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Ecological Engineering: Ecological Management of Coast Zones

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Introduction

This article presents a scientific overview of the processes and the impact of environmental degradation of coastal waters due to human activities on the adjoining land. The direct effects range from eutrophication, harmful algae blooms, to hypoxia and anoxia. The indirect effects are more subtle and can also lead to the collapse of the ecosystem; such is the case of coral reefs. Engineering solutions alone are not available to prevent this degradation that can only be reversed, or prevented, using a basin-wide ecohydrology approach.

The degradation of coastal waters

As highlighted in chapter 44, throughout the world estuaries have experienced environmental degradation and present proposed remedial measures based on engineering and technological fix have been unable to restore the ecological processes of a healthy, robust estuary and, as such, will not reinstate the full beneficial functions of the estuary ecosystem.

This story of degradation is repeated worldwide also for coast zones. The problem is more insidious, and harder to address, because historically coast zones were seen as having essentially infinite capacity to dilute waste from human activities and because the fisheries resources were essentially free for all. Yet, just like estuaries, coastal waters are also suffering from increasing eutrophication, increasing turbidity, harmful algae blooms, fisheries collapse, and an increasing loss of biodiversity. At the same time these waters are increasingly polluted and impacted by hydrocarbons from low-level, chronic oil spills as well as occasional and often catastrophic oil spills. Some of these coastal waters are also showing signs of impacts by climate change.

All these effects have negative socio-economic impacts through the loss of income and employment for coastal communities. They suggest that if these issues are not addressed coastal waters will increasingly be degraded and ultimately may suffer the fate of many estuaries worldwide that have become essentially little more than drains for wastes and channels for navigation (see chapter 44). This scenario runs contrary to the wishes of the human population that, with increasing wealth, demands a high quality of life.

Ecological engineering for eutrophication management in coastal zones

Upwelling zones, which receive infusions of nutrients from deep ocean waters, support some of the most productive marine ecosystems. However, anthropogenic eutrophication of estuaries and coastal zones has been a growing problem since the latter half of the 20th century. The main drivers for this have been the increasing proportion of the population moving to the coastal zones, an increase in the burning of fossil fuels, the increase in the use of synthetic fertilizers and the increase in consumption of animal protein, particularly from encouraging the intensive rearing of poultry and pork. Other contributing factors have been the draining of wetlands and the clearing of riparian vegetation. The result of these human activities has been a very large increase of the inputs of certain plant nutrients, particularly Nitrogen and Phosphorus, into aquatic ecosystems. Whereas Phosphorus is often the limiting nutrient in freshwater systems, Nitrogen is most often the naturally limiting nutrient in estuarine and coastal systems.

Within the estuarine to coastal continuum, multiple nutrient limitations occur among nitrogen, phosphorus, and silicon along the salinity gradient and by season,

Nutrients are essential for the algal production that supports food webs. There are thresholds; however, where the load of nutrients to estuarine, coastal and marine systems exceeds the capacity for assimilation of nutrient-enhanced production, and water quality degradation occurs. An imbalance of these nutrients in combination with silica leads to shifts in phytoplankton community composition. Impacts can include noxious and toxic algal blooms, increased turbidity with a subsequent loss of submerged aquatic vegetation, oxygen deficiency, disruption of ecosystem functioning, loss of habitat, loss of biodiversity, shifts in food webs, and loss of harvestable fisheries.

Rivers play a crucial role in the delivery of nutrients to the ocean. In the sub-basins to the North Atlantic Ocean, specifically in the Baltic catchments, and in the watershed of the Mississippi River, inputs of anthropogenic nitrogen via rivers far exceed other sources of nitrogen input—atmospheric deposition, coastal point sources, and nitrogen fixation. Phosphorus loads, likewise, come mostly from rivers. Direct atmospheric deposition of nitrogen and phosphorus on estuaries and coastal waters may contribute as little as 1% to as much as 30-40% of the total load. The relative sources of nitrogen and phosphorus loads to the coastal ocean correspond to the degree of various anthropogenic activities in the watershed.

The susceptibility of estuaries and coastal waters to eutrophication is largely controlled by the physics of these systems such as the geomorphology, the tidal range, the residence time and flushing rates, and the engineering of river mouths or inlets. Partially enclosed systems with restricted exchange for example lagoons, fjords and large estuaries, such as the Chesapeake Bay, are particularly vulnerable. This is also the case for inland seas, such as the Baltic, the Black Sea and the Adriatic. Some of the symptoms of eutrophication in estuaries may be partially alleviated by ecological engineering measures such as building of treatment ponds, dredging, creating man-made mouths, and wetland restoration and creation.

Several indices are under development or being tested for the evaluation of eutrophication by ecological engineers. They are important management tools and, combined with scenarios of different future outlooks, maybe used as future prediction tools. A widely used screening model is the USA National Estuarine Eutrophication Assessment that has been updated into the ASSETS model. It has been applied in most of the USA estuaries, several European and Chinese systems. Another screening model in widespread use in Europe is the OSPAR Comprehensive Procedure.

