Scotland's Dynamic Coast – The National Coastal Change Assessment

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The Climate Change (Scotland) Act 2009 requires the development of an Adaptation Programme to take forward the risks identified within the UK's Climate Change Risk Assessment (UK-CCRA). The UK-CCRA anticipates increases in sea level, coastal erosion and coastal flooding to affect Scotland's soft coastlines and place at risk the assets found on these coasts. Accurate georectified historic coastal change rates allow the past and present coastline position to be established with confidence and provide the basis for future projections of coastline position. These projections, allow the early identification of coasts, hinterlands and assets that are inherently susceptible to erosion and which may become vulnerable in the future. Shoreline Management Plans have been produced for only short sections of the Scottish coast and so there is a need to provide accurate and up to date information available to coastal managers on a national scale.

To address this gap we report on the National Coastal Change Assessment (NCCA), commissioned by the Scottish Government, which aims to establish historic rates of coastal change and project these into the future. This was done by extracting time series georectified coastline positions from Ordnance Survey (OS) 1:10,000 maps) and comparing these with current coastal positions as defined by the Mean High Water Spring (MHWS) line extracted from the most recent Digital Surface Model (DSM) and corrected to OD using tide gauge data.

Using the historic coastal change rates the coastline position can then be projected into the future, mediated by the GIS-based Coastal Erosion Susceptibility Model (CESM). The function of the CESM is to limit potential erosion to areas where the hinterland is susceptible to erosion. At a 50 m raster resolution, the CESM models the physical susceptibility of the coast using a range of data (elevation, rockhead elevation, proximity to the coast, wave exposure, coastal defences, and sediment accretion) amalgamated into a single raster dataset to reflect erosional susceptibility. Using the current erosion rates, and projected future position of the coastline, combined with a number of socioeconomic datasets, key assets at risk from future coastal erosion can be identified. The outputs of the NCCA include reports, GIS datasets and webmaps.

Areas of present and future erosion were used to identify vulnerable socio-economic, cultural and archaeological assets. Taken together this information aims to inform existing strategic planning (Shoreline Management Plans, Flood Risk Management Planning, Strategic and Local Plans, National and Regional Marine Planning) and to target support toward areas and assets which may remain, or may become, vulnerable over the coming decades. This proactive and strategic approach to coastal erosion should enable more robust management policies and adaptation strategies to be developed.

Webmaps are available at www.dynamiccoast.com.

Ecological Enhancement of Coastal Infrastructure

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Globally, the coastal zone is under increasing pressure with rising sea levels driving coastal erosion and flooding which, together with coastal urbanisation, has major implications for coastal ecology and society and producing a worldwide profileration of hard engineering structures. However, such structures do little to replicate the topographic complexity and microhabitats found on natural rocky shores. They offer poor ecological surrogates for the natural environment, largely due to the physical differences between coastal armouring and natural shores (Firth *et al.*, 2014). To mitigate these negative impacts, ecological enhancement can be seen as a hybridisation of artificial structures, whereby components of nature are incorporated into the construction and design of hard urban structures to improve their sustainability, resilience and multifunctionality (Naylor *et al.*, 2012).

This paper reports on the largest UK experiment of ecologically enhanced surface designs, with 184 test tiles (15 by 15 mm) deployed on vertical concrete coastal infrastructure at three sites across the UK where the surface texture and complexity of tiles were varied to test the effect of settlement surface texture on the success of colonisation and biodiversity in the mid-upper intertidal zone using ecological and biogeomorphological theory. Tile designs included terrestrial laser scanning of creviced rock surfaces to mimic natural rocky shore complexity as well as artificially generating complexity using the computer software ‘Complexity for Artificial Substrate’ (CASU) (Loke *et al.*, 2014). In this way, the different designs replicated the topographic features of high ecological importance that are found on natural rocky shores and promoted species recruitment and community composition on artificial structures (Firth *et al.*, 2014).

Initial observations show that the control tiles, replicating the plain-cast texture of seawalls, have little to no recruitment at all shore heights across all sites. In contrast, higher colonisation can be seen on textured tiles throughout the mid-intertidal zone at all three sites. Of particular importance is that several tile designs have barnacle coverage of 40-75% in the upper shore zone at Blackness, compared to the 0% colonisation of the control at the same height. More complex designs of greater complexity (cm scale) did not perform as well as expected in barnacle recruitment, yet attracted a greater number of littorinidae, as the higher relief offered a greater refuge function. These initial observations highlight the importance of topographic complexity in the recruitment and colonisation of barnacle species. The tiles will continue to be monitored seasonally over the next year and a half, with additional monitoring performed throughout the settlement season.

