Migration and Global Environmental Change

DR7a: Changes in ecosystem services and migration in low-lying coastal areas over the next 50 years

Robert Costanza[1], Ida Kubiszewski[1], Joe Roman[2] and Paul Sutton[3]

[1] **Portland State University, OR, USA**
[2] **University of Vermont, VT, USA**
[3] **University of Denver, CO, USA**

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Abstract

This paper examines the history and current status of ecosystem services in low-lying coastal areas (LLCAs), their potential changes because of wider environmental and social shifts, and the potential impacts of these changes on human migration. We synthesised information from a number of sources on the status and value of ecosystem services in LLCAs, including information about key ecosystems that are likely to be particularly vulnerable to environmental change. We created maps of ecosystem and human population changes in LLCAs and then estimated changes in ecosystem services.

Estimating the impacts of these potential changes depends on the future scenario one assumes. For our analysis four scenarios were developed for future ecosystem and ecosystem services conditions in 2060, based on the four SRES (*Special Report on Emissions Scenarios)* scenarios with additional reference to the Millennium Ecosystem Assessment and the Great Transition Initiative scenarios. The two axes of the SRES scenarios are global vs. regional and material economy vs. environment foci. This allowed an assessment of the plausible range of future uncertainty about ecosystem services in LLCAs and the potential for changes in ecosystem services to drive human migration.

Major findings include:

- Coastal ecosystems are among the most productive on the planet. They provide more than 70% of total global ecosystem services.

- At the same time, these systems are the most threatened by climate change, human settlement and potential coastward migration.

- In the mid-1990s, approximately 25 million people were forced to leave their homelands owing to the inability to secure a livelihood as ecosystem services declined (Myers and Kent, 2009).

- In the coming decades, one estimate puts the number at 240–525 million people globally who may feel impelled to migrate because of loss of ecosystem services (Myers and Kent, 2009).

- Risk factors for coastal populations include over-exploitation of resources, including fisheries; destruction of mangroves, wetlands, and other natural infrastructure; increased storm activity; and reduced resilience to environmental perturbations.

- Coastward population migration is largest in the globalised scenarios because of increased ease of migration in a more globalised world.

- Coastal ecosystem services decline in the material economy-focused SRES scenarios but potentially increase in the environment-focused SRES scenarios, leading to higher overall quality of life.

Policies should aim to preserve and restore coastal habitats. This leads to higher and more stable coastal ecosystem services and human quality of life, along with lower vulnerability to migration pressures. Additional research and integrated modelling are needed, however, to better understand the spatial dynamics of human migration and its dependence on ecosystem

services. Such models could also help illuminate the transition pathways and policies necessary to achieve the preferred future scenarios.

Introduction

Coastal ecosystems are among the most productive in the world and are the most threatened by human settlement (MEA, 2005). Coastal ecosystem services and human migration are connected in complex, dynamic ways (Figure 1). Ecosystem services are negatively influenced by overall population growth, migration to the coasts, gross domestic product (GDP) growth, and climate change (Costanza *et al*., 2010). Migration to the coasts is negatively influenced by climate change, but positively influenced by ecosystem services per capita and overall population growth (MEA, 2005). Climate change is negatively influenced by population and GDP growth, which are positively influenced by each other.
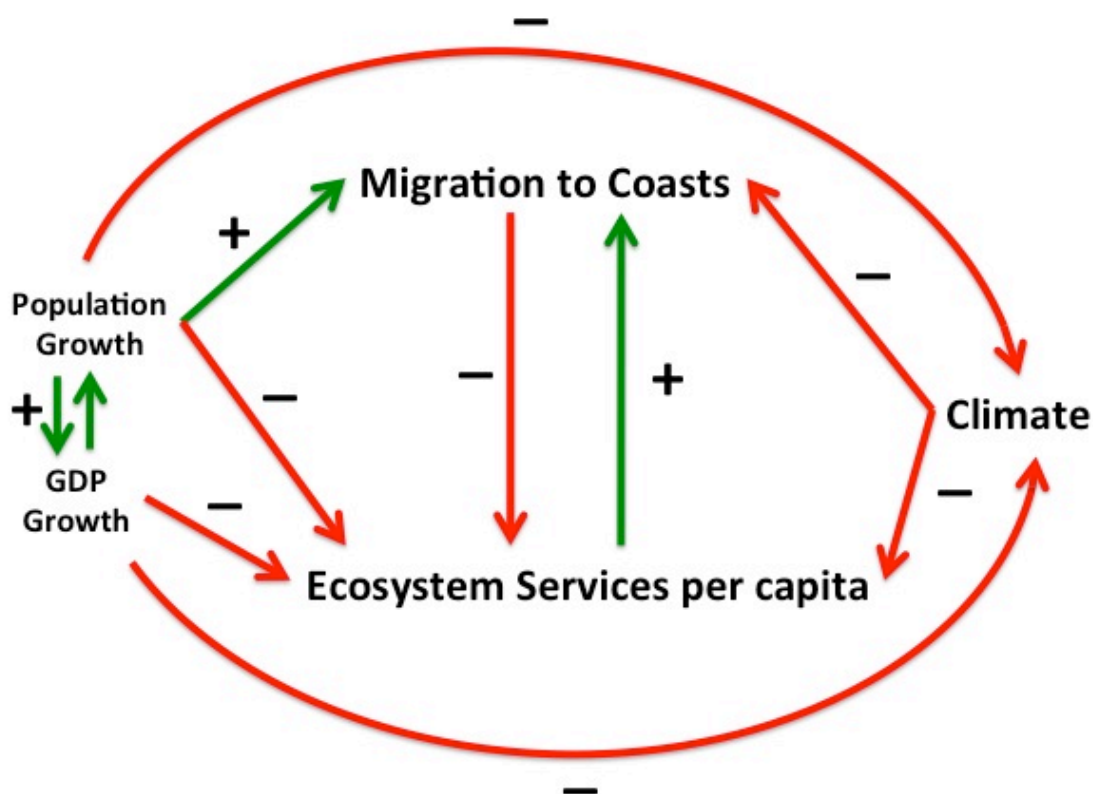
Figure 1: Systems diagram, or conceptual model, of relationships between ecosystem services and migration. Red arrows indicate negative influences while green arrows indicate positive influences.

In this paper, we focus on changes in coastal ecosystem services and how these changes might influence migration to the coasts, yet we recognise that other factors are also at play. Climate change will probably have a major impact on coastal ecosystems and their services in the next 50 years. Different projections of population and economic growth will have varying effects on ecosystem services both globally and in coastal zones (Nicholls *et al*., 2011). Interactions between these forces make it difficult to predict the magnitude of change to the nature, quality and value of ecosystem services in the future. Many of these changes are likely

to be local in scale, as ecosystem services exhibit spatial variation based on their proximity to human populations and infrastructure (Costanza *et al*., 2008).

What major human migration patterns can we expect to see in the next 50 years? Some trends include an increasing global population and continued economic growth in the next 50 years (Nakićenović and Swart, 2000). Such changes are likely to put increasing pressure on coastal areas (Pine, 2011). China is perhaps a poignant harbinger of the global future in that it has experienced significant population and economic growth in the last 30 years. During this period, China's population has also moved to the coastal zone (Han and Yan, 1999). This has been detrimental to fisheries in and around harbours of major Asian cities (Wolanski, 2006). Such pressure may continue for decades. In continental interiors, reduced soil moisture and water availability driven by climate change could drive people toward the coasts, resulting in the loss of significant ecosystems and ecosystem services (Han and Yan, 1999; Costanza *et al*., 2011). Alternatively, coastal migration could increase the value of other services that have yet to be exploited.

In this paper we lay out four possible scenarios for the future, based on different assumptions about how seriously we take environmental issues and how globalised the future might be. This approach allows us to explore some of the major uncertainties about the future, to build consensus around the future we want, and to develop strategies to get us there.

Ecosystem services in low-lying coastal areas

Low-lying coastal areas (LLCAs) are defined as those contiguous areas along the coast that are less than 10 metres above sea level. LLCAs represent only 2% of the Earth's land surface yet are home to 10% of the world's population and 13% of the world's urban population. Most of this population is in the developing world and is growing faster in these areas (McGranahan *et al*., 2007).

One obvious reason for human migration to low-lying coastal areas is their inherent attractiveness for human settlement. These areas harbour some of the most productive ecosystems and they also form the interface between upland and marine systems. People living in LLCAs can thus take advantage of the full spectrum of terrestrial and marine resources. Coastal cities evolved initially as major trading hubs, linking with other ports via efficient water-borne transport. Even in the age of rail and air transport, coastal cities retain a real inter-modal transport advantage. This inherent attractiveness will no doubt drive migration towards LLCAs.

Ecosystem services are the contribution of ecosystems – in combination with other inputs – to human well-being. Ecosystem services provide substantial positive contributions to human well-being and represent a significant portion of the total economic value of the coastal environment (Costanza *et al*., 1997; Daily *et al*., 1997; Agardy *et al*., 2005; TEEB, 2009).

Such services have become more critical as the coastal zone has become more densely populated. Approximately 60% of this LLCA population lives in urban areas (Table 1), which radically alter water, energy and material flows within coastal areas (Rakodi and Treloar, 1997; Timmermann and White, 1997).

We expanded and modified the list of services provided by coastal ecosystems in the Millennium Ecosystem Assessment (Table 2). This table includes onshore habitats as well as

strictly coastal ones, and indicates the relative magnitude of each of the services from each of the 11 coastal ecosystems included. Below we discuss a few of the most important ecosystems and ecosystem services in sustaining coastal populations. Full descriptions of all of the services can be found in MEA (2005), de Groot (2002) and Barbier *et al.* (2011).

