properties (for additional details, see Table S2).

We quantified the costs of using information of the current and potential future spatial distribution of urban areas and coastal ecosystems and compared it to that of applying one adaptation strategy to the whole of the coastal region. We also quantified the difference in benefits and costs of using a strategic versus random approach to allocate different adaptation strategies across the landscape.

Results

We found that SLR is predicted to exert negative impacts on urban development, increasing risk on inundation, and mixed impacts on coastal ecosystems, increasing the total area of available coastal ecosystems but decreasing the number of ecosystems types. Approximately 18 km^2 (12%) and 10 km^2 (6%) of existing and future urban areas in the planning region is more than 50% and 95% likely to be inundated, respectively.

While SLR negatively impacts most coastal ecosystems (on an ecosystem by ecosystem basis), there are marked contrasts in the predicted response of coastal ecosystems to SLR, with some increasing in area dramatically (e.g., upper intertidal mangroves) and others almost becoming locally extinct (e.g., sedgelands, Figures S2 and S3). Therefore, regardless of the adaptation response, as coastal ecosystems are redistributed across space as a response to SLR, trade-offs will occur among conservation objectives. Choices will have to be made between allowing for the expansion of ecosystems and actively maintaining those ecosystems that are predicted to disappear (e.g., tidal marsh) by preventing the expansion of others (e.g., mangroves). The latter strategy can involve substantial costs and decisions are complicated by the value and conservation status (e.g., saltmarsh is protected by the Environment Protection and Biodiversity Conservation Act 1999) of the ecosystems or organisms at risk of being lost. Yet by 2100, if all ecosystems could migrate inland, there would be a net increase in the total area of coastal ecosystems of 17–78 km^2 (23–104%) compared to present day. The increase in the area of some coastal ecosystems with widespread coastal retreat can be regarded as an opportunity to increase fisheries production, water quality, and coastal protection.

The costs and benefits of defend versus retreat contrast markedly when strategies are considered individually. A strategy of defense across all potentially inundated areas of the study region would require 321 km of levees and would cost between AU$1.28–3.21 billion (depending on the cost of levees). With defense, the extent of all coastal ecosystems decreases significantly, ranging from a loss of 0.01 km^2 of sedgelands to loss of 71 km^2 of mangrove

