Implications of global warming and sea-level rise for coastal nesting birds in Bermuda

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Evidence from tide gauge and tectonic measurements world wide suggests that absolute sea level rose by approximately 20cm during the 20th century, but the rate of rise is accelerating and may attain 5mm/yr in the 21st century. This may be the highest rate recorded since the advent of human civilization. Bermuda has long been recognized as a tectonically stable platform and has been used as a benchmark for measuring glacial eustasy. Our own tide gauge measurements since 1930 support the global estimate.

This paper summarizes 50 years of subjective observations by the senior author on the effect of this sea level rise on mangrove, beach/dune and rocky coastal habitats and reviews additional objective research on mangroves. It also provides objective data on the impact of this rise on three species of seabirds which nest in the rocky coastal habitat - the habitat that comprises > 90% of Bermuda's coastline.

Two of the three species, the Bermuda petrel (Cahow) *Pterodroma cahow* and the white tailed tropicbird (Longtail*) Phaethon lepturus catesbyi* have suffered very significant effects, mostly within the last decade, and because both are highly philopatric, they are unlikely to relocate their breeding sites in time to avoid further harm.

The slowly increasing Cahow, is presently restricted to 4 tiny islets totalling < 1 ha. which are protected only partly from the open ocean by Bermuda's unique south shore boiler reefs. Between 1951 and 1995 the worst damage caused by storm waves or hurricane storm surge never affected more than two nesting sites at a time. Then in 1995 and again in 1999 storm surge from two major near-miss hurricanes completely over-washed two of the islets and caused severe erosion and cliff falls on the other two, trashing 40% of the nest-sites on both occasions The Cahow recovery team barely had time to repair the damage before the birds returned for their winter nesting season. Clearly, a direct hit category 3 or a late season hurricane at the beginning of the winter nesting season could be catastrophic. This rapidly growing threat results not only from sea level rise, but also from the predicted increase in frequency and severity of storms with global warming.

The tropicbird is Bermuda's most common coastally nesting seabird, with a breeding population estimated between 1500-2000 nesting pairs. Data from a survey of >200 marked nest sites in the Castle harbour island nature reserve, monitored by Wingate from 1973-1980 and resurveyed by Talbot beginning in 2001, has provided the greatest insight into the process and scale of nest site destruction/ creation, and the relative contribution of sea level rise, normal weathering and catastrophe events to this process.

From a global perspective, the threat to coastal nesting birds from sea level rise results indirectly from the sheer scale of anthropogenic development in coastal areas and our inevitable tendency to try and defend that development against sea level rise by the construction of coastal defences such as seawalls, sand replacement and landfill, rather than dismantling and retreating. By interposing our built environment and trying to hold the line against the natural landward pro-gradation of coastal

habitats that would otherwise occur, we are ultimately dooming both. This problem is already apparent along Bermuda's main island coastline where significant anthropogenic development has already occurred. In our attempts to defend this development from erosional encroachment, an increasing number of property owners are applying for planning permission to build concrete seawalls and other defences, which inevitably destroy the natural erosion cavities and cliff talus in which tropicbirds nest, not to mention the effects on the aesthetic beauty of our coastline. The Tropicbirds' nesting options are becoming increasingly constrained from above by human development and from below by sea level rise.

The only near-term option for helping both the Cahow and the Tropicbird has been to design and build *artificial* nesting cavities on the highest points of the islets and cliff tops in a manner that is safe both from sea-flooding and mammal predators. A longer-term project is being undertaken to attract the Cahow to nest on the much larger and higher predator-free Nonsuch Island.

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Introduction: The Case For Global Sea-Level Rise

Data from tide gauges, satellite altimetry and measurements of tectonic uplift and subsidence taken worldwide suggest that, after a long period of near stasis in the late Holocene, global sea-level rise began accelerating again in the 19th century and rose by approximately 20 cm during the 20th century. The rate of rise is expected to at least double again during the 21st century. The most recent estimates from climate modelling range from 19 to 71cm with a central value of 49cm (Sterr 1998). This would be the highest sustained rate of rise since the advent of human civilization and, whether or not the cause is primarily anthropogenic as most scientists now believe, it will have profound implications for both wildlife and human populations that live on our coastlines.