Table 1.
Source: McGranahan *et al.* (2007)

POPULATIONS AND LAND AREAS IN THE LOW ELEVATION COASTAL ZONE BY REGION							
	Populations and land areas in the LECZ				Shares of population and land in the LECZ			
Region	Popula-tion (10⁶)	Urban pop-ulation (10⁶)	Land (10³ km²)	Urban land (10³ km²)	Share of regional population	Share of region's urban population	Share of re-gion's land	Share of re-gion's urban land
Africa	55	40	206	15	8.2%	14.5%	0.9%	7.9%
Asia	438	232	819	109	12.3%	17.7%	3.3%	11.7%
Europe	48	38	459	54	7.1%	8.1%	2.1%	7.0%
Latin America	28	22	372	32	6.1%	6.9%	2.0%	6.6%
Austrialia/New Zea-land	3	3	134	6	13.8%	14.4%	1.7%	13.4%
North America	25	22	523	52	7.8%	8.5%	2.8%	5.9%
Small island states	6	4	56	5	13.1%	14.0%	16.3%	13.1%
World	602	361	2,571	274	10.5%	13.5%	2.2%	8.2%

Note: The regions are based on, but not identical to, the IPCC regions. Countries not included in the Intergovernmental Panel on Climate Change (IPCC) list were assigned to one of the IPCC regions. Russia, which is split into two regions by the IPCC (Europe and Asia), is entirely attributed to Europe. The small island states region has 66 members, some of which are not listed as small island states in the IPCC regional listing.

Ecosystem Services	Estuaries	Marshes	Mangroves	Lagoons and Salt Ponds	Intertidal	Kelp	Rock and Shell Reefs	Subtidal sand and mud	Seagrass	Coral Reefs	Dunes and Barrier Islands
Food	High	Low	Medium	Low	Medium	Low	Medium	Low	Low	Medium	None
Fiber, timber, fuel	Low	High	Very High	Medium	None	None	None	None	None	None	None
Medicines, other	Low	Low	Low	Low	Low	Medium	None	None	Low	Low	None
Conservation & biodiversity	High	Low	High	Low	Very High	Medium	Very High	High	Medium	Medium	Medium
Biological regulation	Medium	Low	Very High	Low	Low	Medium	Low	Low	Low	Low	None
Nursery and refugia	Medium	Low	Very High	Low	Low	Medium	Low	Low	Medium	Very High	Low
Nutrient cycling	High	High	High	Low	Low	Low	Low	Low	Low	High	None
Hydrological	Low	Low	Low	None	Low	None	None	None	None	None	None
Atmos. & climate	High	High	High	Low	Low	Low	Low	Low	High	Low	None
Human disease control	High	High	High	Medium	None	None	None	None	None	None	None
Waste processing	High	Very High	Very High	High	Low	None	None	None	Low	None	None
Flood/storm protection	Low	Medium	High	Low	Low	None	None	None	Low	Very High	Very High
Erosion control	Low	Medium	Very High	Low	None	None	None	None	Low	Low	High
Cultural and amenity	Very High	Medium	Medium	Medium	Very High	None	Medium	None	Medium	Very High	Very High
Recreational	Very High	Medium	Medium	Low	Very High	None	None	None	Low	Very High	Medium
Aesthetics	High	Medium	Low	Medium	Low	None	None	None	Low	Very High	Very High

Table 2: Ecosystem services in Low-lying Coastal Areas (LCAs) (adapted from Agardy *et al.* 2006). Shading represents relative magnitude of service from each coastal ecosystem.

Legend: Very High; High; Medium; Low; None

Provisioning ecosystem services

Food

Historically, populations have been drawn to live near the coast, particularly on small islands and megadeltas, because of the abundance of essential ecosystem services, especially the provisioning of food. Coastal ecosystems supply high-protein food items such as fish, molluscs, crustaceans and other commercially important species (Béné *et al*., 2011). Estuaries, for example, are nursery areas for many aquatic organisms forming one of the strongest links between coastal, marine and freshwater ecosystems and the services they provide (Beck *et al*., 2001). In tropical and subtropical regions, mangrove forests provide nursery areas for reef organisms, serving as a critical link between seagrass beds and associated coral reefs, even though they occupy only 0.12% of global land area (Mumby *et al*., 2004; Dodd *et al*., 2008). In the Gulf of California, for example, one linear kilometre of the mangrove *Rhizophora samoensis* may contain more than a hectare of essential marine habitat, providing a median annual value of US$37,000 in fish and blue crab harvests (Aburto-Oropeza *et al*., 2008). In an earlier study, the annual market value of seafood supported by mangroves has been calculated to range from US$750 to US$16,750 (in 1999 dollars) per hectare (Ronnback, 1999). Besides food, timber and other raw materials, genetic, medical and ornamental resources are also provided by many coastal ecosystems (Barbier *et al*., 2011).

Coral reefs cover just 1.2% of the world's continental shelf but are the most biodiverse of all marine ecosystems (TEEB, 2009). They are home to between 1 and 3 million species, which includes more than a quarter of all marine fish species (Allsopp *et al*., 2009). An estimated 500 million to more than 1 billion people rely on coral reefs for their food resources (Whittingham *et al*., 2003; Wilkinson, 2004). This includes 30 million within poor coastal and island communities who completely rely on the reef as their primary source of food production, income and

livelihood (Gomez *et al*., 1994; Wilkinson, 2008). One estimate places the overall human welfare benefits from the ecosystem services of coral reefs at around US$172 billion a year (Martinez *et al*., 2011).

Regulating ecosystem services

Coastal protection
Low-elevation coastal zones are particularly vulnerable to cyclones, tsunamis, floods and storm surges. Marshes, mangroves, wetlands, seagrasses, coral reefs and barrier islands have the potential to attenuate waves, buffer the impacts of storms and provide coastal protection (Costanza *et al*., 2008; Martinez *et al*., 2011).

Mangroves, in particular, can protect vulnerable coastal communities, acting as strong natural defences against storm surges, waves and tsunamis. The coastal protection value of these salt-tolerant trees exceeds their direct-use value, such as forest harvesting and aquaculture, by more than 97% (Sanford, 2009). In India, the estimated value of intact mangroves in reducing storm damages to individual households in impoverished villages ranges from US$33 to US$153 per household per year (Badola and Hussain, 2005).

Wetlands can serve as vast horizontal levees absorbing storm surges. The economic impacts of a particular flood event on a community depend largely on the amount of unoccupied floodplains available for floodwaters (Lead *et al*., 2005). The value of coastal wetlands for hurricane protection has been estimated at US$250 to US$51,000 per hectare per year, with an average of US$8,240; coastal wetlands in the USA currently provide storm protection services valued at US$23.3 billion annually (Costanza *et al*., 2008).

Reefs contribute to the formation of beaches and buffer land from waves and storms, reducing beach erosion. On the reefs, organisms that erode reef material – algae, sponges, polychaetes, crustaceans, sea urchins and fishes – produce reef rubble (clay and sand), the essential component of white tropical beaches (Trudgill, 1983).

Atmospheric and climate regulation
Coastal ecosystems play a globally significant role as carbon sinks, with carbon storage rates per unit area of many habitats far exceeding that of terrestrial habitats (Heckbert *et al*., 2011). If these systems are to be incorporated into international and national emission reduction strategies and carbon revenue schemes, there may be a need for a marine equivalent of the Reducing Emissions from Deforestation and Forest Degradation (REDD) scheme (Laffoley and Grimsditch, 2009).

Cultural and information ecosystem services

Aesthetic and recreational value
Although life does not directly depend on it, we should recognise that the attraction to the coast is also driven by its aesthetic and recreational value. Without these services, which support, protect and enhance human life, migration towards the coast would likely stop and reverse, especially in vulnerable deltas and islands (Ghermandi *et al*., 2011).

Coral reefs are an especially important source of fisheries products for coastal residents, tourists and export markets, but they support a high number of colourful species that maintain thriving dive tourism industries. Reefs provide pharmaceutical compounds, opportunities for

bioprospecting, curios, ornamentals for the aquarium trade and materials for coastal construction (Ahmed *et al*., 2005).

Supporting ecosystem services

Productivity

As provisioning services are so important, productivity analyses can be helpful in understanding the value of wetlands and estuaries. Based on habitat values for birds, fish and shellfish, Johnston *et al*. (2002) calculated the average annual abundance per unit area of wetland habitat in the Peconic Estuary System in New York. By totalling all relevant food web values and habitat values for a year, they estimated the annual marginal asset values for three wetland types: eelgrass (US$1,065 per acre per year), salt marsh (US$338 per acre per year) and inter-tidal mud flat (US$67 per acre per year).

Nutrient cycling and waste processing

Marshes can be particularly effective in absorbing and recycling nutrients and preventing eutrophication in areas with high amounts of run-off (Silliman and Bertness, 2002). Because water passes slowly through wetlands, pathogens can be consumed or absorbed by other organisms. If wastes become too concentrated, they can have detrimental effects on wetland functions, though determining this threshold is not easy (Gren and Limburg, 2011). The feasibility of using constructed rather than natural mangrove wetlands to treat sewage and shrimp pond effluents has recently been demonstrated and could offer a low-cost option for waste processing in tropical environments (Boonsong *et al*., 2003; Wu *et al*., 2008).

Conservation

Many coral reef systems have high levels of biodiversity, acknowledged for their value as emergent biological structures and for their role as refugia and nurseries for thousands of species. As chemical diversity is related to the diversity of species, medical resources, such as drugs and other chemicals critical to human survival, are likely to be found in such biodiversity hotspots (Liu *et al*., 2011).

Oceanic islands also typically have high levels of endemism and can be rich in animal and plant specialisation. Isolation can protect these areas from threats common on continents; however, when breached by the introduction of invasive species and exotic diseases, extinction can be relatively rapid. About half of the 724 recorded animal extinctions in the past 400 years were of island species; more than 90% of the bird extinctions were island dwellers (Convention on Biological Diversity, 2004).

Recent changes in ecosystems and their services

The presence of ecosystem services can be a primary pull factor for coastal settlement and migration. Their absence can push people away. The loss of coastal ecosystem services can be due to direct or indirect drivers (Table 3). The primary direct drivers include coastal development and habitat conversion (Myers, 1989), whereas the indirect ones are increased demand on coastal resources. These resources include fisheries and aquaculture and also mining and drilling. In coastal areas, humans have depleted many species of fish that were once ecologically and commercially import. Overfishing to the point of ecological extinction often precedes other pervasive human disturbance to coastal ecosystems, such as habitat

disturbance and pollution (Jackson *et al*., 2001). We have destroyed seagrass and wetland habitats, degraded water quality, and accelerated species invasions. The remaining marine ecosystems are experiencing accelerating loss of populations and species, with largely unknown consequences (Worm *et al*., 2006). Globalisation has been viewed as a major driver of degradation of coastal ecosystems and diminishing services (MEA, 2005).