Some options for the effective control of point sources of nutrients are available to ecological engineers. These include the construction of urban waste water treatment plants or the upgrading of existing plants to tertiary treatment. However, the outlook is much bleaker for the control of diffuse sources such as agricultural runoff and atmospheric deposition. The harmonization of presently conflicting policies such as agricultural subsidies, that encourage the excessive use of fertilizers, and environmental policies, such as the Clean Water Act (USA) and the Water Framework Directive (EU) may in future help resolve some of these issues. Certainly changes in the socio-economic situation of countries and regions can have an effect on eutrophication. The collapse of collective farming practices after the break-up of the Soviet Union was one example of how a change in agriculture can relieve the pressures on coastal ecosystems, in this case the Black Sea. However, changes in lifestyles in European countries as a result of adhesion to the European Union have resulted in an increase in the per capita consumption of animal protein and this has increased the Nitrogen input into the aquatic systems. Similar increases in animal protein consumption are presently occurring throughout South East Asia as a result of booming economies.

Aquaculture is another human activity that can both be affected by eutrophication and can also impact eutrophication. The deterioration of water quality resulting from eutrophication can have serious repercussions on the aquaculture industry. However, the excessive feeding of fish in cage aquaculture can also contribute to the increase in Nitrogen inputs into aquatic ecosystems. Conversely, the culture of filter feeding bivalves may significantly graze algal blooms resulting from the over stimulation of phytoplankton production. An apparently contradictory situation of high Nitrogen-low chlorophyll may develop in such cases. Conversely the destruction by over-harvesting of natural filter bivalve beds may favour eutrophication. Such is the case of the Chesapeake Bay where the loss of the oyster grounds probably contributed significantly to the vulnerability of this large estuary to eutrophication.

Poly-culture practices in Chinese bays effectively use macro-algae to mop up some of the excessive nutrients as well as bivalves and abalone as grazers. These can help control the effects of eutrophication although the aquacultures are still vulnerable to the occurrence of harmful algal blooms.

Hypoxia and Anoxia

A common manifestation of eutrophication is hypoxia (dissolved oxygen concentration DO less than 2 mg l^{-1}) and anoxia (DO=0), i.e. the depletion of dissolved oxygen in coastal waters, leading to ‘dead zones.’ When the DO is less than a critical value (typically 2 mg l^{-1}), mobile animals such as demersal fish, crabs, and shrimp migrate away from the area. Resident animals die when the DO is less than 1 mg l^{-1}. Fisheries have collapsed, notably in the Baltic and Black seas.

Hypoxia occurs naturally in many parts of the world’s marine environments, such as fjords, deep basins, open ocean oxygen minimum zones, and oxygen minimum zones associated with upwelling systems). Hypoxic and anoxic waters have existed throughout geologic time, but their occurrence in shallow coastal and estuarine areas is increasing. The severity of hypoxia (either duration, intensity, or size) has increased where hypoxia occurred historically, and hypoxia exists now when it did not occur before. The severity of hypoxia increased in the northern Gulf of Mexico, primarily since the 1960s. Evidence comes from paleo-indicators in accumulated sediments, long-term hydrographic data, and scenarios based on empirical models. The size and frequency of hypoxia in the Gulf of Mexico have increased as the flux of nitrate increased, and there is a direct correlation between nitrate flux to the Gulf of Mexico from the Mississippi River and the mid-summer size of the hypoxic zone.

Aerobic bacteria consume oxygen during decomposition of the excess carbon that sinks from the upper water column to the seabed. There will be a net loss of oxygen in the lower water column, if the consumption rate is faster than the diffusion of oxygen from surface waters to bottom waters. Hypoxia is more likely when stratification of the water column occurs and will persist as long as oxygen consumption rates exceed those of resupply.

Some of the largest hypoxic zones are in the coastal areas of the Baltic Sea, the northern Gulf of Mexico, and the northwestern shelf of the Black Sea (reaching 84,000 km^2, 22,000 km^2, and 40,000 km^2 (until recently), respectively. Hypoxia existed on the northwestern Black Sea shelf historically, but anoxic events became more frequent and widespread in the 1970s and 1980s reaching over areas of the seafloor up to 40,000 km^2 in depths of 8 to 40 m. Recent reductions in nutrient loads to the northwestern Black Sea resulted in a minimization of the hypoxic zone there. There is also evidence that the suboxic zone of the open Black Sea enlarged towards the surface by about 10 m since 1970. Similar declines in bottom-water dissolved oxygen have occurred elsewhere as a result of increasing nutrient loads and anthropogenic eutrophication, e.g., the northern Adriatic Sea, the Kattegat and Skaggerak, Chesapeake Bay, the German Bight and the North Sea, Long Island Sound, and New York. The number of estuaries with hypoxia or anoxia continues to rise.