Bermuda is one of the smallest and most remote oceanic islands in the world, located at 32^{o}45'N and 64^{o}17'W and with a land area of 57 km^{2}. It has long been recognized as a tectonically stable benchmark for measuring glacial eustasy as recorded in its Pleistocene carbonate sediments (Vacher & Hearty 1989). Bermuda's tide gauge measurements, recorded since 1932 (Barnett 1984, Pirazzoli 1986) are not surprisingly, therefore, consistent with the global estimate of sea-level rise.

Due to the even more rapid sea-level rise of the early Holocene, >4000 years ago, most of Bermuda's coastline is already erosional, comprised mainly of sea-cliffed aeolianite dunes of marine carbonate sediment in various stages of cementation and diagenesis. Coastal cliffs, or low rocky shores and islets, presently make up 93% of the coastline, beaches comprise approximately 6% and mangroves only about 1%.

This paper summarizes fifty years of subjective observations by the senior author on the effect of the recent accelerating sea-level rise on Bermuda's mangrove, beach/dune and rocky coastal habitats and reviews additional objective research on mangroves. It also provides specific information on the impact of this rise on three species of coastally nesting seabirds, all of which nest in the rocky coastal habitat.

Effects of Sea-Level Rise on Bermuda's Coastal Habitats

1) Mangrove Habitat

In a classic study of the effect of sea-level rise on the rate of formation or destruction of mangroves,

carried out at Hungry Bay mangrove swamp, Bermuda (Ellison 1993), it was demonstrated that "low island" mangroves, i.e. those without any input of estuarine sediment, build at a rate of only 7-9 cm per 100 years and that any sea-level rise in excess of this rate results in erosion and destruction.

Ellison measured and dated the mangrove peat profiles of Hungry Bay in relation to ordinance datum (mean present day sea-level). Mangrove peat forms between mean sea-level and high water mark and has been shown to be a definitive sea-level indicator (Ellison 1989). Hence the dated stratigraphy in Hungry Bay provides several points for sea-level reconstruction.

Her data show that sea-level was rising at 25cm/100yr before 4000BP, 6cm/100yr between 4000BP and 1200BP and up again to 14.3cm/100yr between 1200BP and the present. As the rate of mangrove peat formation only exceeded sea-level rise in the period between 4000BP and 1200BP the mangrove swamp has probably been retreating for the last 1200 years. The stratigraphy near the mouth of the swamp not only confirms this, but provides an actual measure of the loss, which is 2.24 acres, nearly one quarter of the original area of 8.5 acres. Moreover, there has been direct visual confirmation of this process occurring at an accelerating rate over the past four decades.

The situation with continental mangrove swamps, or their salt marsh equivalent, where estuarine sediment input permits a more rapid build up of peat (up to 18.8cm/100yr) is somewhat better, but nevertheless now below the present rate of sea-level rise. As the land gradients in these two habitats are extremely shallow, just a few centimetres of sea-level rise can result in many metres of landward erosion and inundation following the Bruun rule (Bruun 1962), which states that increased wave erosion with higher sea-level removes sediment from shore faces in the upper part of the tide range and re-deposits it in the lower part, typically resulting in low cliffing of the peat along the seaward margin of mangroves or salt marshes.

There have already been huge losses of marshland important to nesting and wintering water birds in Louisiana from this process (Gosselink & Baumann 1980, Childers & Day 1990). Bermuda's mangroves are very diminutive, however, and do not in any case provide exclusive nesting or feeding habitat for any locally breeding species.

2) Beach/Dune Habitat

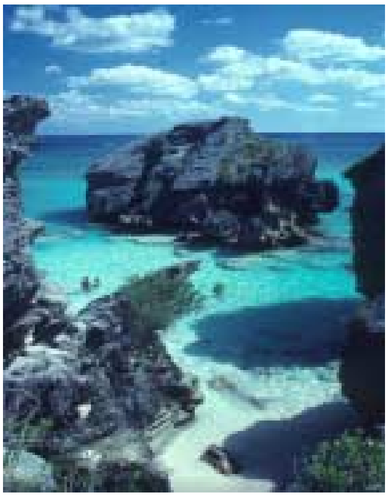
Bermuda's beach/dune habitat is more extensive than the mangrove habitat, primarily because the source material - carbonate sediments derived from the growth, respiration and decomposition of shallow water coral-reef and sea-grass communities and from re-cycled rubble and sand from coastal cliff erosion - has a much higher, and larger scale, depositional rate than mangrove peat in the tropical marine environment.