Island states and their exclusive economic zones constitute 40% of the world's oceans; they have been particularly impacted by these changes (Wong *et al*., 2006). Coastal fisheries, an important and traditional source of food, protein and employment on many islands, have been seriously depleted, and overfishing has deprived many communities of subsistence fishing, causing conflicts in tropical islands across Asia (Wong *et al*., 2006).

Aquaculture has impacted many mangroves and coastal ecosystems. Ninety-two per cent of global animal aquaculture occurs in developing countries such as China, Indonesia, Vietnam and Thailand (Bourillón, 2009). Around the world, mangrove species in the high inter-tidal and upstream estuarine zones, which tend to have specific freshwater requirements and patchy distributions, are threatened: they are often the first to be cleared for agriculture and aquaculture (Polidoro *et al*., 2010).

Mangroves and marshes can act as horizontal levees during flood events and protect against coastal disasters (Costanza *et al*., 2008). Yet many of these coastal wetlands have been lost, and those that remain are often under threat from development, pollution and invasive species. Increased storm frequency and intensity can also degrade the wetlands that remain: during the 2005 hurricane season, the storm surge and wave field associated with Hurricanes Katrina and Rita eroded 527 sq km of wetlands within the Louisiana coastal plain (Howes *et al*., 2010). The destruction of this natural infrastructure can result in huge losses of ecosystem services. Deaths from tropical storms, surges and floods along coastlines have risen in the past 50 years, a combination of increased coastal populations and reduced services (Myers, 2002).

Land reclaimation through the filling of wetlands and expansion of coastlines often requires importation of sand or other dredge spoil from neighbouring coastlines. Such dredging can threaten fisheries, marine conservation efforts and biodiversity. A report by the environmental group Global Witness indicates that Singapore imported 14.2 million tonnes of sand worth US$273 million from Vietnam, Malaysia and Cambodia in 2008. In response to the loss of land, several countries have banned the sale of dredged sand, but the trade continues in Cambodia, even within protected areas (Global Witness, 2010). As sea levels rise, this unsustainable practice has the potential to accelerate land loss in dredged areas.

Invasive species

Modern shipping and globalisation have accelerated the rate of dispersal of coastal and marine invasive species (Molnar *et al*., 2008). The increase of eutrophic-polluted waters has also helped alien species become established; in the Mediterranean, the invasive algae *Caulerpa* outcompetes native seagrasses in areas impacted by humans (Occhipinti-Ambrogi and Savini, 2003). In the Black Sea and Sea of Azov, the ctenophore *Mnemiopsis leidyi* lead to the catastrophic decline of zooplankton and of the once-flourishing pelagic fisheries (Kideys, 1994). Invaders can operate synergistically with overfishing and climate change to create new community states (Harris and Tyrrell, 2001).

Such changes can degrade habitats and their services. Annual aerial surveys suggest that invasive nutria have severely damaged about 1,000 sq km of coastal wetlands in Louisiana.

The damage is strongest in the Mississippi Deltaic Plain, where submergence is occurring at more than a centimetre a year (Pyke *et al*., 2008). Researchers have suggested that properly managed harvests could aid the return of large alligators and protect the marshes and their services (Keddy *et al*., 2009).

Coral reefs

Coral reefs are vulnerable to overuse and habitat degradation; the removal of individual elements from this interconnected ecosystem can cause negative feedback loops and cascading effects (Nystrom *et al*., 2000). The removal of predators or a rise in invasive species, such as algae, can have strong impacts when the abundance of corals falls below a certain threshold (Birkeland, 2004). Such ecological processes are self-enforcing, inhibiting the recruitment and survival of reef-building corals and favouring alternative stable states, such as those dominated by algae. The shift in ecosystem state can result in a massive loss of services (Barbier *et al*., 2011).

The potentially disruptive effects of climate change on these systems was demonstrated in 1998, the hottest year of the millennium. In that year, an El Niño event caused heatwaves, droughts and floods around the world; approximately 16% of the world's coral reefs died.

Since 1950, approximately 19% of the original area of coral reefs has been effectively lost (Wilkinson, 2008). Another 20% has been badly degraded or is under imminent risk of collapse (MEA, 2005) while 58% of global reefs are threatened by human activity. Such damages can have high costs to local communities. Cesar (1996) estimated that damages from coral reef destruction cost up to US$1,000,000 per kilometre of coastline in decreased coastal protection (based on 0.2 m per year of coastal erosion, 10% discount rate and a 25-year period).

Deltas

Dynamic processes and human activity often converge at deltas (Agardy *et al*., 2005), in part because of the importance of shipping and other navigational services and because these regions can be rich in seafood and other provisioning services. Yet throughout the world large proportions of water are extracted from rivers for agriculture and domestic supplies (Postel *et al*., 1996). Such activities can threaten fisheries, naviagtion, wildlife and the freshwater lens essential to productivity in estuaries. Floods of increasing intensity in the Mekong delta of Vietnam have threatened rice agriculture and driven migration to large urban areas (de Sherbinin *et al*., 2011).

Kelp forests

Kelp forests are highly productive ecosystems in cold-water rocky marine coastlines around the world. Over the past two centuries, human harvests of top predators such as lobster, cod and sea otters have been implicated as a cause of global kelp forest degradation (Estes *et al*., 1978; Steneck *et al*., 2002). Land-use practices and coastal discharges form municipal, agricultural and industrial wastes can also negatively impact kelp beds by increasing turbidity, sedimentation and nutrient loads (Howarth *et al*., 2000). This decline can negatively impact nurseries and refugia, conservation, medical resources and other ecosystem services. It can also change the management of coastal carbon sinks on a global level (Laffoley and Grimsditch, 2009).

How have changes affected settlement patterns?

Ecosystem services are integral to providing many material factors essential for human well-being such as food, water, shelter, clothing and clean air. However, they also play a key role in providing non-material aspects of well-being such as good health, a sense of security, good social relations, freedom and choice (Butler and Oluoch-Kosura, 2006). The conservation and maintenance of sustainable ecosystem services can significantly contribute to real poverty reduction (not just monetary income), human health, equity and security (Mainka *et al*., 2005). The lack of these services, or the perception of insufficient services, can create conflicts over the management of common pool resources (Adams *et al*., 2003).

Ecosystems can also provide more indirect services to human well-being. These services are on occasion displaced in space and time, and can be dependent on a number of modifying forces. One example of an indirect impact of an ecosystem service on human well-being can be seen when climate change alters agriculture or fishery production (Béné *et al*., 2011). Such an alteration can lead to malnutrition, stunted childhood growth, susceptibility to infectious diseases and other ailments (MEA, 2005).

Areas facing environmental degradation often experience migration pressure (Afifi and Warner, 2008). In 1995, approximately 25 million people were forced to leave their homelands due to the inability to secure a livelihood as ecosystem services declined (Myers, 2002). Migration can be a response to changing environmental conditions and simultaneously changing economic conditions (Ruitenbeek, 1996; Warner and de Sherbinin, 2009). An inmigration can, however, exacerbate environmental and economic condition within the receiving area (Figure 1).

Coastal areas remain highly vulnerable to a range of natural and man-made disasters, including tropical storms and earthquake-induced tsunamis. The 2011 tsunami in Japan is a stark reminder of the disadvantages of living near the coast. Most of these events remain unpredictable enough to allow people to discount those risks, though climate change is likely to exacerbate the frequency and impact of storms (Webster *et al*., 2005). Better understanding of the dynamics of the integrated natural system and human system, with an eye towards the effects of these dynamics on migration patterns, will help us to do a better job of striking a balance between attractiveness and risks.

Often, sudden or one-time events, such as flooding or storms, create short-term and predominantly domestic migration: ecosystem goods and services can return after an event has passed (Myers, 2002). However, long-term and international migration, generally across the nearest border, is seen when ecosystems are degraded permanently to a point where essential life-sustaining services no longer exist and will not return soon. Slow degradation of the environment is often primarily detected through the downturn of the local economy, which was dependent on those ecosystem services (Bates, 2002).

Some people have claimed that the 4,000-km fence being built along the border between India and Bangladesh is being built in part to prevent the anticipated massive migration of Bangladeshis into India that will be driven by the inundation of much of Bangladesh. This would constitute a very expensive and ineffective policy response to an anticipated demographic shift that is predicted to result from the consequences of climate change (Banerjee, 2010). Clearly, this would be an example of a decrease in coastal ecosystem services driving migration either

away from or along the coasts. However, climate change-caused droughts in inland areas may well drive population migrations *towards* the coast (imagine a climate change-driven 'Dust Bowl' scenario). It is virtually impossible to predict who will move and where they will go; yet, it is likely that climate change and its impact on ecosystem services will spur many human migrations, large and small (de Sherbinin *et al.*, 2011).

Spatio-demographic shifts such as these complicate any analyses attempting to anticipate changes to ecosystem services in LLCAs. This is because human presence changes the value of ecosystem services in ways similar to how human presence changes the value of real estate. If a large human migration occupies a previously uninhabited area with many coastal wetlands then that act of migration and settlement has just dramatically increased the storm protection services provided by those wetlands. Incorporating a sophisticated spatio-demographic analysis into this assessment of changes to ecosystem services in LLCAs is beyond the scope of this paper. On the demographic front the most we can say with a high degree of certainty is that the next 50 years will see a growing human population trying to survive on a materially finite planet that is likely to see many significant climate change- and population growth-driven impacts to the ecosystem services provided by LLCAs.

The world's urban population has increased by approximately an order of magnitude during the past century, from 224 million in 1900 to 2.9 billion in 1999 (United Nations, 1999). This is expected to increase to 4.9 billion, 60% of the world's population, by 2030. Such growth may be quicker on the coast, increasing from 1.2 billion people in 1990 to anywhere between 1.8 and 5.2 billion people by 2080, depending on the scenario (Nicholls *et al.*, 2007).

Migration towards an urban living increases the vulnerability of greater losses during major and minor events. Currently, it is estimated that flooding affects at least 520 million people each year, and 1 billion people are at risk. Tropical cyclone hazards exposed 120 million people to danger (Nicholls *et al.*, 2007). The majority of those affected are in underdeveloped and poor areas. Countries that will be most influenced by sea-level rise and flooding include Bangladesh, Vietnam, China, India, Pakistan, Thailand, Indonesia, the Philippines, Egypt, Mozambique, Senegal, Suriname and Indian Ocean and Pacific islands (Myers and Kent, 2009; de Sherbinin *et al.*, 2011).