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Tipping points in salt marsh and mangrove vegetation dynamics

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Salt marshes and mangroves are prime examples of non-linearly behaving ecosystems with critical transitions between bare and vegetated ecosystem states driven by biogeomorphic feedback mechanisms and external forcing (van de Koppel *et al.* 2001; Marani *et al.* 2010; Wang & Temmerman 2013; Balke *et al.* 2014). Their survival depends on sufficient vertical accretion with rising sea levels to avoid drowning and a balance between lateral retreat and new establishment on tidal flats. Whereas most studies have confirmed that vertical accretion in salt marshes can keep pace with current rates of sea level rise (if sufficient sediment is supplied), lateral dynamics still remain poorly understood (reviewed in Kirwan *et al.* 2016).

Balke *et al.* 2014 (2014) recently proposed the Window of Opportunity (WoO) concept to identify sudden transitions from bare tidal flat to salt marsh/mangrove vegetation. This concept highlights that stochastic variability of water levels and hydrodynamic forcing is essential to allow establishment of marsh and mangrove vegetation. A WoO is loosely defined as a minimum period below a critical level of external forcing which is required for an individual or entire ecosystem to gain sufficient stability against average external forcing. This enables a system to suddenly shift from the bare state to the vegetated state (and hence enter a sedimentation feedback loop) under otherwise disturbance-limited conditions. Such events can be extremely stochastic with years of no change and sudden progradation of the salt marsh in one growing season (Balke *et al.* 2014). Whether a tidal flat can shift from a bare to a vegetated state mainly depends on the temporal distribution of inundation and hydrodynamic forcing (i.e. tides and currents/waves) in relation to the time that is required for the seedling to anchor on the tidal flat and gain sufficient stability against subsequent disturbance events. On the contrary, a prolonged period with high external forcing (e.g. storm events) may lead to the sudden disappearance of recently established salt marsh vegetation. This requires much higher forcing than establishment failure of individual seedlings due to positive feedback provided by the dense vegetation (i.e. erosion protection and sediment trapping). Size and time dependent survival at the seedling level can be tested experimentally and used to parameterize salt marsh vegetation establishment models with real physical forcing (Hu *et al.* 2015; Balke *et al.* 2015). These models generally produce an output of establishment chances for elevation intervals depending on species specific failure thresholds and the physical forcing by tides and local weather pattern. Moreover, changing tidal range has shown to affect salt marsh lateral development even if mean sea level remains constant. This is because inundation frequency in the upper intertidal is the main driver to vegetation establishment as explained by the WoO concept (Balke *et al.* 2016).

Tidal range is predicted to locally change with accelerated global sea level rise (Pickering *et al.* 2012) in addition to the effects of coastal infrastructure and dredging. Reducing uncertainty about the response of lateral salt marsh and mangrove vegetation dynamics to changing tides with suitable models is thus not only key to understand the effects of climate change but it is also a major bottleneck preventing incorporation of wetland vegetation into coastal protection measures (Bouma *et al.* 2014). Regulating ecosystem services are of high economic importance (Turner *et al.* 2007; Barbier *et al.* 2011) and coastal vegetation is set to play an increasingly important role in safeguarding coastal resilience (Temmerman *et al.* 2013). If we want to make use of coastal regulating ecosystem services we need to understand and predict the short term tipping points under changing physical forcing regimes.

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Saltmarsh restoration in the Eden Estuary: sediment dynamics and carbon storage potential

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Coastal wetland ecosystems can act as large-capacity, long-lived carbon sinks; predominantly through sediment accumulation and organic matter burial. This function could provide climate change mitigation services, the ‘value’ of which could, in part, subsidise saltmarsh restoration efforts.

The saltmarshes of the Eden Estuary in Fife have experienced significant degradation and face future pressures through increasing relative sea level rise and climate change and being backed by high value land employing ‘hold-the-line’ approaches to coastal defence. As such, saltmarsh restoration (through transplantation of *Bolboschoenus maritimus*) commenced in 2003 to encourage marsh expansion and protect high marsh cliffs. The additional carbon storage within the estuary resulting from these efforts is being assessed to better appreciate the holistic value of such conservation initiatives.