Although some sediment is lost through down-slope erosion off the edge of the Bermuda platform in storms and hurricanes, the generally high rate of sediment generation probably accounts for the fact that long-shore current derived beaches often front coastlines that are otherwise erosional, being backed by cliffs rather than beach dunes.

A high proportion of Bermuda's South Shore beaches are of this type and regularly wash away temporarily when major storms or hurricanes re-assert the long term erosional trend. As with mangrove swamps and salt marshes, erosion of beaches with sea-level rise follows the Bruun rule of landward pro-gradation, hence those beaches presently backed by cliffs will ultimately be lost.

This is not a good scenario for an island whose economy depends largely on tourism! Although beaches elsewhere are important as nesting habitat for certain shorebirds and terns, there are no present day beach nesting species in Bermuda.

3) Rocky Coastal Habitat



As indicated in the introduction, the rocky coastal habitat makes up more than 90% of Bermuda's coastline. Its ruggedly beautiful aspect is shaped by two fundamentally different erosional processes.

One is on-going and almost imperceptably subtle and slow in its effect and includes wind abrasion, freshwater solution and bio-erosion under the general heading of "weathering". (The dark grey surface colour that develops on our otherwise white aeolianite is caused by a blue-green algae (cyanobacteria) that colonizes the surface.)

The other process is stochastic but catastrophic in scale and caused entirely by hurricane waves. Fifty years of personal observation has convinced the senior author that the macro features of our coastline - those jagged ledges, stacks and gullies and huge blocks of fallen cliff and rock talus - have been shaped by major catastrophe events occurring at rare intervals on the order of a century, or even several centuries apart. Weathering provides only an aesthetic veneer to those features.

Effects of Sea-Level Rise on the Coastal Nesting Seabirds

Common tern

The common tern *Sterna hirundo* with a current breeding population of only 25 pairs, (Wingate, unpublished data) nests only on small rocky islets

located within Bermuda's larger enclosed sounds and harbours where their sheltered location from ocean waves makes them safe from all but hurricanes. Interestingly, a unique bio-erosional notch threatens to topple a few of the smallest islets in Harrington Sound, but if sea-level rise accelerates as predicted, these and some others will be submerged during the 21st century. This need not necessarily be a problem for this non-philopatric species, which can readily move to new locations. However, because the Bermuda tern population tends to nest territorially, one pair per islet, the population might decline further if the number of nesting islets declines.

Bermuda petrel or Cahow

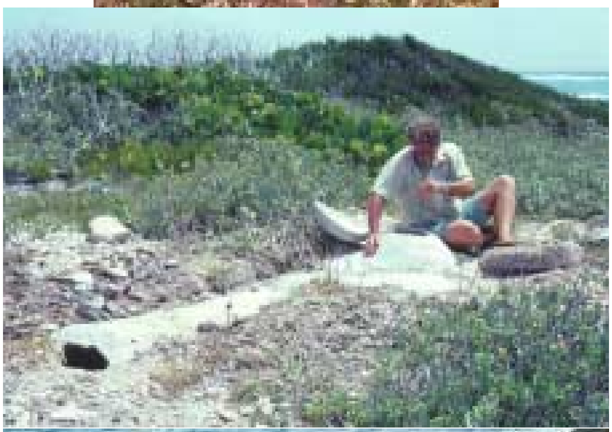
Of far greater concern is the endangered endemic Bermuda petrel or Cahow *Pterodroma cahow.* Pre-colonially this then super abundant seabird was an inland nester, excavating its burrows in soil under the forest. However, introduced mammal predators and human harvesting for food rapidly reduced it to the verge of extinction (Lefroy 1877). At the

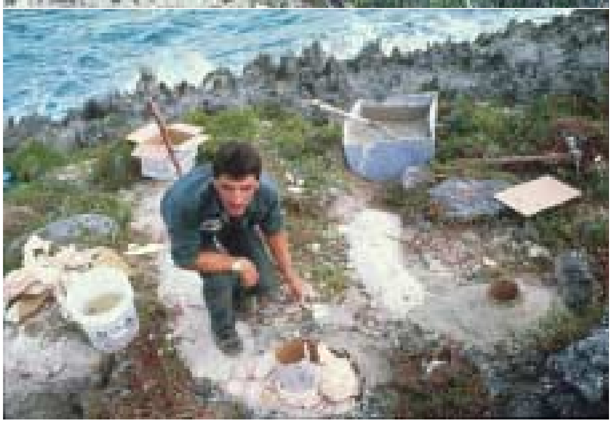
time of its rediscovery in 1951 (Murphy & Mowbray 1951), it survived only on a few tiny predator-free off-shore islets totalling less than one hectare in area and comprised exclusively of rocky