Within these and other countries, much of the population lives in high-density, urban areas. Approximately two-thirds of the world's large cities (populations over 5 million inhabitants) are at least partially within LLCAs. This includes about half of the cities in Africa (Huq *et al.*, 2007). About 600 million people (10% of the population) live less than 10 metres above sea level (2% of land area). By 2050, approximately 1300 sq km of coastal land loss is projected if current global, regional and local processes continue, much of it occurring during episodic events such as cyclones (Nicholls *et al.*, 2007). Infrastructure destruction has been found to be spatially varied depending partially on deforestation (Hellin *et al.*, 1999).

This has significant implications on ecosystems because the linkage between rural and urban areas is one of co-dependence. Urban areas rely on rural areas for subsistence: food, forest products and other essential products for survival. However, their existence also fragments, isolates and degrades natural habitats; simplifies and homogenises species composition; disrupts hydrological systems; and modifies energy flow and nutrient cycling (Alberti *et al.*, 2003).

Estimates show that in 1997, cities utilised approximately 500–1,000 times larger areas of ecosystem services outside the cities than the area of the cities themselves (Folke *et al.*, 1997). Much of this use becomes apparent in rural areas surrounding cities. Food, freshwater

and other renewable resources come from outside the city borders, as does clean air and the processing of waste.

However, ecosystems also exist within urban areas, which may include street trees, lawns and parks, urban forests, cultivated land, wetlands, lakes and the sea and streams (Bolund and Hunhammar, 1999). These urban ecosystems may provide local services such as air filtration, microclimate regulation, noise reduction, rainwater drainage, sewage treatment and recreational and cultural values.

In Asia, many of the world's largest cities are in floodplains or cyclone-prone coastal areas (Table 3). The risk within these urban areas has increased as the lifetime and intensity of cyclones has increased significantly since the mid-1970s (Emanuel, 2005). Adding to this risk, sea-level rise in many heavily populated deltaic areas can exceed the global average because of subsidence due to human activity (Saito, 2001). Approximately 16,000 sq km of deltaic wetlands have been lost over the past 14 years as a result of human development (Coleman *et al.*, 2008).

Table 3: Drivers of loss of coastal ecosystem services

Direct Drivers	Indirect Drivers
Habitat Loss or Conversion	
Coastal development (ports, urbanization, tourism-related development, industrial sites)	Population growth, poorly developed industrial policy, tourism demand, environmental refugees and internal migration
Destructive fisheries (dynamite, cyanide, bottom trawling)	Shift to market economies, demand for aquaria fish and live food fish, increasing competition in light of diminishing resources
Coastal deforestation	Lack of alternative materials, increased competition, poor national policies
Mining (coral, sand, minerals, dredging)	Lack of alternative materials, global commons perceptions
Civil engineering works	Transport and energy demands, poor public policy, lack of knowledge about impacts and their costs
Environmental change brought about by war and conflict	Increased competition for scarce resources, political instability, inequality in wealth distribution
Aquaculture-related habitat conversion	International demand for luxury items, regional demand for food, demand for fishmeal in aquaculture and agriculture, decline in wild stocks or decreased access to fisheries
Habitat Degradation	
Eutrophication from land-based sources (agricultural waste, sewage, fertilizers)	urbanization, lack of sewage treatment or use of combined storm and sewer systems, unregulated agricultural development, loss of wetlands and other natural controls
Pollution: toxics and pathogens from land-based sources	lack of awareness, increasing pesticide and fertilizer use (especially as soil quality diminishes), unregulated industry
Pollution: dumping and dredge spoils	lack of alternative disposal methods, increased enforcement and stiffer penalties for land disposal, belief in unlimited assimilative capacities, waste as a commodity
Salinization of estuaries due to decreased freshwater inflow	demand for electricity and water, territorial disputes
Alien species invasions	lack of regulations on ballast discharge, increased aquaculture-related escapes, lack of international agreements on deliberate introductions
Climate change and sea level rise	insufficient controls on emissions, poorly planned development, stressed ecosystems less able to cope
Overexploitation	
Directed take of low-value species at high volumes exceeding sustainable levels	population growth, demand for subsistence and market goods (food and medicinal), industrialization of fisheries, improved fish-finding technology, poor regional agreements, lack of enforcement, breakdown of traditional regulation systems, subsidies
Directed take for luxury markets (high value, low volume) exceeding sustainable levels	demand for specialty foods and medicines, aquarium fish, and curios; lack of awareness or concern about impacts; technological advances; commodification
Incidental take or bycatch	subsidies, bycatch has no cost
Directed take at commercial scales decreasing availability of resources for subsistence and artisanal use	marginalization of local peoples, breakdown of traditional social institutions

Coastal zones are attractive places to live, provide easy access to rivers and sea harbours, are often strategic locations to trade, supply fresh water or are fertile deltas. They are also often very rich in natural and renewable resources. For example, the global marine fishing industry is estimated to be worth approximately US$90 billion annually and it provides jobs to 27 million people, many in small-scale and artisanal fisheries. This industry is at risk of collapse over the

next 40 years, a collapse that would affect the health of over a billion people in the developing world who depend on fish for their primary source of protein (TEEB, 2009).

Many ecosystem services are required for human livelihood, without those services people migrate to areas that provide more services. Fresh water is essential for drinking, growing food, livestock production, personal hygiene, washing, cooking and recycling of wastes (MEA, 2005). However, the destruction of wetlands, and hence the service of filtering freshwater, creates a situation where freshwater supplies are limited, jeopardising food production, human health, economic development and geopolitical stability. Global freshwater availability has declined per person markedly within the past few decades to the point that one-third of the world's population is experiencing moderate to high water stress. Six per cent of all deaths globally are due to water-associated infectious diseases (MEA, 2005).

Food is also a prerequisite to life. Current global food production is insufficient to feed everyone. Many people in low-income countries do not obtain enough protein and calories. The health of local ecosystems can be directly correlated with the health of human communities and basic nutrition (Sala and Knowlton, 2006). Local food production promotes rural development as there is no capacity to import food.

Energy accessibility by a community has many health impacts as it is required in critical healthcare applications. Over 25% of the world's population relies on solid fuels, such as biomass and coal, for cooking and heating (EIA, 2010). This creates indoor air pollution, accounting for mortality and morbidity from respiratory disease, particular among children (Smith *et al*., 2011). Lack of accessibility to energy increases vulnerability to illness and malnutrition through the consumption of uncooked water and food. The limited supply of energy within a community also is a primary reason for the inability to develop economically. However, exploitation of local forests for energy degrades the ecosystem through fragmentation of habitats and loss of species diversity and can introduce new infectious diseases into human populations (MEA, 2005).

Sea-level rise, increased storm frequency and intensity, more extreme floods, dwindling local food supplies and loss of freshwater availability are all likely to cause changes to the nature, quantity and value of ecosystems services provided by LLCAs. These changes will undoubtedly act as 'push' factors in human migrations, large and small, in the next 50 years. These push factors will occur in tandem with pull factors that are often associated with vastly differing levels of economic development to further drive continued migration from less developed countries to more developed countries (e.g. Latin America to North America and from Africa to Europe) (de Sherbinin *et al*., 2011).

Quantitative methods to assess changes in ecosystems and their services

Attempts to anticipate changes to ecosystems and their services over the next 50 years is an assessment of our confidence in future scenarios and should be orientated towards influencing long-term planning responses rather than emergency responses. Long-term planning in the form of prudent land use, building codes and transportation planning pays off for quality of life in general and for the various and inevitable natural and man-made disasters that do manifest as emergency management situations (Alberti *et al*., 2003). In the USA, for example, the city of Norfolk, Virginia, has begun to expand parks and wetlands that can reduce flooding and make

a greater area of the coast available to the public (Kaufman, 2010). The outputs and geographic scenarios of various General Circulation Models (CCSM3, ECHAM5, CGCM31 T47 and IPSL), such as average temperature, cloud fraction, diurnal temperature range, rainfall and sea surface temperature, have been used to predict phenomena such as sea-level rise. Even modest sea-level rise scenarios (38 cm from the 1990s to the 2080s) suggest a fivefold increase in people flooded by storm surge and a 22% loss of the world's coastal wetlands from flooding alone (Nicholls *et al*., 1999). While we are quite confident that global sea levels will be rising, our spatially explicit predictions of temperature, precipitation and cloud fraction are subject to high degrees of uncertainty. For example, comparisons of the Intergovernmental Panel on Climate Change (IPCC) climate change models driven with observed sea surface temperatures have typical correlation coefficients with observed rainfall of less than 0.3 (Funk and Brown, 2009). In certain places, such as East Africa, the IPCC simulations predict increasing rainfall when in fact rainfall is decreasing substantially (Funk *et al*., 2008). Significant errors exist in current maps of contemporary measurable phenomena such as GDP, population and land cover (coastal wetlands are particularly difficult to map globally) – putting too much faith in spatially explicit global *predictions* of temperature, precipitation and cloud cover 50 years into the future may not be particularly useful for anticipating changes to coastal ecosystems.

Quantitative assessments of ecosystem changes and exposure to hazard in low-lying coastal areas demand a suite of spatially explicit information from myriad sources. Reliable, spatially explicit and valid data from the following four broad areas would be needed to provide a fundamental knowledge base from which to conduct analyses to drive actionable policies: (i) demography, (ii) economy, (iii) land/ocean status and ecosystem health and (iv) quality and character of institutions. Global, spatially explicit datasets of the aforementioned can be used in tandem with events such as floods, droughts, depleted fisheries, famines and civil wars to both tactically and strategically manage our way into the future.

Datasets

For the purposes of our assessment, four datasets were used in mapping and projecting changes in ecosystem services:

1. Global population at 1 sq km (an annually updated product such as Landscan or GRUMP).
2. Night-time lights at 1 sq km (annually updated) can be used as proxy measure of economic activity, carbon dioxide emissions, informal economy, energy consumption and urbanisation.
3. The physical world: GLC 2000 global land cover at roughly 1 sq km (annually updated).
4. Government/institutional effectiveness/ecosystem management map (continuously updated).

