Costs and opportunities for preserving coastal wetlands under sea level rise

Rebecca K. Runting[1,2*], Catherine E. Lovelock[3], Hawthorne L. Beyer[2], Jonathan R. Rhodes[1,2]

1 School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane, 4072, Australia.

2 ARC Centre of Excellence for Environmental Decisions, The University of Queensland, Brisbane, 4072, Australia

3 School of Biological Sciences, The University of Queensland, Brisbane, 4072, Australia.

*Correspondence to: E-mail: r.runting@uq.edu.au

Abstract

Rises in sea level can alter the distribution of coastal wetlands through migration landward and loss due to inundation. The expansion of coastal developments can prevent potential wetland migration, exacerbating loss as sea levels rise. Pre-emptive planning to set aside key coastal areas for wetland migration is therefore critical for the long term preservation of species habitat and ecosystem services, yet we have little understanding of the economic costs and benefits of doing so. Using data and simulations from Queensland, Australia, we show that the opportunity cost of preserving wetlands is likely to be much higher under sea level rise than under current sea levels. However, we find that payments for ecosystem services can alleviate these costs, and in many cases may make expanding the reserve network profitable in the long run. This highlights the need to develop markets and payment mechanisms for ecosystem services to support climate change adaptation policies for coastal wetlands.

Introduction

Coastal ecosystems have important biodiversity values, with ~2,700 threatened species globally using these habitats for at least part of their life cycle (IUCN 2013). Additionally, coastal wetlands provide substantial benefits to humans through the provision of ecosystem services, such as the maintenance of fisheries, coastal protection, and carbon sequestration (Barbier et al. 2011). However, under sea level rise, coastal wetlands can be lost through inundation (Lovelock et al. 2015), but they can also migrate landward in the absence of steep gradients in topography or anthropogenic barriers, such as built structures (Kirwan & Megonigal 2013). The establishment of anthropogenic barriers to wetland migration could be prevented by pre-emptively expanding the coastal reserve network (i.e. adding to the set of protected areas) to accommodate wetland response to sea level rise. However, we know little about the likely costs and benefits of such an approach.

Global sea level rise is one impact of climate change that has seen recent upward revisions as further information becomes available (IPCC 2007; Church et al. 2013). These revisions, combined with the accelerated subsidence of deltas from anthropogenic activity (such as fossil fuel and water extraction and the trapping of sediment in reservoirs) (Syvitski et al. 2009), warrants urgent attention and the development of sound pre-emptive adaptation strategies. Despite this imperative, current spending on climate change adaptation remains low relative to the anticipated future costs (Parry et al. 2009). However, emerging markets for ecosystem services, such as the carbon market (voluntary or otherwise), may have the potential to relieve the financial burden of preserving coastal wetlands under sea level rise.

Previous studies have estimated the impact of sea level rise on coastal ecosystems (FitzGerald & Fenster 2008; Craft et al. 2009) and the species that depend on them (Traill et al. 2011; Iwamura et al. 2013), but none have quantified the costs of preserving wetlands under increasing rates of sea level rise and the potential of payments for ecosystem services to mitigate this cost. There has been a focus on the costs arising from human displacement or damage to private property and infrastructure (Dasgupta et al. 2009; Bin et al. 2011; Arkema et al. 2013; Hinkel et al. 2014), but there has been little consideration of the costs of preserving wetlands to facilitate their migration. Setting aside land for wetland migration has an opportunity cost, as this land might have otherwise been developed (e.g. for urban use) (Mills et al. 2014). Whilst the human element is undoubtedly important, it is vital that strategies to preserve wetlands under climate change are considered alongside anthropocentric impacts in order to conserve species and ecosystem services.

The aims of this research were to (i) determine if the opportunity costs of preserving coastal wetlands is higher under sea level rise compared to current sea levels, and (ii) determine the extent to which potential payments for ecosystem services can alleviate these costs. Here we show that, because coastal land value increases with elevation, coastal wetlands are likely to migrate into more expensive land with sea level rise, thus increasing the costs of pre-emptively preserving those wetlands. We also demonstrate that, even when the area of coastal wetlands is projected to expand under sea level rise, the cost of preserving these wetlands is still likely to be greater with sea level rise than without it. Despite the higher costs of preserving wetlands under sea level rise, we show that payments for ecosystem services have the potential to offset the opportunity cost of the reserve network.

Methods

To establish why preserving coastal wetlands might cost more under sea level rise we quantified the relationship between coastal land values and elevation for the state of Queensland, Australia. We then undertook a local scale case study to compare the cost of expanding the reserve system with and without sea level rise and payments for ecosystem services, to determine the change in costs and potential of ecosystem services (Fig. 1).

Coastal land value and elevation

To understand how land values vary with elevation we quantified the relationship between coastal land values and elevation for the entire 6,973 km coastline of Queensland. This coastline traverses 5 global ecoregions (WWF 2000) and 4 climatic zones (equatorial, tropical, subtropical and grasslands) (Stern et al. 2000), with human settlement patterns varying from urban to remote (Pink 2011). As extensive elevation data were required, we used a 1 second (~ 30 m) Digital Elevation Model (DEM) (Gallant 2010). We obtained unimproved land values for 2012 from the Queensland Valuation and Sales database (DERM 2013) and converted these into a value per hectare at a resolution of ~30 m (to match the elevation data). We then categorised the DEM into 100 classes based on 10 cm elevation increments up to 10 m above sea level. These categories were used to derive the mean land value for each 10 cm interval of elevation. To determine the effect of urban, regional or remote areas on this pattern, we separated the results based on the remoteness classes from the Australian Statistical Geography Standard Remoteness Structure (Pink 2011).