Sediment deposition and settlement data were collected seasonally across spring to neap tidal ranges. Study sites were located on the north and south shore of the estuary with four strata types defined in each: ‘natural’ (*B.maritimus* marsh or high marsh dominated by *Puccinellia maritima*), ‘old planted’ (planted in 2003), ‘young planted’ (planted in 2010) and bare mudflat.

Samples provided total sediment and organic content deposited or settling over two flood tides. Data suggest that over a season (Summer) there is significantly more sediment deposited as strata become less vegetated (e.g. North Shore, average sediment weight, natural = 1.05003g mudflat = 1.54083g, $p = 0.00183$). Higher depositional rates on the mudflat suggest a ‘higher’ potential value for carbon storage through sediment accumulation, however average percentage organic content to strata follows an inverse relationship to that of sediment weight; so the deposits are not as ‘valuable’ as in vegetated areas. Furthermore, carbon storage benefit results from the ability to retain deposited material which is not necessarily reflected though deposition measurements; long term data will be collected on accretion values in these areas to resolve this.

Factors influencing these differences could be attributed to type and density of vegetation present (to be assessed through image analysis) and elevation of each area (or immersion period). These factors will be considered to better understand the way in which they interact to influence the rates of sediment deposition and quantity of organic content and so suggest their effect on carbon benefit.

At present these data provide a limited insight into the degree of additional carbon storage offered by this type of restoration, however it does suggest that vegetation presence plays an important role and increases depositional ‘value’ through increased organic matter content.

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Dating shore platforms and measuring long-term rates of coastal erosion on rocky coasts

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Retreating cliffs threaten important cliff-top infrastructure and livelihoods. These risks may increase due to anticipated sea level rise and increased frequency and severity of storm events over the coming decades. In order to predict how coastal erosion might proceed in the future we need reliable records of past erosion. Historical observations of cliff retreat and shore platform erosion typically span no more than the last 150 years. During this time, humans have modified the coastal environment, and human-induced acceleration in sea-level rise has begun. There is little or no quantitative information on coastal erosion prior to this time. Application of cosmogenic radionuclides (CRNs) geochronology to shore platforms has the potential to reveal whether shore platforms are inherited or contemporary geomorphic features, and to yield estimates of shore platform lowering rates and cliff retreat rates. We developed a numerical model for shore platform evolution and the accumulation of CRNs in the platform surface. Here we explore the sensitivity of CRN concentrations to required assumptions about the nature of shore platform erosion the distribution of erosion, the types of erosion processes operating, and the role of beach cover. We illustrate our approach through application to shore platforms in East Sussex, where we have measured concentrations of the CRN ^{10}Be in the shore platform. At this site we find that cliff retreat rates during the Holocene were significantly slower (2-6 cm yr^{-1}) than those derived from recent historical observations (15-25 cm yr^{-1}). Modelled accumulation of ^{10}Be requires retreat rates that increase rapidly in recent times (during the last 200-600 years).

How does economics fit into social-ecological aspects of marine and coastal ecosystems management?

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In the last 50 years we have been assisted by different paradigms or ways of thinking about nature conservation. In its infancy conservation was mainly based on prioritizing wilderness and intact natural habitats, with little attention to social aspects. However, in the last 15 years focus has shifted to a more anthropocentric perspective based on the instrumental value of nature where what counts is what provides services and benefits to humans ("nature for people", Mace, 2014). The strong emergence of this approach was promoted by the surge of monetary valuation of use and non-use values of biodiversity under the principle of welfare economics as an approach to overcome the failure of resources allocation by the "invisible hand". This has provided both corporate and public bodies evidence of the value of natural capital and a stimulus for implementing biodiversity finance mechanisms based on nature commodification. Notwithstanding difficulties in applying historical economic approaches to valuation (Hanley et al., 2015), recent EU and UK legislations have introduced economic criteria of comparing costs and benefits to environmental policies. For instance, the Marine Strategy Directive Framework Directive (2008/56/EC) asks Member States to consider the "cost of degradation" of the marine environment, or in other terms the benefits foregone if the MSFD is not implemented.