The availability of these datasets in time series for change detection is crucial. At the global level, the world 'next year' looks a lot like it did 'last year'; however, with spatially explicit datasets important significant local changes can often be easily identified. Time series of these kinds of datasets used in conjunction with time series of 'event' data such as floods, famines, hurricanes and civil wars will be useful for identifying areas in which we might want to focus effort and resources. Clearly, there is an abundant amount of data already available. Our collective challenge is to distinguish that which is significant from that which is not. No amount of data would have prevented the Deepwater Horizon Oil spill in the Gulf of Mexico. No amount of data alone will prevent severe and irreversible damage to coastal ecosystems in the coming decades. We have the data to see the trends now. The real question is: Can we envision various realistic and probable scenarios and diligently implement, enforce and maintain the policies and practices needed to achieve those scenarios that we collectively decide are most desirable?

Projected changes in ecosystem services

Climate change, population growth, habitat alteration and migration to the coast may present the most significant challenges to coastal ecosystems in the coming decades. These increased stresses will have direct and indirect impacts on societies. Once coping mechanisms are exhausted, people will have no other option but to migrate as a permanent or temporary adaptation strategy (Bogardi and Renaud, 2006).

A recent study of the impacts of several key drivers of climate change on coastal and marine ecosystems in the USA is probably indicative of global trends. Scavia *et al.* (2002) found that increasing rates of sea-level rise and intensity and frequency of coastal storms and hurricanes over the next decades will increase threats to shorelines, wetlands and low-lying coastal areas. Estuarine productivity will change in response to alterations in the timing and amount of freshwater, nutrients and sediment delivery from upstream. Increased water temperatures will change estuarine stratification, residence time and eutrophication. Increased ocean temperatures will lead to increases in coral bleaching and ocean acidification, which may reduce coral calcification (Scavia *et al.*, 2002). This will make it difficult for corals to recover from disturbances. As other species move to higher latitudes, commercial species may disappear from some areas and increase in others, with many secondary effects on predators and prey. Although the potential impacts of climate change will vary from system to system, it is important to recognise that other ecosystem stresses, such as pollution, overharvesting, habitat destruction and invasive species, will amplify the changes to coastal ecosystems (Scavia *et al.*, 2002).

The median projection of global population growth by the United Nations will require a near doubling of agricultural output from 2000 to 2050. Such increases are likely to directly impact coastal ecosystems. At the same time, the next few decades will see large increases in rates of eutrophication as levels of agricultural nutrients and wastes rise and oceans warm (Agardy *et al.*, 2005). Approximately 77% of the pollutants reaching coastal ecosystems originate on land; 44% of this comes from improperly treated wastes and run-off (Cicin-Sain *et al.*, 2002). Without regulation, dead zones are likely to increase in size and appear in new areas in the future, affecting fisheries and other coastal services.

Much of the projected population growth is expected to occur along the coast. In the USA, for example, a 2001 study projected that 27 million additional people – more than half of the population increase – would funnel into the narrow corridor along the edge of the ocean in the next 15 years (Beach, 2002). Many areas are already under great pressure: about 1 billion people live on the rural coast of the Asia-Pacific region, and 85% of the world's 35 million fishers live in this area (Talaue-McManus, 2006). Australia has more than 85% of its population living near the coast, placing significant pressure on marine resources and increasing risks of inhabitants of low-lying areas to sea-level rise. The driver for the movement to the coast, away from large urban areas, is largely related to a lifestyle change (Burnley and Murphy, 2004).

Population growth and coastal migration, whatever their causes, will almost certainly put a greater strain on these coastal communities and ecosystems as further pressure is put on extracting nutrients from the oceans, an increase that is occurring at the same time as sharp drops in global fish stocks. Thirty per cent of marine fisheries have collapsed and are producing less than 10% of their original landings; more than 20 million people in the fishing industry, the great majority of them living along the coasts, will probably have to be retrained in the next 40 years to avoid a final ecological collapse of the world's oceans and their fish stocks (TEEB, 2009).

Climate change projections for sea-level rise will affect LLCAs around the world. In many heavily populated deltaic areas, such rises may exceed the global average because of subsidence due to human activity (Saito, 2001). Approximately 16,000 sq km of deltaic wetlands have been lost over the past 14 years due to human development (Coleman *et al*., 2005). Small island states are also at risk. The Republic of Maldives is already preparing for the international migration of its citizens because the country is becoming inundated (see box). It is more than just a gradual rise. In the north-eastern USA, 100-year storm surge events could occur every 8 years in cities such as Boston and Atlantic City. Even under moderate projections such events are likely to occur every 30 years (Kirshen *et al*., 2008). Climate change is also expected to alter rainfall patterns. Approximately 1.1 billion people currently live without access to clean drinking water; twice as many lack proper sanitation (UNDPI, 2002). Unless changes are made in protecting ecosystems and conserving water, up to half of the world's population could live in areas without water to meet their daily needs.

Shifts in the recharge of aquifers because of climate change, together with increasing demand by humans on water resources, could have important implications for coastal ecosystems (Kennedy *et al*., 2002). In the Gulf of Mexico, for example, significant influx of fresh water into estuaries and bays comes from groundwater (Herrera-Silveira, 1996). The increased upstream consumption of water by agricultural, urban and industrial users has reduced outflows of groundwater downstream. The combination of increased demand and decreased recharge of ground water as a result of climate change and population growth could reduce estuarine productivity. In addition to changes in groundwater, reduced nutrient inputs from surface waters during droughts can be a major cause of the loss of productivity of a river-dominated estuaries (Livingston *et al*., 1997). Humans impact coastal systems on a range of scales, but when degradation becomes chronic, the cumulative impact can be quite large (Agardy *et al*., 2005).

The IPCC identified deltas, estuaries and small islands as the coastal systems most vulnerable to climate change and sea-level rise. Islands are particularly vulnerable to sea-level rise and increased storm events. Reef systems are expected to change, with some coral species disappearing entirely, over the next 50 years. To protect remaining reefs and LLCAs, strong policy decisions to reduce the rate of global warming will be required along with management strategies that support reef resilience (Hughes *et al*., 2003). Such strategies include a strong focus on reducing pollution, protecting food webs and managing key functional groups – such as reef constructors, herbivores and bioeroders (McClanahan *et al*., 2002).

Vulnerability on particular islands can be reduced through planning and preparation: casualties from hurricanes have declined in Cuba, which has a high level of national planning and provision for cyclones (Clayton, 2004). After the warming event of 1997–98, some Pacific islanders have responded effectively to the threat of over-harvesting and the death of coral by (i) developing proactive rather than reactive interventions, focusing on prevention and restoration; (ii) dealing with the ultimate causes such as over-population as well as the proximate causes of decline such as seawater warming and over-fishing; and (iii) promoting responsible human behaviour.

The Republic of Maldives

The Republic of Maldives is the smallest country in Asia, with an average ground level of 1.5 m above sea level. The highest point in this atoll nation is only 2.3 m. The economy on these islands depends on tourism, fisheries and other biodiversity-based sectors; 71% of national employment, 89% of GDP and 98% of exports are in these sectors, mostly through tourism (IUCN, 2009). This dependence has created what one journalist called the 'Maldivian

dilemma': carbon emissions are sinking the island, but the greenhouse gases emitted by international tourists to reach the islands drive much of its economy (Gill, 2010).

In spite of this dependence, or perhaps because if it, the natural capital of the Maldives is being eroded with the over-harvesting of several marine species, such as sharks, lobsters and sea cucumbers, increase in pollution and damage to reefs from construction. Coral blocks, rubble and sands are the main construction materials in the Maldives. A study in the 1990s estimated that approximately 20,000 m^3 of corals were mined there every year (Cesar, 1996). Artificial substitute breakwaters (i.e. concrete piers) are expensive. The International Union for Conservation of Nature (IUCN) has estimated that the cost of replacing coral reef shoreline protection services for the 195 inhabited islands with man-made infrastructure ranges between US$1.5 billion and US$2.7 billion (IUCN, 2009).

Fisheries account for 9.0% of GDP, 17.0% of employment and 66.3% of export commodities by value in the Maldives. Tuna is 89% of the total catch, which is estimated at about 5,000 tonnes per year. Until recently, reef fisheries were limited and largely sustainable. With the rapid socioeconomic development following the expansion of tourism, together with improved air and sea transport, a number of reef fisheries have developed for both local consumption and export markets (De Young, 2006). Approximately 20% of the capture fisheries are considered over-exploited, and that number is expected to increase, as little government funding is directed at research or management (De Young, 2006).

This loss of services, accompanied by anticipated land loss because of rising sea levels and the subsidence of islands as subsurface water is depleted, draining the freshwater lens, has prompted the president of the Maldives, Mohamed Nasheed, to announce that he would begin looking into purchasing new lands in Sri Lanka, India and perhaps Australia (Ramesh, 2008). These new lands would provide insurance in case the country loses all or much of its habitable land. Despite its dependence on tourism, the president has pledged to make the Maldives the first carbon-neutral country by moving to solar and wind power.

Louisiana, New Orleans and the Mississippi Deltaic Plain

The Mississippi Deltaic Plain in Louisiana is rich in ecosystem services, with a long tradition of fisheries and agriculture, and a more recent focus on tourism. Yet the area is also particularly vulnerable to hurricanes, oil spills and other natural and human-caused disasters (Batker et al., 2010). The devastation of New Orleans by Hurricane Katrina was, unfortunately, both predictable and predicted. A large number of reports in both the academic and popular press before the incident depicted possible scenarios very close to what actually happened. It was clear from studies published in the past 50 years that New Orleans was becoming more vulnerable with each passing year. The wetlands surrounding New Orleans provide protection from storm surges (Costanza et al., 2008). These wetlands, the result of six millennia of land building, have been lost at an average rate of 65 sq km per year since the beginning of the 20th century. The barrier islands are rapidly eroding as well. Almost 5000 sq km of coastal wetlands have been lost since the 1930s, and the situation has continued to deteriorate. The cause of this dramatic land loss was a combination of natural and human forces. For millennia, the natural process of geological subsidence was counterbalanced by riverine inputs into a deltaic plain. However, in the 20th century there was a massive disruption of the hydrology of the delta. Riverine input was drastically reduced by the creation of levees and the closure of distributaries, and the internal hydrology of the delta was pervasively altered, mainly because of canal dredging for oil and gas exploration and extraction (Day et al., 2000). As a result, the blanket of freshwater, sediments and nutrients from the Mississippi River basin that used to spread across the delta is no longer

there. The heavily managed Mississippi River was forced to dump most of its load off the continental shelf into the deep waters of the Gulf of Mexico and the wetlands deteriorated because of canal dredging, subsidence and salt-water intrusion.