Wetland transition model

The Sea Level Affecting Marshes Model (SLAMM, (Clough et al. 2012)) was used to predict wetland transitions under sea level rise for a 600 km^2 section of Moreton Bay, Australia (Fig. 2). SLAMM simulates the main processes driving coastal wetland conversions and shoreline modifications under sea level rise, including salt water intrusion, erosion and sedimentation, wetland transition dynamics, and anthropogenic barriers to these dynamics (Craft et al. 2009; Clough et al. 2012). When executed, SLAMM calculates the relative change in elevation and associated wetland transitions for each cell in each year through to 2100. The inclusion of these processes at a fine spatial and temporal resolution enables SLAMM to give an accurate assessment of sea level rise, particularly when combined with LiDAR-derived elevation data (McLeod et al. 2010; Geselbracht et al. 2011). We parameterised SLAMM for Moreton Bay with a combination of field based and remotely sensed data for the area (Supplementary Methods). Moreton Bay was chosen because it is located near two urban centres (Brisbane to the north and the Gold Coast to the south) and contains a variety of ecosystem types, along with agricultural land. As the future rise in sea level is uncertain, we used a range of projections to 2100 (28 cm, 55 cm, 98 cm and 128 cm) from the IPCC's fifth assessment report (Church et al. 2013) to account for this variation (Supplementary Methods). This produced fine resolution (~5 m) simulations of changes in the distributions of wetlands for each year (2013-2100) for each SLR scenario.

Ecosystem services

Whilst there are a range of ecosystem services provided by coastal wetlands, we focused on quantifying and valuing soil carbon sequestration and nursery habitat value for commercially important species. To quantify soil carbon sequestration, we used local field measurements for the different wetland types, and applied a range of carbon prices from the voluntary carbon market (mean \$6.1 AUD MgC^{-1}) and estimates of the social value of carbon (from \$10.94 to \$96.94 AUD MgC^{-1}, Supplementary Methods). To determine the value of nursery habitat, we linked a potential levy on the gross value of production of three mangrove-dependent and commercially important species (*Penaeus merguiensis*, *Scylla serrata*, and *Lates calcarifer*) to the area of mangroves that interface with the ocean. When combined with the simulations of wetland change, this produced an economic value in each year to 2100 for both services for all properties within the study site. These values were discounted to form a net present value that was appropriate to compare with land values (Supplementary Methods).

Finding the optimal reserve network

We used integer linear programming to find the optimal reserve network for a range of wetland area targets for the least cost under sea level rise (Supplementary Methods). Each property parcel was either set aside for wetlands (i.e. protected), or assumed to be lost to future development. The opportunity cost was initially based on unimproved land values (plus a transaction cost), but in subsequent scenarios the capitalised value of payments for ecosystem services was subtracted from the opportunity cost for each property. Spatial dependencies among planning units were enforced, to allow for the process of wetland migration. The resulting reserve networks were compared across sea level rise projections and ecosystem service payment schemes, based on the total cost of the solution and the area of wetlands preserved within the reserve network.

Results

Land value and elevation

Our analysis of coastal land values and elevation for the coastline of Queensland, Australia showed a generally positive association between land value and elevation in the narrow coastal strip (up to 10 m above sea level, Fig. 2). The positive relationship was most apparent in major cities and regional settlements, but values were consistently low in remote areas (Fig. 2). This rise in land values for cities and regional settlements is likely due to the declining flood risk with elevation. The shapes of the curves differ as the confounding drivers of land value (such as slope, accessibly, and amenity) are regionally variable.

Cost of reserve network

We predicted a substantial change in the distribution and extent of wetlands under sea level rise for our case study in Moreton Bay, Australia (Fig. 3). Under the current reserve network, the landward movement of wetlands resulted in fewer wetlands protected under sea level rise. We estimated a loss of 4-31% of the current area of protected wetlands, with higher sea level rise scenarios resulting in lower levels of protection, despite an overall increase in wetland extent (Fig. 4).

Therefore, to maintain the area of wetlands protected under future sea level rise, additional resources are required to expand the reserve network to allow for wetland migration. Under the lower rates of sea level rise (28 and 55 cm), matching the current level of protection would only require a modest additional investment (up to \$40,000 AUD), yet a much larger investment is required under the higher rates of sea level rise (98 and 128 cm, a 377% [\$151,000 AUD] and 677% [\$271,000 AUD] increase respectively over lower rates of sea level rise) (Fig. 5 and Supplementary Fig. 1). Further, increasing the level of protection beyond current levels exacerbates the increase in cost even further. For example, under current sea levels, a 20% increase in the area of wetlands protected would cost \$105,000 AUD, with much of this target being met on public lands. However, as coastal wetlands move landward onto private land under the higher sea level rise scenarios, the required investment to match this target could be up to \$1.3 million AUD (a 1,138% increase over current sea levels, Fig. 5).