coastal habitat. Lacking soil for burrowing, the Cahow was forced to occupy erosional crevices in the coastal cliffs where it came into nest-site competition with the much more common White-tailed Tropicbird (Wingate 1978). Despite these limitations, an intensive conservation effort employing defences against tropicbirds and the

construction of artificial burrows has enabled it to increase from 18 pairs in 1961 (when the *entire* breeding population first began to be monitored), to 65 pairs in 2003 (Wingate 1985 and unpublished data).

The Cahow's nesting islets at the mouth of Castle Harbour are protected only marginally from the





open ocean by Bermuda's unique algal-vermetid "boiler" reefs (Ginsberg & Schroeder 1973).

Consequently they are extremely vulnerable to over-wash and wave erosion in major storms and

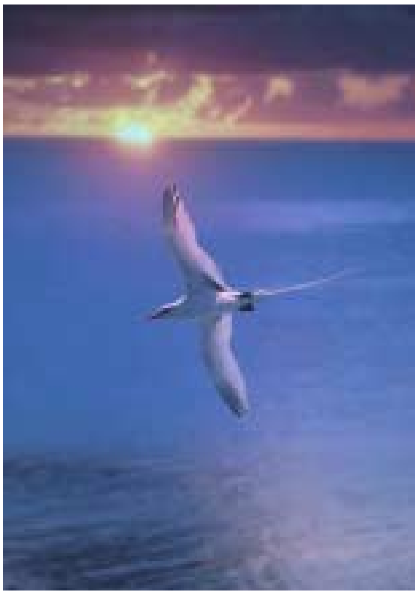
hurricanes. Between their rediscovery in 1951 and 1989, however, the worst damage experienced never affected more than two nesting sites at a time. Hurricanes Dean and Gabrielle in 1989

caused damage to six of the nest sites. Then in 1995 and again in 1999, storm surge and ground swell from two major near-miss hurricanes, Felix and Gert, completely over-washed two of the islets and caused major erosional damage to two others, trashing 40% of the nest sites on both occasions! The Cahow recovery team barely had time to repair the damage before the birds returned for their winter nesting season (Wingate 1995). These were category 2 and 3 hurricanes, which missed Bermuda by 40 miles and 125 miles respectively. Quite clearly a direct hit category 3 or 4, or a late season hurricane overlapping the beginning of the nesting season in late October or November, could be catastrophic. This rapidly growing problem results not only from sea-level rise but also from the predicted increase in the frequency and intensity of storms with global warming.

The Cahow is a very long-lived species with some breeding pairs occupying nest sites for 15 to 20 years before mortality disrupts them. They are also highly philopatric, with new pairs establishing closely adjacent to the pre-established pairs. Thus all of the population increase so far has been confined to the relic breeding islets. There is an urgent need to attract new pairs of Cahows to nest

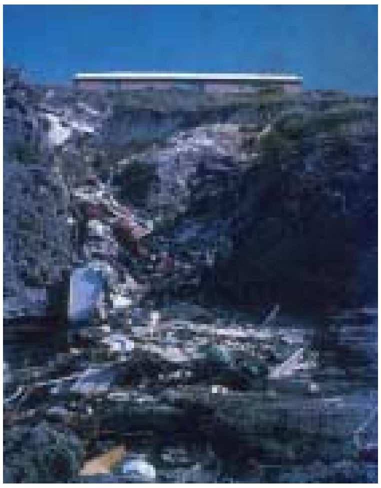
on larger and higher predator-free islands and the Nonsuch "Living Museum" nature reserve was established in 1961 with this ultimate goal in mind (Wingate 1978, B. Cartwright, L. Nash and D. B. Wingate 2001). Techniques have already been developed elsewhere for attracting petrels to new islands (Bell 1996, Podolsky & Kress 1989) and we hope to begin implementing these for the Cahow as soon as possible.