This loss of coastal wetlands and their storm protection services allowed the storm surge from Hurricane Katrina to do enormous damage, causing one of the most significant migrations in US history away from the coast. The diaspora from New Orleans spread across the USA and beyond, but was concentrated in upland Louisiana and nearby states. It is estimated that New Orleans now has only 70% of its pre-Katrina population (Burdeau, 2009) and many former residents will never return.

Sea level is rising, precipitation patterns are changing, hurricane intensity is increasing, energy costs are predicted to rise and New Orleans is continuing to sink. Most of New Orleans is currently from 0.6 to 5 m below sea level. The conventional approach of simply rebuilding the levees and the city behind them will only delay the inevitable. But, if New Orleans, and the delta in which it is located, can develop and pursue a new paradigm (Costanza et al., 2006), it could be a truly unique, sustainable and desirable city, and an inspiration to people around the world. It would need to pursue a strategy of rebuilding the coastal wetlands with sediment diversion and other mechanisms, and acknowledge and work with (rather than against) the coastal deltaic system on which it is built.

Bangladesh

Bangladesh is one of the most disaster-prone countries in the world. Most of the land area consists of the deltaic plains of the Ganges, Brahmaputra and Meghna rivers, but it contains seven major and more than 200 minor rivers. Half of the population of 162 million people live within 100 km of the coast, which sits less than 12 m above sea level. One-third of cultivated land and half of all rice land are located in coastal zones (Mondal et al., 2007).

Over the years, human activity has converted natural coastal defences, such as mangroves, into aquaculture (Woodroffe et al., 2006). However, extensive deforestation in the Himalayan highlands has also exacerbated flooding in Bangladesh (Daily, 1997). More than 5 million people live in areas that are highly vulnerable to cyclones and storm surges. Yearly flooding and loss of key ecosystems displaces approximately 500,000 people each year (Warner and de Sherbinin, 2009). Most of the displacement is temporary migration to major urban centres such as Dhaka, caused by both natural and socioeconomic processes that can wreak havoc on human lives, crops, cattle, poultry, fisheries, forests and many other types of property and economic infrastructure. Although the livelihoods and culture of many Bangladeshis are structured around seasonal flooding, recent extreme floods have affected more than two-thirds of the country's total area (Islam, 1992).

Coastal fishing villages are experiencing increasing land loss because of accelerated erosion related to stronger and higher tides. Estimates show that approximately 26 million people are at risk of sea-level rise in Bangladesh (Myers, 2002). Such land loss endangers the ability of entire villages to remain. With the world's ninth highest population density, the majority of Bangladesh is densely populated and under cultivation. When conditions require permanent exodus from a region, 88% of migrant communities remain within 3.2 km of their previous residence, in an attempt to hold on to similar livelihoods (Zaman, 1989). By moving further, their traditions surrounding fishing and farming practices would have to change. However, many migrants are often forced to move into urban slums, creating greater stresses on the remaining ecosystems around the urban areas.

In 2007, Bangladesh experienced two major weather events that killed 3,363 people and affected 10 million through a 13% reduction in crop yield (Warner and de Sherbinin, 2009). This is a significant improvement from the half a million people who died in the 1970 cyclone and tidal surge or the 1991 cyclone that killed 140,000 people. Although early warning systems were able to decrease the number of deaths, the damage to homes, large areas of croplands and mangroves have had a dramatic impact on livelihoods. It is estimated that approximately 15 million environmental refugees will leave Bangladesh by 2050 (Myers, 1993).

To counteract these trends, a large reforestation programme has been undertaken in Bangladesh to reduce flood and cyclone damage. Between 1966 and 1990, an area of 120,000 ha (29% of the total mangrove area in Bangladesh) was reforested, creating a overall gain in mangrove cover within this time period. Besides providing protection from storms, the reforestation of mangroves increased the potential for fisheries production, provided 600,000 m^3 of forest products, and generated approximately 5 million man-days of employment for coastal communities (Moberg and Rönnbäcka, 2003).

Scenarios for the future

Most of the developing world lacks the capacity to manage current coastal population growth in any equitable fashion. Nor do most developing countries have the political motivation, expertise, or money to introduce comprehensive coastal management plans. At the same time, the developed world has not come to grips with the implications of these demographic and resource trends.

(Hinrichsen, 1999)

To deal with the future we have to deal with possibilities. Analysis will only tell us 'What is'.

Edward de Bono (1973)

Predicting the future is impossible. But what we can do is lay out a series of plausible scenarios that help to better understand future possibilities and the uncertainties surrounding them. As Nicholls *et al*. (2011) put it: 'Scenarios enable decision makers to consider a variety of plausible storylines of how the future might unfold and are exploratory tools where factors shaping the future are especially uncertain or the complex nature of systems makes them unpredictable.' They have become an important way to inform decision-making under uncertainty.

Scenario planning is based on four assumptions (DTI, 2003):

1. The future is unlike the past, and is significantly shaped by human choice and action.
2. The future cannot be foreseen, but exploring possible futures can inform present decisions.
3. There are many possible futures; scenarios therefore map within a 'possibility space'.
4. Scenario development involves both rational analysis and creative thinking.

Several scenario-planning exercises have been conducted in recent years at a range of spatial scales and for a range of purposes (e.g. Gallopín *et al*., 1997; Raskin *et al*., 2002; Shell International, 2003; MEA, 2005; European Environment Agency, 2009). The most relevant to

this exercise are the *Special Report on Emissions Scenarios* (SRES) (Nakićenović and Swart, 2000). The SRES scenarios have been widely used to study the potential impacts of future climates, especially within the IPCC process. The SRES scenarios are based on four global 'storylines' (termed the A1, A2, B1 and B2 worlds, respectively), which represent different world futures based on two distinct axes or dimensions: (i) economic versus environmental concerns, and (ii) globalised versus regional/national-based development patterns. These two axes define four distinct quadrants for future development. Table 4 arrays these two axes and lists some of the characteristics of each of these four future scenarios. For example, both of the 'A' worlds focus on the material economy and economic growth. This leads to continued ecosystem destruction in both cases. The globalised version (A1 – world markets) envisions moderate global population growth (due to improved economic conditions) but large coastward migration (due to the ease of migration in a globalised world). The regional/national version (A2 – national enterprise) envisions the highest population growth due to the diversity of economic growth rates and small coastward migration (due to the restrictions on migration in a regionalised world). The 'B' worlds focus on both environment and quality of life more broadly construed to include non-market contributions such as natural and social capital. Both versions envision the preservation and restoration of ecosystems and their services. The globalized version (B1 – global sustainability) relies on global cooperation and convergence, which produces moderate global population growth but large coastward migration. The regional/national version (B2 – local stewardship) is more heterogeneous, producing high global population growth but small coastward migration due to the restrictions a regionalised world embodies. Tables 5–8 and Figures 2 and 3 provide more details on the implications of these scenarios for ecosystem services and coastward migration.

Table 4: A summary of the most important characteristics of each SRES Storyline (Nakićenović and Swart, 2000). The scenario names are a national interpretation by the UK Climate Impacts Programme (2000), among others.

Axes	A. Focus on Material Economy and Growth	B. Focus on Environment and Quality of Life
1. Globalised	"A1 World" (World Markets) ▪Increasing globalisation/convergence ▪Rapid global economic growth ▪Materialist / consumerist ▪Rapid uniform technological innovation ▪Moderate population growth ▪Largest coastward migration ▪Continued ecosystem destruction	"B1 World" (Global Sustainability) ▪Increasing global cooperation/ convergence ▪Environmental priority ▪Clean and efficient technologies ▪Moderate population growth ▪Large coastward migration ▪Ecosystem preservation and restoration
2. Regional/National	"A2 World" (National Enterprise) ▪Heterogeneous world ▪Rapid regional economic growth ▪Materialist/consumerist ▪Diverse technological innovation ▪Highest population growth ▪Small coastward migration ▪Continued ecosystem destruction	"B2 World" (Local Stewardship) ▪Heterogeneous world/local emphasis ▪Environmental priority ▪Clean and efficient technologies ▪High population growth ▪Smallest coastward migration ▪Ecosystem preservation and restoration

Table 5: Trends for selected global-mean _non-climatic_ environmental and socioeconomic drivers relevant to coastal areas for the 20th and 21st centuries. (Trend: ↑ increase; ↓ decrease). Substantial regional and local deviations are expected and climate change will be an additional driver of change (see Table 2) (adapted from Nicholls _et al._, 2007, 2008, 2011)

Environmental and Socio-economic Drivers		20th Century Trend	21st Century trends (by SRES Future)				Relevant studies (not necessarily SRES-based)
			"A1 World"	"A2 World"	"B1 World"	"B2 World"	
Global	Population in 2100 (billions)	↑	−7[1]	−15	−7[1]	−10	Nakićemović and Swart (2000); Arnell _et al._ (2004)
	GDP in 2100 (trillions US 1990 dollars)	↑	525-550	243	328	235	
	Average GDP/capita in 2100 (thousands US 1990 dollars)	↑	75-79	16	47	24	
	Human Impact (GDPxPopulation) (x10^{21} person$)	↑	3710	3645	2296	2350	Calculated
Coastal Areas	Coastward population migration (influencing coastal population)	↑	Most likely	Less likely	More likely	Least likely	Nicholls (2004); Nicholls and Lowe (2004); UNEP (2005)
	Infrastructure (e.g., urban areas, industry, ports)	↑	Largest increase	Large increase	Smaller increase	Smallest increase	Fankhauser (1995); Tol (2007); Nicholls et al. (2007b)
	Human-induced subsidence[2]	↑	More likely		Less likely		Nicholls (2004); Nicholls et al. (2007b); Ericson et al. (2006)[6]
	Terrestrial freshwater/sediment supply[3]	↓	Greatest reduction	Large reduction	Smallest reduction	Smaller reduction	Ericson et al. (2006)[6]
	Desalination	↑	Largest increase	Large increase	Smaller increase[7]		little or no analysis of potential future effects
	Aquaculture	↑	Large increase		Smaller increase		Cork et al. (2005)
	Extractive industries	↑	Larger increase		Smaller increase		little or no analysis of potential future effects
	Tourism	↑	Highest growth	High growth	High growth	Lowest growth	Hamilton et al. (2005a ; 2005b); Bigano et al. 2005
	Marine Renewable Energy	↑	Variable growth[4]	Lowest growth	Highest growth	High growth	little or no future analysis
	Habitat destruction (direct and indirect)	↑	Continued loss		Reduced loss, stability or even restoration		Kennish (2002)[5]; Nicholls (2004); Hoegh-Guldberg and Hoegh-Guldberg (2004); Cork et al. (2005)

[1] In 2050, global population peaks at 8.7 billion.