Payments for Ecosystem Services

Payments for ecosystem services have the potential to attenuate the opportunity costs of protection. We found that a carbon payment alone (at \$6.11 MgC^{-1} AUD) completely compensated for the cost of protecting an additional 32-33 km^2 of wetlands (a ~60% increase over the current reserve network) under the baseline (0 cm) and lower SLR scenarios (28 and 55cm, Fig. 5). However, under higher rates of sea level rise (98 cm and 128 cm), including a carbon payment only compensated for the cost of protecting an additional 20 km^2 and 15 km^2 (a 37% and 27% increase from the current reserve network) respectively (Fig. 6). Stacking carbon payments with a potential nursery habitat payment provided only a modest additional expansion over carbon payments alone (up to an additional 1.3 km^2 [~2% increase]), as the most cost-efficient areas for nursey habitat were already selected by a payment for carbon (Fig. 6). Protecting a smaller area of wetlands (than given by the above values) would be more than compensated for by ecosystem service payments, as the capitalised value of the ecosystem services exceeded the opportunity cost of the reserve network (Supplementary Fig. 2).

Discussion

We have shown that substantial changes in the distribution of coastal wetlands under seal level rise are likely to lead to increases the costs of protecting them. Consistent with other studies, we predicted a landward movement of wetlands (particularly mangroves) under sea level rise (Traill et al. 2011; Di Nitto et al. 2014; Saintilan et al. 2014) (Fig. 3b). This landward movement, combined with the positive association between land values and elevation (Fig. 2) drives the increase in cost of pre-emptively protecting wetlands to facilitate landward wetland migration under sea level rise. In fact we show that the higher the sea level rise projection, the higher the opportunity cost of expanding the protected area network (Fig. 5). This higher cost of preserving coastal wetlands is likely to be a general consequence of sea level rise, particularly in regions where the potential for urban development places further upward pressure on coastal land values.

Despite these higher costs, payments for ecosystem services have the potential to substantially reduce the net cost of expanding the reserve network under sea level rise. It is possible that the benefits from payments for ecosystem services could be further increased under different market conditions. For example, even more wetlands could be preserved if the carbon price reflected the social value of carbon (i.e. the total economic damages from emitting an additional 1 MgC^{-1}), or if these higher carbon payments were combined with those for the total value of nursery habitat. In both of these cases, the capitalised values of the services exceed the opportunity cost for all modelled wetland targets (up to 80% of the total wetland area in each scenario) (Supplementary Table 2). Furthermore, including payments for additional ecosystem services not quantified here, such as storm protection or nutrient retention, would likely increase the economic benefits of coastal wetland protection.

Whilst receiving payments for ecosystem services reduces the costs of coastal wetland protection for local planning authorities, this cost is shifted to the beneficiaries of the services. Carbon sequestration has potential buyers in both the public and private sectors, and transactions can be facilitated through the relatively well-established voluntary carbon market (Hamrick et al. 2015). In this case, shifting the cost burden to the buyer is unlikely to be problematic, as the buyers' participation is voluntary (such as individuals who purchase voluntary carbon offsets for air travel (Mair 2011)). In contrast, a nursery habitat payment shifts the costs to local fisheries via a compulsory levy. This may face opposition from commercial fishers if the additional cost is perceived to threaten the economic viability of their enterprise (Marshall 2007). Given that stacking nursery habitat payments with carbon payments facilitated only a modest additional expansion of the reserve network over carbon payments alone (~2%, Fig. 6), the additional administrative burden and potential controversy of a nursery habitat levy might not be justified in this case.

It is imperative that local planning authorities pre-emptively limit development in dryland areas that are likely to transition to wetlands under climate change. The primary difficulty in implementing this strategy is that the opportunity costs of purchasing properties or re-zoning land are borne immediately, whereas the benefits take much longer to materialise and often flow to beneficiaries external to the local area (Friess et al. 2015). Even when the capitalised value of payments for ecosystem services exceed the opportunity cost of expanding the reserve network, the revenue from ecosystem service markets would not start flowing until the wetlands had migrated sufficiently landward. This delay in receiving benefit could explain why this strategy is not adopted in many vulnerable areas, despite the long term advantages. For example, local and state governments along the USA Atlantic coast plan to develop 60% of land below 1m elevation (Titus et al. 2009), and

Australian state governments across the eastern sea board have removed sea level rise from state planning policies (Bell & Baker-Jones 2014). However, climate change adaptation policies are emerging in other areas, such as the Thames Estuary 2100 plan (for London and the tidal reaches of the Thames river) which incorporates a projected sea level rise of up to 1.9 m and includes provisions for intertidal habitat creation (Environment Agency 2012).

Given the dynamic nature of land markets under sea level rise, coastal land may be cheaper in the future as flood risk increases (Bin et al. 2011). However, this does not necessarily justify local planning authorities delaying the purchase or re-zoning these areas. If new dwellings or other hard structures are permitted in the potential future locations of wetlands or their migration pathways, this will not only impact biodiversity through arresting wetland migration, but will also have socio-economic impacts. For example, the costs may be shifted to the coastal property owner who may face reduced property prices, periodic flooding, or relocation in a worst-case scenario. Furthermore, it may not always be the case that the cost of coastal land will decline. Despite increasing risks, coastal populations are large and growing (Martínez et al. 2007), which is likely to create upward pressure on land prices in future (Glaeser et al. 2005). Furthermore, future risks may not be given appropriate consideration (Newell et al. 2015), particularly if insurance companies are able to compensate damages (Bagstad et al. 2007) or the impacts of sea level rise are predicted to occur outside of the investors’ outlook.