White-tailed tropicbird or "Longtail"



The White-tailed tropicbird or "Longtail" *Phaethon lepturus catesbyi* is the only pre-colonial nesting seabird of Bermuda which has survived in substantial numbers, owing primarily to its obligate cliff hole nesting niche which makes most of the nest sites inaccessible to the introduced mammal predators (Gross 1912). Like the Cahow,

it is a long-lived and highly philopatric species with some breeding pairs occupying nest sites for ten or more years before mortality disrupts them. An estimated 2000 breeding pairs still breed along most of the main island coastline and adjacent islets, but they are declining gradually for a number of anthropogenic reasons apart from the effects of sea-level rise. These include dog, cat, rat and American crow predation; competition from cliff nesting feral pigeons; coastal development by man; and blockage of nest sites by dumped vegetation and trash, or overgrowth by invasive alien plants (Wingate unpublished data).



The Castle Harbour national park islands are free of the foregoing problems but subject, like the Cahow islets, to ocean swells. This paper reviews data from a 200+ nest site study there; this was carried out by Wingate from 1970 to 1983, and revisited 20 years later by Talbot, beginning in 2001.

As the emphasis of this survey was on nest site parameters and breeding success, rather than biometrics, and tropicbirds tend to be more sensitive to human disturbance than Cahows or terns, the methodology was designed to be as non-invasive as possible. Birds were not handled or ringed and nests were checked only in late afternoon or at night when the birds were less active or sleeping.

As incubation lasts 43 days and fledging approximately 60, once monthly checks were determined to be adequate for confirming success or failure in more than 95% of cases. Birds remaining on nests overnight were assumed to be brooding an egg or chick even if the latter were not visible (chicks are brooded for about 20 days). The final nest check was timed to be as close to fledging stage as possible. Nest failures were usually confirmable by the presence of broken eggshell or a dead chick or by their disappearance well before hatching or fledging time. Nests which still contained healthy looking chicks close to fledging age were assumed to be successful if vacant on a subsequent check.

This survey has so far provided the clearest insight into the process, and scale, of nest-site destruction and creation resulting from normal weathering, catastrophe events, and sea-level rise, respectively.

Tropicbirds are able to play only a minor role in the excavation of nest sites because they nest primarily in a rocky environment. The basic requirements for a viable tropicbird nest site are: a sandy or soily substrate (they do not use nest material); protection from direct sunlight, at least in the hotter hours of the day; and shelter from the rain. Four types of cavities provide these conditions:

1. Eroded pocket holes in cliffs, generally formed where un-cemented sand replaced decomposed tree stems, roots or branches following burial by a dune in the younger aeolianites, but also formed by solution pipes and caves in the older and more modified aeolianites.

2. Deep erosional crevices where certain dune strata or accretionary soils have a lesser degree of cementation.

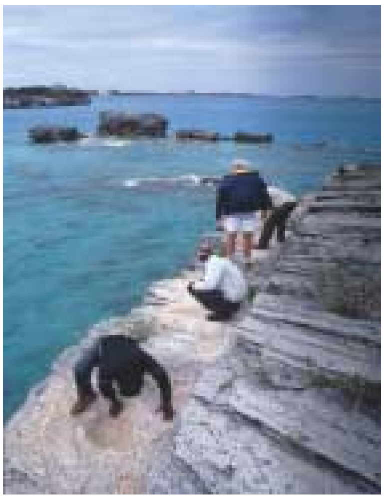
3. Cliff-fall rock talus, which provides natural cavities between rock slabs that gradually accumulate enough sand in them to become useable.

4. Sandy areas under dense vegetation. This last type of nest site is now very rare on Bermuda, and no longer viable on the main islands, because of greater exposure to rain and predators.

Our surveys revealed that weathering plays the major role in nest-site creation, with new nest-sites being created only gradually by differential erosion of the cliff faces and accumulation of sand or soil

in the cliff holes or under cliff-fall talus. Hurricane catastrophe events, on the other hand, play the major role in nest site destruction by causing cliff falls and re-working cliff-base talus, or by washing sand and soil out of the nesting crevices and back-filling or blocking them with rocks. These events are stochastic, resulting in immediate episodic losses of nest sites, which then requires many years or decades of normal weathering before new ones are created.