[2] Subsidence due to sub-surface fluid withdrawal and drainage of organic soils in susceptible coastal lowlands.

[3] Due to catchment management (as opposed to climate change per se). Most relevant for deltas, estuaries and lagoons.

[4] Depends on which A1 variant is considered – lowest under the A1FI storyline and highest under the A1T storyline.

[5] The coastal population scenario in this study appears much higher than realistic.

[6] Assumes that present conditions continue to 2050.

[7] B1/B2 worlds will focus on desalination via non-carbon energy sources – green innovation would promote its uptake.

Table 6: SRES scenarios compared with the Millennium Ecosystem Assessment and
Great Transition Initiative scenarios in terms of overall quality of life

Scenario exercise	Overall Quality of Life of the Scenario			
	Most desirable (highest quality of life)	Intermediate (based on cooperation)	Intermediate (based on individuals and markets)	Least Desirable (lowest quality of life)
Special Report on Emissions Scenarios (SRES)	"B1 World" (global sustainability)	"B2 World" (local stewardship)	"A1 World" (world markets)	"A2 World" (national enterprise)
Millennium Assessment	Adapting Mosic	Global Orchestration	TechnoGarden	Order from Strength
Great Transition Initiative	Great Transition	Policy Reform	Market Forces	Fortress World

Services	A1	A2	B1	B2
Food				
Fiber, timber, fuel				
Medicines, other				
Conservation and biodiversity				
Biological regulation				
Nursery and refugia				
Nutrient cycling and fertility				
Hydrological				
Atmospheric and climate regulation				
Human disease control				
Waste processing				
Flood/storm protection				
Erosion control				
Cultural and amenity				
Recreational				
Aesthetics				

Table 7: Impacts on coastal ecosystem services in each of the four SRES scenarios

Legend:
- Highest loss
- High loss
- Medium loss
- Low loss
- Gain

Nicholls *et al.* (2011) have summarised the trends for coastal areas for each of the four main SRES scenarios (Table 5). We use this assessment as the basis for our analysis of the effects of these changes on coastal ecosystems services.

At the global scale, a proxy for the magnitude of human impact on ecosystems in general, and coastal ecosystems in particular (given the concentration of people near the coasts), is GDP multiplied by human population. We have added this proxy to Table 5. The two 'A' worlds have significantly higher human impact than the two 'B' worlds, but from different combinations of population and GDP.

Table 5 also shows the characteristics of coastal areas in each of the scenarios. Of particular relevance is the estimated likelihood of coastward human migration. Here the two '1' (globalised) worlds are seen to be more likely to experience coastward migration than the two '2' worlds (regional/national) due to the increased ease of human migration in the more globalised worlds.

Another particularly relevant variable is the estimated habitat destruction. Here there is a significant difference between the 'A' worlds and the 'B' worlds. In the two 'A' worlds there is continued loss of coastal habitat (and the ecosystem services they provide) whereas in the two 'B' worlds there is reduced loss, stability or even restoration, leading to the possibility for increased ecosystem services.

Table 7 shows the impacts on coastal ecosystem services in each of the four SRES scenarios on a scale from red (highest loss) to green (highest gain). The table clearly shows the high rates of loss of various services in the two 'A' worlds, and the moderate loss to gain in the 'B' worlds. The B1 world is clearly superior in terms of ecosystem services.

Table 7 shows the impacts of coastal ecosystem service change on coastward migration for each of the four scenarios.

Figures 2 and 3 are maps of these future scenarios. Figure 2 shows current global ecosystem services per capita, with blow-ups of the Mississippi Delta and Bangladesh. It also shows an estimate for changes in ecosystem services for 2060 for the SRES 'A' scenarios (top) and 'B' scenarios (bottom). The 'A' scenarios (A1 and A2) both have continued ecosystem destruction (see Table 1) whereas the 'B' scenarios (B1 and B2) both have ecosystem preservation and restoration.
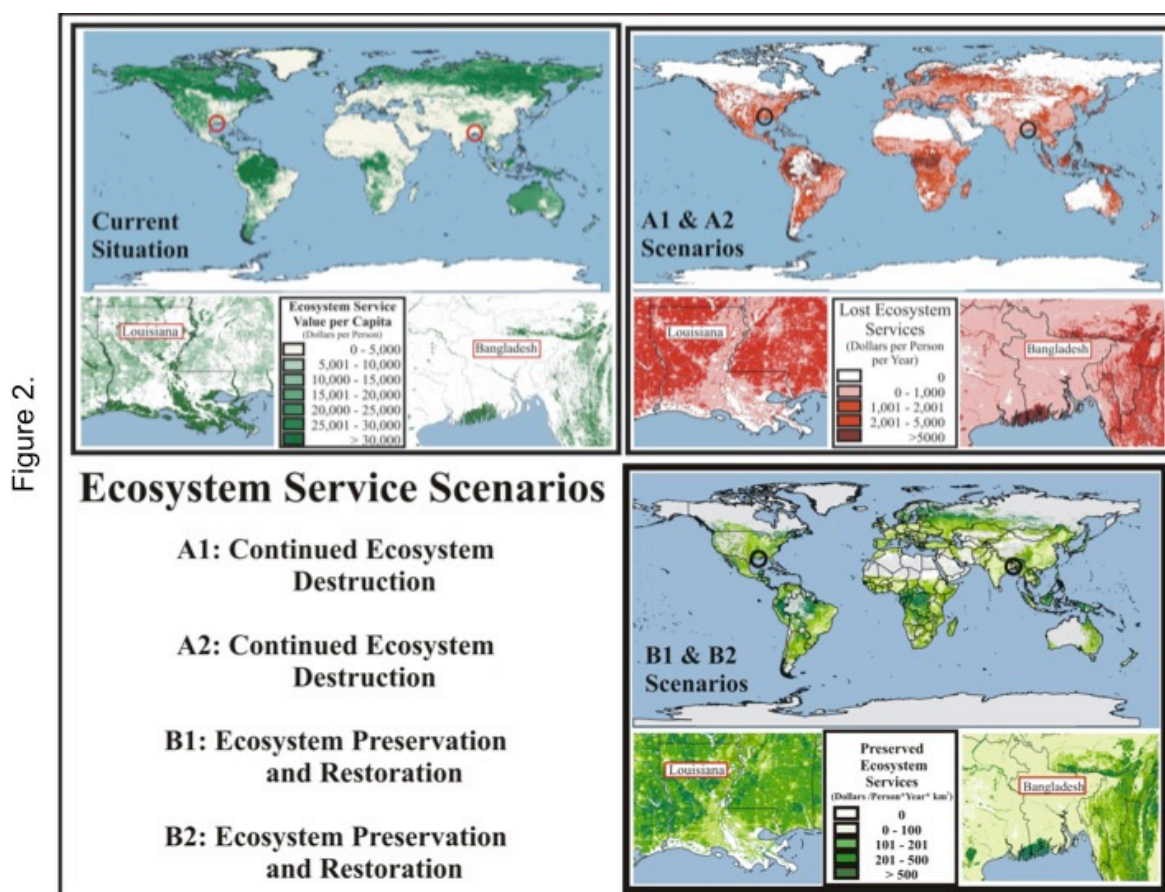

Figure 2.

Figure 3 shows current global population with blow-ups of the Mississippi Delta and Bangladesh, along with estimates for population change in 2060 for the SRES '1' scenarios (top) and '2' scenarios (bottom). The '1' scenarios (A1 and B1) both have moderate global population growth but large coastward migration, whereas the '2' scenarios (A2 and B2) both have high global population growth but small coastward migration. Coastward population migration is largest in the globalised scenarios (A1 and B1) because of increased ease of migration in a more globalised world. Coastal habitat change is negative in the material economy-focused scenarios (A1 and A2) but potentially positive in the environment-focused scenarios (B1 and B2).
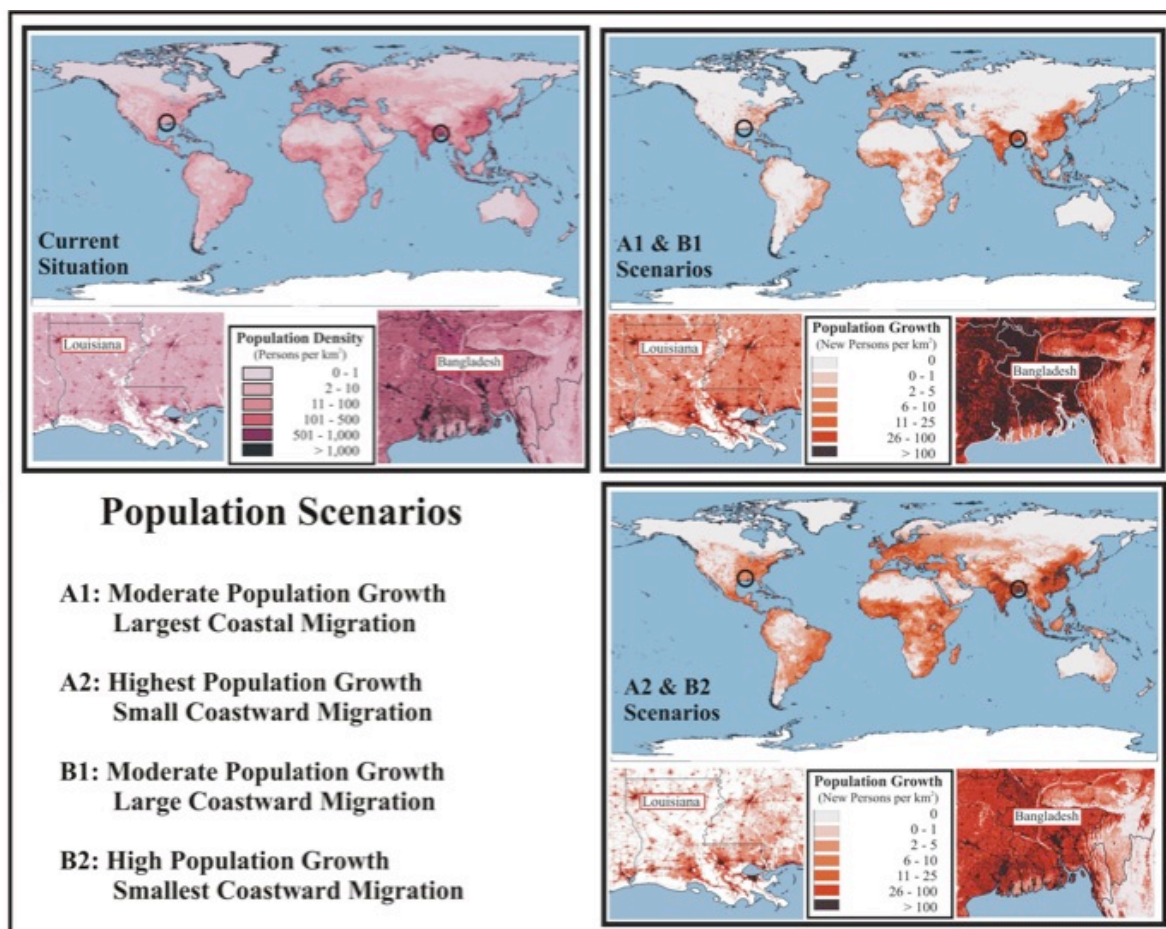
Figure 3.