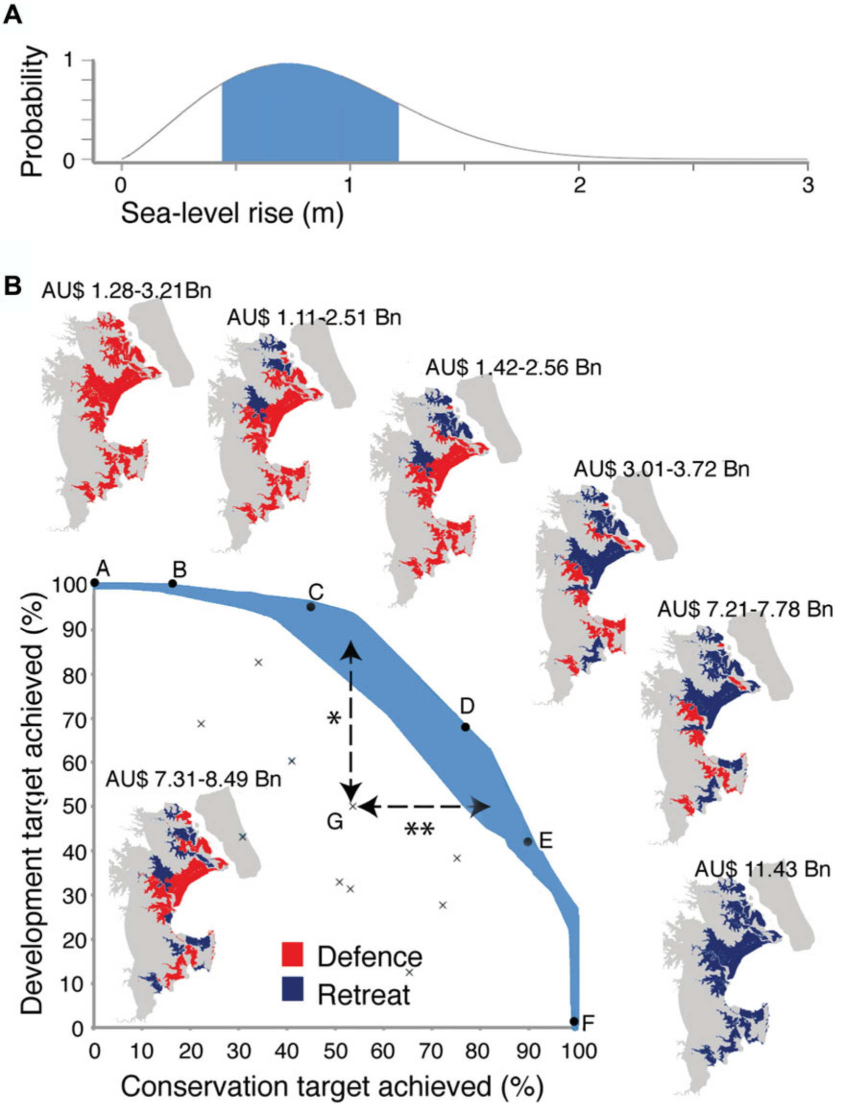

Figure 3 (A) Probability distribution function representing global mean SLR (Weibull distribution scale 0.95 and shape 2.2; Johansson *et al.* 2014; Mills *et al.* 2014). The blue shading on the curve represents the trade-off based on "likely" SLR scenarios (66% probability of occurrence, from 0.44 to 1.23 m). (B) Trade-off curve between conservation objectives (average % area of each ecosystem) and development (% area of urban development). Trade-offs are calculated for different SLR scenarios based on the global mean SLR probability distribution function represented in (A). The blue shading on the graph represents the trade-off based on "likely" SLR scenarios (66% probability of occurrence, from 0.44 to 1.23 m). Points represent the configuration of SLR adaptation strategies along the Pareto frontier (e.g., point A to F within the 0.98 m scenario). Point A and F represent scenarios where all land parcels have been selected for defense and retreat, respectively. The black crosses represent random allocation of coastal adaptation strategies (point G is illustrated by the map of the bottom left of the figure). "*" and "**" illustrate the gain in development and conservation objectives, respectively, by moving from a random allocation to a strategic approach to coastal adaptation. The range of costs for each scenario is calculated as the cost of land acquisition plus the cost of building a levee (AU$4,000–10,000 per meter).

(Tables S1 and S3, Figure S3). For the adaptation strategy of retreat, coastal ecosystems were predicted to expand by approximately 19 km^2 (17%) by 2100 (Figure 3). In order to halt development where coastal ecosystems will occur in 2100, land must be purchased for conservation, costing approximately AU$11.27 billion. This cost does not include the removal of existing coastal defense structures as this information is not available.

However, if it is assumed the relevant authority decides to either defend or retreat from each inundated land parcel (i.e., an adaptation option had to be assigned), cost-effective strategies are found by strategically combining both defense and retreat. These solutions are skewed toward achieving development objectives, because the cost of achieving the conservation objective of protecting all expanding ecosystems by retreat is generally higher than that of defense (Figure 3). However, there are hidden costs in the form of lost ecosystem services (e.g., fisheries, water purification, carbon storage) from coastal defense that, if factored in, could potentially make retreat a more attractive financial option. For example, defense would lead to 5–27 km^2 of mangrove and marsh loss, which in 1997 was estimated to have an average global value of AU$1.05 million per km^2 (U$9900 per ha) per year for the provision of ecosystem services (Costanza *et al.* 1997). This would equal between AU$0.2–1.3 billion loss in ecosystem services between now and 2100 (assuming linear ecosystem loss from 2014), making the total relative cost advantage of engaging in retreat decrease or disappear, thus emphasizing the benefits of an ecosystem

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approach to adaptation. Additionally, the risk of levees being overwhelmed or collapsing is not factored into this study. Failure of levees would mean an economic loss equivalent to or greater than that estimated for retreat, as development behind levees will often intensify as people assume their properties are protected.