In the long term, rising sea-level should not cause an overall reduction of nest-sites except on the low relief islets where there are no higher options to escape sea flooding. On Bermuda's mainland, however, where interposing anthropogenic development along the coastline constrains the ability of the tropicbirds to find safe new nest sites higher up on the cliffs, this has become a major cause of decline. An effort is now being made to mitigate



this problem by developing specifications and designs for mass producible artificial nest sites safe from mammal predators, and requiring that they be included in any planning approval for coastal development

(Wingate 1988, Dobson 2002). There is an extraordinary opportunity here because tropicbirds have no aversion to nesting in close proximity to people; require only 0.5 cubic metre of nest cavity on land; and always land and depart directly from that nest cavity.

The approximately 25-year hiatus between the mid-point of our two tropicbird surveys has additionally provided a sobering indication of the scale of nest site disruption and breeding failure that has resulted from accelerating sea-level rise and increased intensity of storms (Table 1).

Over this quarter century period, an extraordinary 90 (45.7%) of the 197 nests in the original survey were destroyed, mainly by the hurricane events of 1995 and 1999. While 50 (24.5%) new natural nest sites out of 204 nests have gradually been created and colonized since the original survey, the

Table 1 Comparison of breeding success* in a predator-free population of white-tailed tropicbirds *Phaethon lepturus* nesting on the Castle Harbour Islands Nature Reserve, Bermuda, monitored from 1970 to 1983 and again in 2001-2002.
* % breeding success is defined here as the percentage of nests regularly visited by adults that fledged a chick, whether or not an egg was confirmed.

Original Survey (All natural nests)

Year	Occupied Nests	Fledglings	% Success
1970	118	87	73.7
1971	129	64	49.6
1972	128	90	70.3
1973	143	89	62.2
1974	166	121	72.9
1975	168	103	61.3
1976	169	121	71.6
1977	178	125	70.2
1978	179	119	66.5
1979	197	139	70.6
1980	191	134	70.2
1981	171	103	60.2
1982	No survey conducted		
1983	192	127	66.1
		Mean	66.6

Repeat Survey (Natural nests only *)

Year	Occupied Nests	Fledglings	% Success
2001	132	63	47.7
2002	130	65	50.0
		Mean	48.8

* The repeat survey includes a number of man-made or radically repaired natural nests which would not otherwise have existed or been useable following hurricane destruction. These have deliberately been excluded from this table in order to compare results as they would have been without human intervention.

majority are still so marginal that they are experiencing very low breeding success due mainly to crow predation and exposure to sun and rain.

This, plus increased short-term competition for the reduced number of optimal nests (which often results in vicious fights to the death), has lowered the breeding success in occupied natural nest sites from 66.6% in 1970-83 to 48.8% in 2001-2. This comparison is preliminary, of course, and may not be as statistically significant in the longer run, because the repeat survey has been under way for only two years, and one of the ten years of the original survey *did* have a breeding success rate that matches the current mean of the repeat survey.

It is worth mentioning here that the repeat survey additionally includes a number of man-made nest-sites that were rebuilt after the hurricanes or added to the survey islands after the initial survey. These were deliberately excluded from the foregoing breeding success comparison because they would not otherwise have existed. However, if we consider what percentage of the new survey they represent, particularly in regard to breeding success (Table 2), it becomes possible to get some idea of how many additional man-made nests might have to be provided in order to restore the breeding success to the level of the original survey.

Table 2 The results of the 2001-2002 survey with the data from the additional man-made nests included.

Year	Occupied Nests	Fledglings	%Success
2001	149	75	50.3
2002	155	79	51.0
		Mean	50.7

Conclusions

The evidence provided from these studies on Bermuda suggests that, on the global scale, we can expect an increasing trend towards erosional coastlines, resulting in an increasing proportion of rocky or cliffed coastlines and a proportionate loss of mangrove, salt marsh and beach/dune habitat. Provided that there is space for these habitats to pro-grade naturally inland, however, they can keep pace with sea-level rise to a varying degree.

The main problem arises from the sheer scale of anthropogenic development along coastlines and our obvious reluctance to abandon this built environment in the face of sea-level rise. In our efforts to protect, rather than abandon and retreat, we construct coastal defences such as sea-walls, sand-replacement and landfill and thus either destroy or block the natural landward pro-gradation of the coastal habitats. Taking a longer-term view, this approach can result only in the destruction of both the habitats and the species that breed or feed in them. Ultimately, of course, our built environment becomes doomed as well, when the rising costs of defending it can no longer be justified economically.

Acknowledgements

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