Table 8 shows the impacts of coastal ecosystem service change on coastward migration in each of the four SRES scenarios. It is clear from this table that changes in ecosystem services would have the most impact on migration in the B1 and A1 scenarios, again because of increased ease of migration in a more globalised world. A major difference is that in the B1 world, ecosystem services are being preserved and restored, so even though migration is more sensitive to changes in ecosystem services, the likelihood is reduced.

Services	A1	A2	B1	B2
Food	Large	Smallest	Largest	Small
Fibre, timber, fuel	Large	Smallest	Largest	Small
Medicines, other	Large	Smallest	Largest	Smallest
Conservation and biodiversity	Large	Small	Largest	Smallest
Biological regulation	Small	Small	Large	Small
Nursery and refugia	Large	Smallest	Largest	Small
Nutrient cycling and fertility	Small	Small	Large	Small
Hydrological	Small	Small	Large	Small
Atmospheric and climate regulation	Large	Small	Largest	Smallest
Human disease control	Large	Smallest	Large	
Waste processing	Large	Smallest	Small	Small
Flood/storm protection	Large	Small	Largest	Small
Erosion control	Large	Small	Largest	Smallest
Cultural and amenity	Small	Small	Largest	Small
Recreational	Small	Small	Large	Small
Aesthetics	Large	Smallest	Large	Small

Table 8: Impacts of coastal ecosystem service change on coastward migration in each of the four SRES scenarios

Legend:
- ■ Largest coastward migration
- ■ Large coastward migration
- ■ Small coastward migration
- ■ Smallest coastward migration
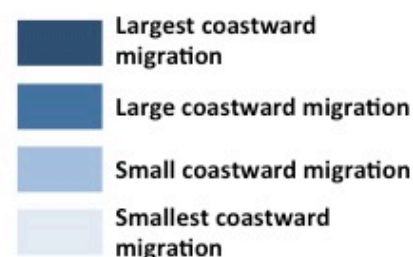
Comparison with other scenario-planning exercises

Scenarios have been developed for a range of applications from global to local scales, including corporate strategy (Wack, 1985; Chermack, 2011), political transition (Kahane, 1992), global envisioning (Costanza, 2000) and community-based natural resource management (Wollenberg *et al*., 2000; Evans *et al*., 2006). Table 6 compares the SRES scenarios described above with two other important global scenario exercises: (i) the Millennium Ecosystem Assessment (MEA, 2005) scenarios and (ii) the Great Transition Initiative scenarios. An interesting feature of these three exercises is that their scenarios are all fairly consistent and fall along a spectrum of 'quality of life' or human well-being. We have grouped the scenarios in that way in Table 6. Below we briefly describe the MA and GTI scenarios and how they correspond to the SRES scenarios.

The Millennium Ecosystem Assessment (MEA) scenarios used the two axes of global connectedness (from highly connected to disconnected) and approaches to ecosystem services management (from reactive to proactive) to evaluate the future status of ecosystem services and human well-being (MEA, 2005). The two globally connected scenarios were *TechnoGarden*, which envisions a globally connected world relying strongly on environmentally sound technology, and *Global Orchestration*, which envisions a globally connected society that focuses on global trade and economic liberalisation. The two regionalised and disconnected scenarios were *Order from Strength*, which envisions a regionalised and fragmented world, concerned with security and protection, and *Adapting Mosaic*, which envisions that regional watershed-scale ecosystems are the focus of political and economic activity. All but the *Order*

from Strength scenarios showed that significant changes in policy can partially mitigate the negative consequences of growing pressures on ecosystems.

The Great Transition Initiative (Raskin *et al*., 2002) involves four major scenarios. *Fortress World* envisions the grim possibility that the social, economic and moral underpinnings of civilisation deteriorate, as emerging problems overwhelm the coping capacity of both markets and policy reforms. The *Market Forces* scenario is a story of a market-driven world in the 21st century in which demographic, economic, environmental and technological trends unfold without major surprise relative to unfolding trends. The *Policy Reform* scenario envisions the emergence of strong political will for taking harmonised and rapid action to ensure a successful transition to a more equitable and environmentally resilient future. The *Great Transition* scenario explores visionary solutions to the sustainability challenge, including new socioeconomic arrangements and fundamental changes in values. This scenario depicts a transition to a society that preserves natural systems, provides high levels of welfare through material sufficiency and equitable distribution, and enjoys a strong sense of local solidarity. This scenario is similar to the MEA *Adapting Mosaic* and SRES B1 scenarios.

Conclusions

Life on the edge of the ocean can be dangerous. Many coastal populations are exposed to natural hazards such as erosion, saltwater intrusion, subsidence, tsunamis, storm surges and river flooding. Multiple exposures to such hazards are common (Nicholls, 2002). If ecosystem services continue to erode, it is likely that more populations will be at risk in the next 50 years.

The magnitude of these risks, the quality of life and vulnerability of coastal populations and the propensity of these populations to migrate depend on the choices we make today. How humanity responds to changes driven by population growth, GDP growth and climate change will probably vary dramatically from nation to nation and region to region. An important consideration with respect to these potential changes is the strength and efficiency of governmental and non-governmental institutions for planning, monitoring and enforcing laws, practices and behaviours. The 2010 earthquakes in Haiti and Chile provide a stark contrast of how important the roles of government and institutions are with respect to both long-term planning and emergency management (Padgett, 2010). It seems that coastal ecosystems will continue to be negatively impacted by climate change, population growth and GDP growth. In light of these anticipated changes it seems prudent to develop a good understanding of the institutional effectiveness of governments around the world in order to focus efforts and allocate resources effectively and efficiently.

We have highlighted four possible futures in line with the SRES scenarios (with reference to the Millennium Ecosystem Assessment and Great Transition Initiative scenarios) and their impacts on ecosystem services and human migration. To summarise:

1. In the A1 world, coastal habitats are being destroyed, overall global population growth is moderate, but coastward migration is high, leading to decreased ecosystem services and quality of life per capita on the coasts along with increased vulnerability to climate change. Migration is high in both this and the other 'globalised' world (B1) because globalisation implies lowering inter-regional barriers to trade and migration. Overall population growth is moderate in these scenarios because world culture and education (particularly of women) is more homogeneous and the 'demographic transition' has progressed more broadly.

2. In the A2 world, overall population growth is highest, but migration to the coasts is less likely, both due to the more regional focus. Coastal habitats are still being destroyed, leading to decreased ecosystem services and quality of life per capita on the coasts and increased vulnerability to climate change. The potential in this world for large numbers of 'environmental refugees' is high, however, because of the degradation of coastal ecosystem services, and these refugees will have a harder time moving and adapting in the more regionalised world.
3. In the B1 world, overall population growth is moderate, while coastward migration is high. But in this scenario coastal habitats are being preserved or restored, leading to higher ecosystem services and quality of life per capita. Threats from climate change are managed and moderated by intact coastal ecosystems, and the threat of environment-induced migration is reduced.
4. In the B2 world, overall population growth is high, but coastward migration is low and coastal habitats are being preserved or restored. This leads to increased ecosystem services, high quality of life per capita and managed threats from climate change in the coastal zone. However, high population growth leads to larger stresses on ecosystem services generally.

It seems obvious which of these possible futures are preferable. The B1 world combines moderate population growth with preservation and restoration of ecosystem services, leading to a higher global and coastal quality of life, lowered threats of environment-induced migration, and a more sustainable and resilient system. The B2 world has high overall population growth causing higher stress on global ecosystem services, but also preserves and restores coastal ecosystem services and maintains a high quality of life.

Several studies (Balmford *et al.*, 2002; MEA, 2005; Stern, 2007; Costanza *et al.*, 2008) have shown that the benefits of investing in the preservation and restoration of ecosystem services far outweigh the costs. The trade-offs in terms of human well-being and sustainability seem to clearly favour a 'B' type of scenario.

It remains to devise the policies and politics to achieve the transition to something like the B worlds, in the face of the huge inertia of 'business as usual'. It will certainly require a change in worldview, social goals and culture, as well as massive technical change (Costanza, 2008; Beddoe *et al.*, 2009). Understanding the complex dynamics that drive human migration patterns and their relationship to ecosystem services is an ongoing research challenge. It is difficult to provide specific policy recommendations without better knowledge of these relationships. In addition, policies should be cast in an 'adaptive management' framework that acknowledges the huge uncertainty involved with policy actions (Holling, 1978; Gunderson *et al.*, 1995). Ultimately, we will need better, spatially explicit, dynamic, predictive models that integrate ecological, demographic, climate, economic, psychological and sociological data and relationships (Costanza and Voinov, 2003; Meyerson *et al.*, 2007). Such models are beginning to be developed, and they hold the promise of helping us to better understand these complex relationships in order to design a more sustainable, resilient and desirable future.

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