The complexities to the implementation of welfare economics into the linkages existing between ecosystems, functioning, final services and derived benefits are highlighted by the UK NEA (2011). To be operational, this framework requires scientists to estimate how ecosystem services supply will change following changes in the functionality and /or the extent of ecosystems; and economists to identify how changes in ecosystem services supply affect the flow of direct and indirect benefits.
These complexities refer primarily to the ecology-economics domain. However, the broader social-ecological dimension of ecosystem management does not fully accept, without conflict, the implementation of a utilitarian approach to nature valuation.

Using examples of three different marine services (assimilative capacity of wastes, coastal defense, and energy production from renewables), we provide evidence of how utilitarian solutions run into complex social issues. We show that valuation can provide efficient and fair allocations (waste assimilation service), but also lead to social clashes between cost benefit analysis outputs and citizens' expectation (case of coastal defense). Moreover, some controversies can also be generated through regulatory mechanisms that are not necessarily aligned with societal preferences, when a broad spectrum of cultural values (Kenter et al., 2015) are not taken into account in a more inclusive and deliberative process supporting decision-makers (case of renewable energy). We conclude that there is a need to integrate with the utilitarian allocation of resources a parallel strategy based on collective arrangements that brings citizens within deliberative mechanisms capable to reconcile conflicting interests into an enlarged social-economic ecosystems (Tett and Sandberg, 2011). This can facilitate the implementation of marine resource management based on ecosystem approach principles and good environmental governance through a more integrated use of coastal resources (within the ICZM framework) and marine uses (within Marine Spatial Planning).

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Communicating research on economic valuation of coastal and marine ecosystem services

Quantifying the monetary value of ecosystem services provided by coastal and marine resources can help policy makers assess the trade-offs and synergies inherent in ecosystem-based management of marine and coastal environments, thus increasing the social efficiency of decision-making processes. As shown by the valuation literature, the number of coastal and marine management settings where valuation researchers have attempted to make a contribution to is rising fast. However, this rise in research activity has not been matched by the increase in the use of economic valuation (EV) in the actual management of coastal and marine resources. This raises an interesting question for valuation researchers: Is EV responding to the needs of policy makers? This paper provides a comprehensive overview of the knowledge base regarding the economic values for coastal and marine ecosystems. It then discusses how to improve the uptake of ES valuation research by focussing on two core issues which are thought to be essential for more effective communication with the policy community.

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Enhancing biodiversity on artificial coastal defences

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The combination of coastal urban development and climate change associated threats has resulted in a rapid and worldwide increase in the construction of hard defences such as seawalls. These are generally designed with civil engineering goals and do not function as surrogates for the natural habitats they replace. Consequently, ecosystem services and resilience are lost. In highly urbanised Singapore, where seawalls constitute approximately 63% of the coastline, 'hard' engineering mitigation options such as increasing structural complexity remain the most practical approach to enhancing seawall biodiversity. However, complexity comprises multiple parameters and it is critical to disentangle their relative effects. Towards this end, we developed the software "CASU" and used it to design concrete tiles of two different levels of complexity. These were deployed for one year to test the effects of complexity and structural component type on intertidal diversity and community composition. Our results demonstrate that structures with greater informational complexity (specifically, increased microhabitat size variability) can support greater diversity, richness and different communities and that these effects are independent of surface area. In addition, we show how the type of structural component can have an effect on diversity that is independent of complexity. In a follow-up study, we increased the scale of structural manipulation from 4-28 mm to 8-56 mm to test the effects of complexity on species richness at these larger sizes. We also conducted a flume experiment to examine whether differences in hydrodynamic properties as a result of tile topography that could potentially explain richness differences. Results revealed that, again, complex tiles supported greater species richness but that intertidal organisms are unlikely to colonise the tiles differentially as a result of local-scale hydrodynamic variation. Upon examining the patterns of algal succession on 'simple' and 'complex' concrete tiles and 'granite control' tiles we also found that the latter generally supported fewer algal functional groups. Incorporating the results of these studies (e.g. optimal size range and structural component designs), a composite tile was devised to test the effects of varying deployment densities and spatial arrangements. Hundreds of these tiles were installed on seawalls in nine different plot arrangements and left in-situ for one year. Analyses of the results revealed that, while species richness did not significantly differ between plots with 14% and 21% tile cover, these two treatments supported greater richness than plots with 7% cover. More importantly, we demonstrate how fragmentation can influence species diversity within plots of low habitat cover (14-21%) independently of the total habitat amount. These findings not only represent rare experimental evidence for the independent and interactive effects of habitat amount and fragmentation, but also provide important practical insights for successful seawall reconciliation.

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