We have shown here that payments for ecosystem services can alleviate some of the costs of expanding the coastal reserve network under climate change, and in many cases may result in a profit in the long run. These cost reductions are possible because the costs are shifted from planning authorities to the beneficiaries of the services, which may not always be well received. Higher rates of sea level rise can reduce the effect of payments for ecosystem services, which highlights the importance of ambitious climate change mitigation efforts alongside adaptation plans. Although profits are possible in the long run, planning authorities may be strained in the short term, as some of the revenue from ecosystem service payments would not be received until wetland migration occurred. Alternatively, delaying the implementation of climate change adaptation policy may risk losing key areas of coastal wetlands, the species they support, and services they provide.

References

Alongi, D.M. (2014). Carbon cycling and storage in mangrove forests. *Ann. Rev. Mar. Sci.*, 6, 195–219.

Arkema, K.K., Guannel, G., Verutes, G., Wood, S.A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M. & Silver, J.M. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Chang.*, 3, 913–918.

Bagstad, K.J., Stapleton, K. & D'Agostino, J.R. (2007). Taxes, subsidies, and insurance as drivers of United States coastal development. *Ecol. Econ.*, 63, 285–298.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C. & Silliman, B.R. (2011). The value of estuarine and coastal ecosystem services. *Ecol. Monogr.*, 81, 169–193.

Bell, J. & Baker-Jones, M. (2014). Retreat from Retreat – The Backward Evolution of Sea-Level Rise Policy in Australia, and the Implications for Local Government. *Local Gov. Law J.*, 19, 23.

Bin, O., Poulter, B., Dumas, C.F. & Whitehead, J.C. (2011). Measuring the impact of sea-level rise of coastal real estate: A hedonic property model approach. *J. Reg. Sci.*, 51, 751–767.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D. & Unnikrishnan, A.S. (2013). Sea Level Change. In: *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.* (eds. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clough, J.S., Park, R.A., Polaczyk, A. & Fuller, R. (2012). *SLAMM 6.2 Technical Documentation*. Warren Pinnacle Consulting, Waitsfield, Vermont.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H. & Machmuller, M. (2009). Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Front. Ecol. Environ.*, 7, 73–78.

Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D. & Yan, J. (2009). The impact of sea level rise on developing countries: a comparative analysis. *Clim. Change*, 93, 379–388.

Department of Environment and Resource Management (DERM) & Department of Environment and Resource Mangement (DERM). (2013). *Queensland Valuation and Sales (QVAS)*. Queensland Government, Brisbane, Australia.

Environment Agency. (2012). *Thames Estuary 2100 (TE2100 Plan) November 2012*. Environment Agency, London, UK.

FitzGerald, D. & Fenster, M. (2008). Coastal impacts due to sea-level rise. *Annu. Rev. Earth Planet. Sci.*, 36, 601–47.

Friess, D.A., Phelps, J., Garmendia, E. & Gómez-Baggethun, E. (2015). Payments for Ecosystem Services (PES) in the face of external biophysical stressors. *Glob. Environ. Chang.*, 30, 31–42.

Gallant, J. (2010). *1 second SRTM Level 2 Derived Digital Elevation Model v1.0*. Geoscience Australia, Canberra.

Geselbracht, L., Freeman, K., Kelly, E., Gordon, D. & Putz, F. (2011). Retrospective and prospective model simulations of sea level rise impacts on Gulf of Mexico coastal marshes and forests in Waccasassa Bay, Florida. *Clim. Change*, 107, 35–57.

Glaeser, E.L., Gyourko, J. & Saks, R.E. (2005). Urban growth and housing supply. *J. Econ. Geogr.*, 6, 71–89.

Hamrick, K., Goldstein, A., Peters-Stanley, M. & Gonzolez, G. (2015). *Ahead of the curve: State of the voluntary carbon markets 2015*. Forest Trends' Ecosystem Marketplace, Washington DC.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C. & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U. S. A.*, 111, 3292–7.

IMF. (2015). *Australia: Selected Issues. IMF Country Report No. 15/275*. International Monetary Fund, Washington, D.C.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

IUCN. (2013). The IUCN Red List of Threatened Species. Version 2013.1. [WWW Document]. URL http://www.iucnredlist.org

Iwamura, T., Possingham, H.P., Chadès, I., Minton, C., Murray, N.J., Rogers, D.I., Treml, E.A. & Fuller, R.A. (2013). Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations. *Proc. R. Soc. B Biol. Sci.*, 280, 20130325.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S. & Beach, R. (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. *Proc. Natl. Acad. Sci. U. S. A.*, 105, 10302–7.

Kirwan, M.L. & Megonigal, J.P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, 504, 53–60.

Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L.X. & Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, 526, 559–563.

Mair, J. (2011). Exploring air travellers' voluntary carbon-offsetting behaviour. *J. Sustain. Tour.*, 19, 215–230.

Marshall, N.A. (2007). Can policy perception influence social resilience to policy change? *Fish. Res.*, 86, 216–227.

Martínez, M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P. & Landgrave, R. (2007). The coasts of our world: Ecological, economic and social importance. *Ecol. Econ.*, 63, 254–272.

McLeod, E., Poulter, B., Hinkel, J., Reyes, E. & Salm, R. (2010). Sea-level rise impact models and environmental conservation: A review of models and their applications. *Ocean Coast. Manag.*, 53, 507–517.

Mills, M., Nicol, S., Wells, J.A., Lahoz-Monfort, J.J., Wintle, B., Bode, M., Wardrop, M., Walshe, T., Probert, W.J.M., Runge, M.C., Possingham, H.P. & McDonald-Madden, E. (2014). Minimizing the Cost of Keeping Options Open for Conservation in a Changing Climate. *Conserv. Biol.*, 28, 646–653.