While a trade-off exists between achieving conservation and development objectives, a concave trade-off curve (Figure 3) indicates that SLR adaptation strategies can be allocated within the study region to increase the delivery of one objective without a substantial impact on the other. A high proportion of both the conservation and development objectives could be achieved by a strategic allocation of a combination of adaptation strategies (Figure 3). Large gains of either development or conservation objectives can be attained, for a given conservation or development objective, respectively, by strategically allocating coastal adaptation measures with consideration of current and future distribution of coastal ecosystems and development. Even considering uncertainty in SLR, the gain in the achievement of objectives through the use of such models can be seen when comparing these with a random allocation of adaptation options (simulating decisions of adaptation undertaken locally, without insight into changes in ecosystems and urban areas). For example, the objectives achieved by random allocation of coastal adaptation G (Figure 3) could be increased by 30–45% for development or 28–40% for conservation, for a saving of AU$0.1–5.93 billion dollars in each case. However, there remains a trade-off between the percentage of development that can be defended from SLR and the amount of coastal ecosystem migration that may be facilitated through coastal retreat. For example, while 70% of both objectives can be achieved, achieving more than 80% of either objective results in a rapid decline of the other. Uncertainty in SLR impacts the trade-off between conservation and development objectives, with the impacts being increasingly uncertain when aiming to achieve over 40% of either of the two objectives. Notably, this trade-off is also habitat-specific and is only significant for most of the vegetation types after around 60% of the development objectives have been achieved (Figure S4). Trade-offs between and among development and conservation goals should be considered simultaneously as the interactive and potentially cumulative impact of multiple changes (e.g., ecosystem migration and coastal squeeze) can exacerbate negative impact on biodiversity.

Discussion

This study found that SLR adaptation strategies that consider the current and future distribution of urban areas and coastal ecosystems can substantially increase the achievement of conservation and development objectives given rising seas, achieving approximately 70% of both objectives and saving billions of dollars (see Figure 3B). We advance SLR adaptation studies by integrating cutting edge science from multiple fields. Previous studies have tended to focus on the costs of adaptation to achieve a single goal (e.g., Ng & Mendelsohn 2005; Nicholls & Tol 2006) or included relatively simple models defining change, based on large assumptions and considered to have high levels of uncertainty, thus providing only indicative results of impacts (Fankhauser 1995; Mills *et al.* 2014). Our study provides a clear direction for the implementation of adaptation options, grounded in the reality of the study region. Additionally, the ability to quantify the probability of inundation for individual properties increases the ability of decision makers to effectively incorporate and communicate risk when undertaking adaptation decisions. Our results can be incorporated in existing coastal plans, and can be updated within a dynamic decision-making framework as more information on the extent and impacts of SLR is gathered.

There are several important caveats to this study (Table S4). First, the time scales between the urban growth and SLR models were different (2031 vs. 2100) resulting in a conservative estimate of the area of urban expansion used in the trade-off analyses and a potentially low estimate of the costs of retreat, which could increase with increasing urban growth. In the future, researchers from multiple fields should codevelop models to ensure time scales match and facilitate integration. Second, predicting the future distribution of coastal vegetation in response to SLR is dependent on a number of assumptions simplifying ecological processes that vary spatially, temporally, and with environmental conditions. These assumptions could result in errors regarding the prediction of the coastal ecosystem extent as a whole and a change in the predictions of ecosystem transition from one type to another. Third, large-scale geomorphic (e.g., erosion and migration of channels or dunes) or climatic changes (e.g., frequency and intensity of drought and intense storms) were not encompassed by our models and can increase the erosion within the coastline, changing the predictions of ecosystem distribution. Finally, when considering adaptation, governments may need to undertake broader institutional reforms to expand the range of available options for progressively transferring private property to public use, such as by acquiring properties and granting back licenses or leases to occupy, rezoning land to public use, or placing restrictions on the sale or transmission of property (Titus 1991). Implementing such reform is politically difficult when societal settings

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favor short-term and private economic development objectives (Tol *et al.* 2003).

Adaptation to SLR is a complex problem involving social and ecological dimensions and there are several important future research directions that can build on this study to better inform policies for SLR adaptation. For example, incorporating a broader range of adaptation options, (e.g., accommodation can help people live with flooding while limiting impact to ecosystems), better incorporation of the human response to SLR and investigating how to optimally adapt through time. Understanding the preference of coastal dwellers and the preference structures (risk-averse or risk-seeking) will improve our understanding of what adaptation options are feasible.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Review of previous studies of SLR adaptation

Table S2. Details and assumptions of random and systematic SLR adaptation

Table S3. Ecosystem impacts of SLR adaptation strategies in the Moreton Bay Regional Council coastal zone planning region

Table S4. Model uncertainties

Figure S1. Study region, planning units, and levees.

Figure S2. Predicted ecosystem change scenarios.

Figure S3. Impact of adaptation to SLR on coastal ecosystems.

Figure S4. Trade-off between individual conservation and development objectives.

Text S1. Urban model.

Text S2. Digital elevation model and SLR mapping.

Text S3. Sea-level affects Marshes Model.

Text S4. Seagrass response to SLR Model.

Text S5. Land acquisition costs.

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