Newell, B.R., Rakow, T., Yechiam, E. & Sambur, M. (2015). Rare disaster information can increase risk-taking. *Nat. Clim. Chang.*, in press.

Di Nitto, D., Neukermans, G., Koedam, N., Defever, H., Pattyn, F., Kairo, J.G. & Dahdouh-Guebas, F. (2014). Mangroves facing climate change: landward migration potential in response to projected scenarios of sea level rise. *Biogeosciences*, 11, 857–871.

Parry, M., Lowe, J. & Hanson, C. (2009). Overshoot, adapt and recover. *Nature*, 458, 1102–3.

Pink, B. (2011). *Australian Statistical Geography Standard (ASGS): Volume 5 - Remoteness Structure*. *Aust. Bur. Stat.* Australian Bureau of Statistics, Canberra, Australia.

Saintilan, N., Wilson, N.C., Rogers, K., Rajkaran, A. & Krauss, K.W. (2014). Mangrove expansion and salt marsh decline at mangrove poleward limits. *Glob. Chang. Biol.*, 20, 147–57.

Stern, H., Hoedt, G. de & Ernst, J. (2000). Objective classification of Australian climates. *Aust. Meteorol. Mag.*, 49, 87–91.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L. & Nicholls, R.J. (2009). Sinking deltas due to human activities. *Nat. Geosci.*, 2, 681–686.

Titus, J.G., Hudgens, D.E., Trescott, D.L., Craghan, M., Nuckols, W.H., Hershner, C.H., Kassakian, J.M., Linn, C.J., Merritt, P.G., McCue, T.M., O’Connell, J.F., Tanski, J. & Wang, J. (2009). State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environ. Res. Lett.*, 4, 044008.

Traill, L.W., Perhans, K., Lovelock, C.E., Prohaska, A., McFallan, S., Rhodes, J.R. & Wilson, K.A. (2011). Managing for change: Wetland transition under sea level rise and outcomes for threatened species. *Divers. Distrib.*, 17, 1225–1233.

WWF. (2000). G200 Maps (1999-2000) [WWW Document]. *WWF Glob.* URL http://wwf.panda.org/about_our_earth/ecoregions/maps/

Acknowledgements

We would like to thank Yann Dujardin for assistance with formulating the integer linear programming problem, Lochran Traill and Karin Perhans for providing a parameterised Sea Level Affecting Marshes Model, and Kerrie Wilson for comments on the manuscript. This research was funded by the Australian Research Council Centre of Excellence for Environmental Decisions and Australian Research Council Discovery Project DP130100218. RKR is supported by the University of Queensland – Commonwealth Scientific and Industrial Research Organisation (CSIRO) Integrated Natural Resource Management Postgraduate Fellowship. CEL is supported by the Australian Research Council Superscience project FS100100024. HLB is supported by the Australian Research Council Discovery Early Career Researcher Award.

Figure legends

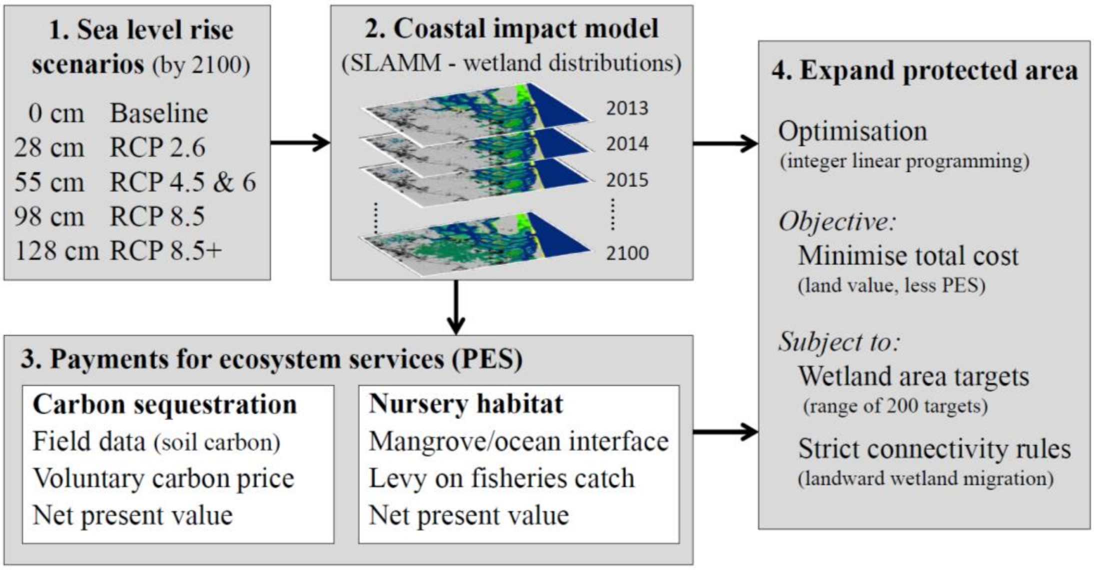

Figure 1 | Diagram of the methodology used to expand the reserve network under a range of sea level rise scenarios and potential payments for ecosystem services. The Sea Level Affecting Marshes Model (SLAMM) was used to simulate coastal wetland change under a range of sea level rise projections. This produced a map of coastal wetlands for each year to 2100 for as section of Moreton Bay, Queensland, Australia. Based on these wetland distributions, we modelled the provision of ecosystem services (carbon sequestration and nursery habitat for commercially important species) at each time step, and calculated the net present value of potential payments for these services (Supplementary Methods). Using integer linear programming, we then optimised the selection of additional wetland sites under the range of sea level rise projections and compared the resulting opportunity cost under different combinations of payments for ecosystem services. This allowed us to determine the potential of payments for ecosystem services to compensate the cost of reserve expansion under sea level rise.

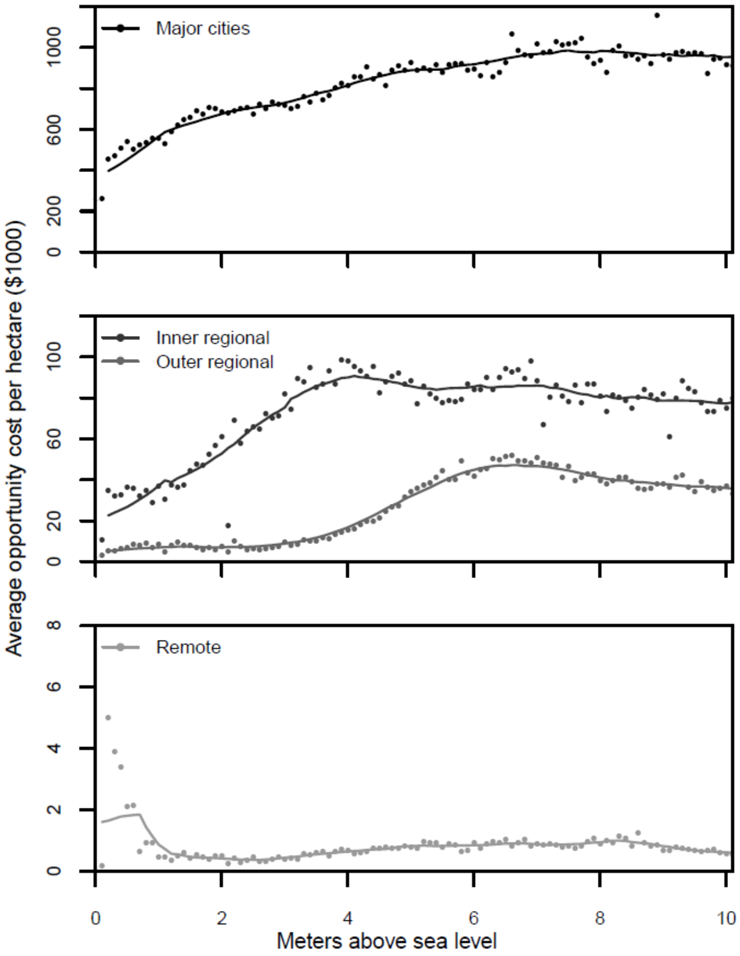

Figure 2 | The average value of coastal land at increasing elevation in Queensland, Australia, separated by remoteness class. The remoteness classes are categorised based on the level of accessibility to remoteness to various service centres via the road network (Pink 2011). Trend lines indicate the moving average.

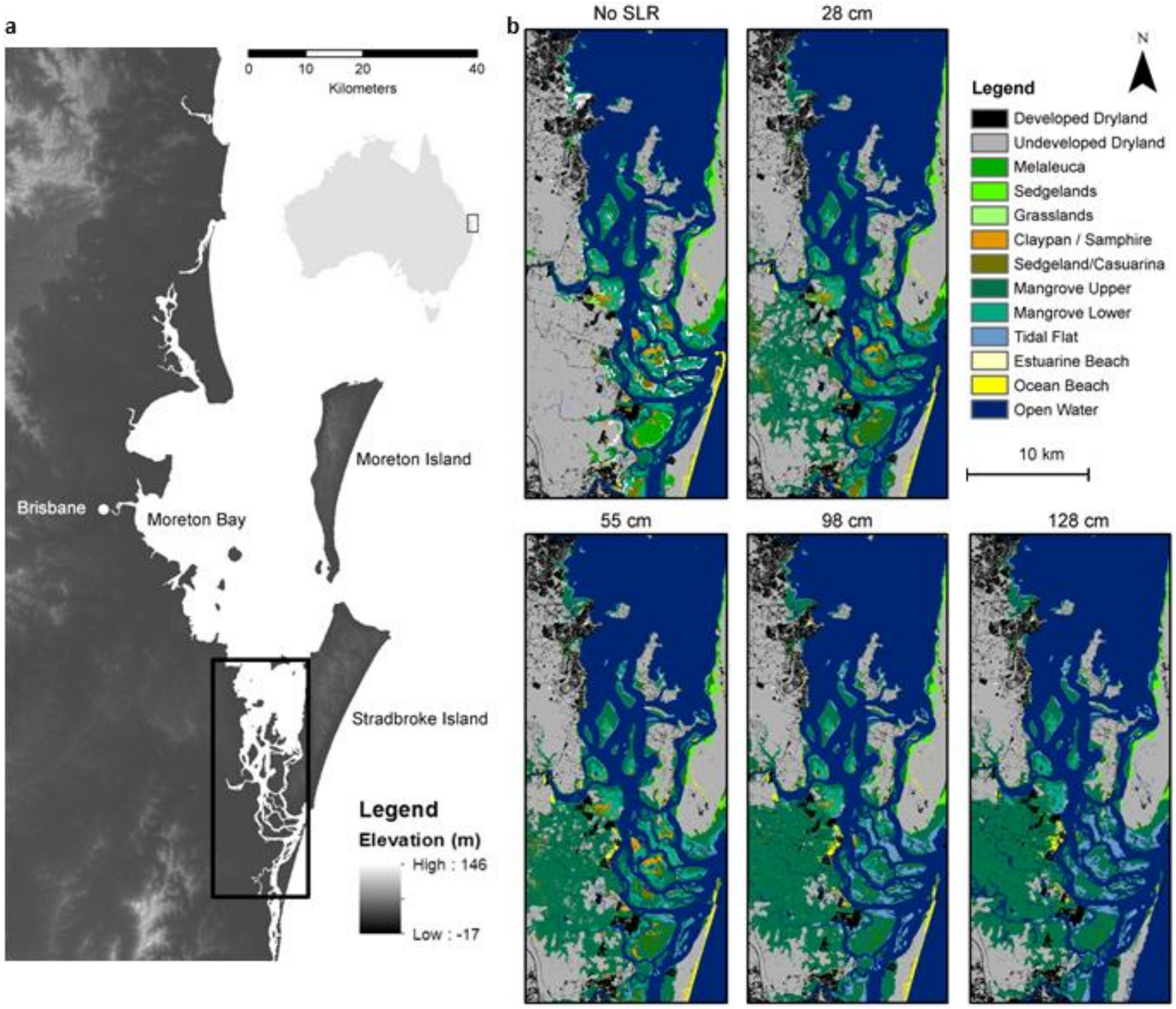

Figure 3 | The distribution of coastal vegetation in the south of Moreton Bay, Australia. Panel (a) shows the location of the case study (specifically latitude 27.3°S to S27.5°S and longitude 153.15°E to 153.25°E), and panel (b) shows the distribution of coastal vegetation in 2100 based on no sea level rise, a rise of 28 cm, 55 cm, 98 cm and 128 cm.

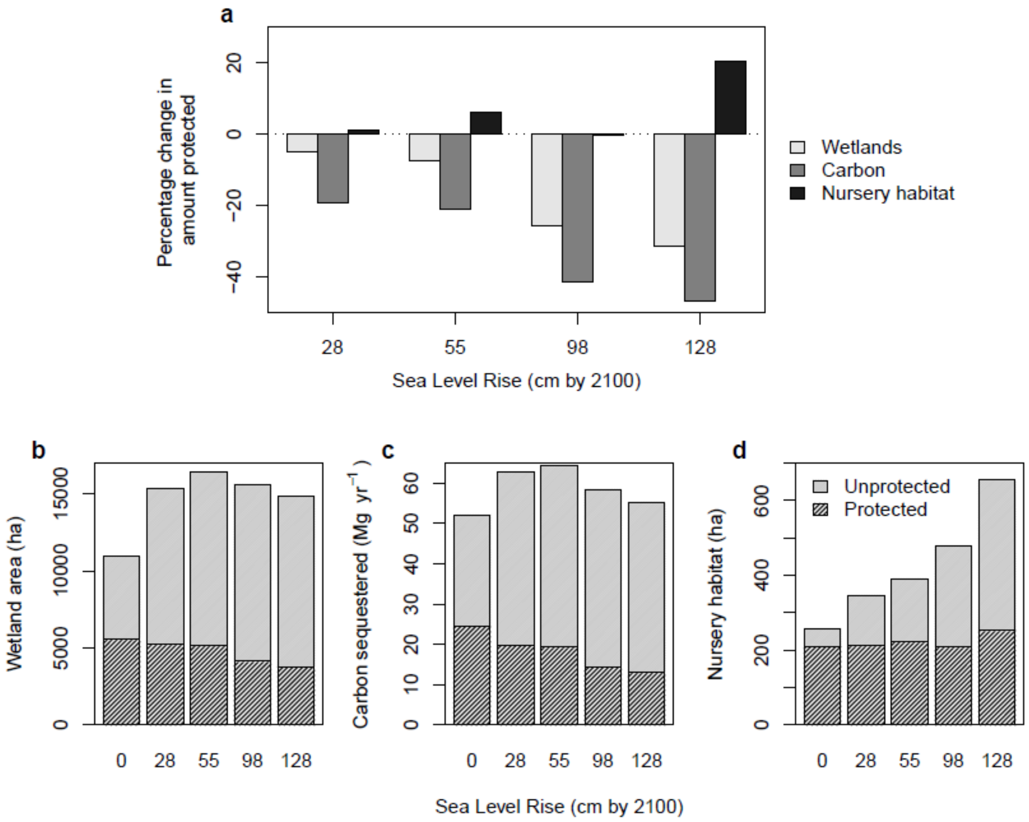

Figure 4 | The change in the provision of wetlands and ecosystem services under sea level rise. Panel (a) shows the percentage change in the area of wetlands (wetlands), amount of carbon sequestration (carbon), and area of nursey habitat for commercially important species (nursery habitat) under sea level rise based on the current reserve network. The remaining panels show the area of wetlands (b), amount of carbon sequestration (c), and area of nursery habitat for commercially important species (d) that would be protected and unprotected in 2100 based on the current reserve network in Moreton Bay. 'Protected' refers to areas that are currently contained within the reserve network, and 'unprotected' refers to all other areas.

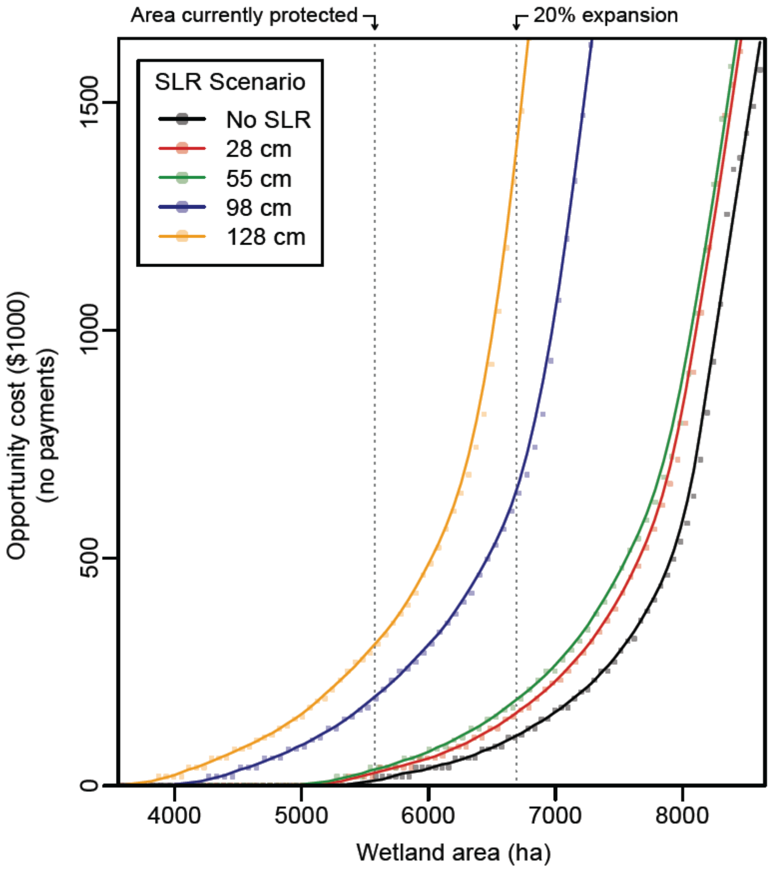

Figure 5 | The total cost of preserving increasing wetlands under different rates of sea level rise (SLR) in the absence of payments for ecosystem services. Dotted lines indicate the area of wetlands that are currently contained within the reserve network (5577 ha), and a 20% expansion of the area of wetlands protected (6692 ha).

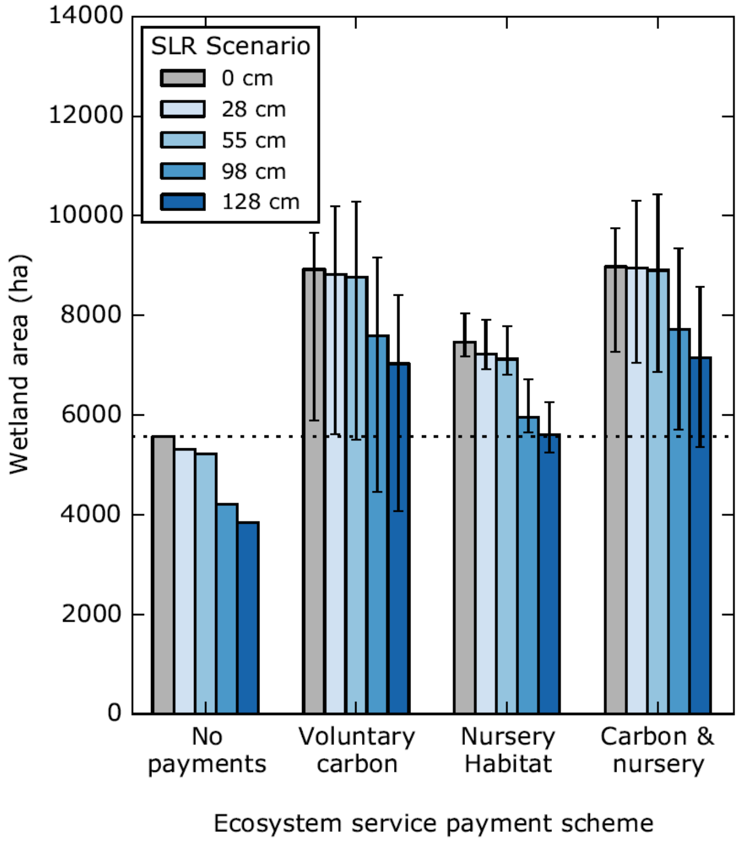

Figure 6 | The maximum area of wetlands that can be preserved and still 'break-even' ($0 cost) under different sea level rise (SLR) scenarios and payments for ecosystem services. The 'break even' point is where the capitalised revenue from ecosystem service payments exceeds the opportunity cost of expanding the reserve network. 'No payments' refers to the baseline case where there are no payments for any ecosystem services. 'Voluntary carbon' is the result of an active voluntary carbon market with recent (2012) carbon prices. 'Nursery habitat' refers to payments that could flow from a levy on the gross value of production for commercially important and mangrove dependent species. 'Carbon & nursery' is the result from stacking payments for carbon and nursery habitat. Error bars represent the minimum and maximum wetland area based on variations in discount rates, voluntary carbon payments, and the method used to calculate the amount of nursery habitat. The dotted line indicates the wetland area that is currently contained within the reserve system (5577 ha).