The obvious effects of hypoxia/anoxia include the displacement of pelagic organisms and selective loss of demersal and benthic organisms. These impacts may be aperiodic if recovery occurs, may occur on a seasonal basis with differing rates of recovery, or may be permanent so that there is a long-term shift in ecosystem structure and function. As the oxygen concentration falls from saturated or optimal levels towards depletion, a variety of behavioral and physiological impairments affect the animals that reside in the water column or in the sediments or attached to hard substrates. Hypoxia also affects optimal growth rates and reproductive capacity. Mobile animals, such as shrimp, fish, and some crabs, flee waters where the oxygen concentration falls below 3 to 2 mg l^{-1}. Movements of animals onshore can result in “jubilees” where stunned fish and shrimp are easily captured, or result in massive fish kills. As dissolved oxygen concentrations continue to fall, less mobile organisms become stressed and move up out of the sediments, attempt to leave the seabed. As oxygen levels fall from 0.5 mg l^{-1} towards 0, there is a fairly linear decrease in benthic infaunal diversity, abundance, and biomass.

Entire taxa may be lost in severely stressed seasonal hypoxic/anoxic zones. Larger, longer-lived burrowing infauna are replaced by short-lived, smaller surface deposit-feeding polychaetes, and certain typical marine invertebrates are absent from the fauna, for example, pericaridean crustaceans, bivalves, gastropods, and ophiuroids. Increasing oxygen stress for the Skagerrak coast of western Sweden in semi-enclosed fjordic areas resulted in declines in the abundance and biomass of macroinfauna, particularly mollusks, suspension feeders and carnivores. These changes in benthic communities result in an impoverished diet for bottom-feeding fish and crustaceans.

Harmful algal blooms

Cultural and natural eutrophication have both contributed to changes in nutrient input to coastal waters, and led to an overall increase in nutrient availability and an alteration in nutrient composition. The first result of these changes is often an increase of total algal biomass and shifts in species composition potentially leading to secondary disturbance such as harmful algal blooms (HABs). HAB species range from marine, brackish to freshwater organisms and cover a broad range of phylogenetic types (dinoflagellates, diatoms, raphidophytes, cyanobacteria). Most HAB species form massive blooms of various colors (red, brown or green). A few species can produce potent toxins. These toxins can directly kill marine mammals and transfer through the food chain causing harm at different levels from plankton to humans. A potential impact of HABs on human health occurs through the consumption of shellfish that have filtered toxic phytoplankton from the water or planktivorous fish. All poisoning syndromes are serious and can be fatal. They are named paralytic (PSP), diarrhetic (DSP), neurotoxic (NSP), azapiracid (AZP) and amnesic shellfish poisoning (ASP). All syndromes, except for ASP, are caused by dinoflagellates. ASP is caused by diatoms, a group of phytoplankton usually thought to be non toxic. In tropical and sub tropical zones, another human poisoning syndrome, ciguatera fish poisoning (CFP) is caused by toxic dinoflagellates that grow on substrate in coral reef communities. CFP toxins are transferred from herbivorous to carnivorous fish that are commercially valuable. Some algal toxins, brevetoxins, are airborne in sea-spray, causing respiratory distress in coastal population e.g. in the Gulf of Mexico. Cyanobacteria (blue-green algae) naturally bloom in still inland waters, estuaries and the sea during summer. Some cyanobacteria produce potent cyanotoxins (anatoxins, microcystins, nodularin), which are dangerous and sometimes fatal to livestock, wildlife, marine animals and humans. These toxins represent a serious health risk in water bodies used for recreational and/or as freshwater supply reservoirs.

Although references to HABs date back to biblical times, the number of toxic events and subsequent economic losses linked to HABs has increased considerably in recent years around the world. Many reports point out an obvious link between pollution and HABs, but there are also other reasons to the expansion of the HAB problem.

Numerous new bloom events have been discovered because of increased awareness and improved detection methodologies (e.g. molecular probes for cell recognition, PCR probes for rDNA specific to genera or species of HABs, Enzyme Linked Immunosorbent Assays (ELISA), remote sensing data from satellites, qualified observers, efficient monitoring programmes). The global increase of aquaculture activities and trade of exotic species has led to improved safety and quality controls that revealed the presence of HAB species and/or toxins in e.g. aquaculture pens, contaminated seafood. Mortality events and toxicity outbreaks in fish or bivalves resources can no longer go unnoticed. Transport of toxic species in ship ballast water undeniably contributes to the increasingly damaging effect of HABs on fisheries, aquaculture, human health, tourism and the marine and brackish environment. UNEP has recently ranked HABs among the 10 worst threats of invasive species transported in ballast water.

Dispersal of HABs is influenced by oceanic and estuarine circulation, and river flow combined with currents, upwelling, salinity, nutrients and specific life-cycles of various HAB species. The apparent increase in toxic diatoms (*Pseudonitzschia* spp.) off the US and Canada coast is often coupled to physical forcing (storm, wind, rain, upwelling) and more rarely to the increase in nitrate-N in rivers, e.g. from the Mississippi River. Both nutrient and harmful dinoflagellate taxa are introduced from upwelling/downwelling areas to estuaries, coastal bays or lagoons e.g. the Atlantic coast of France, Spain and Portugal, Chesapeake Bay, the Benguela region. Similar processes are observed for cyanobacteria in the Gulf of Finland. Physical convergence, advection or accumulation process of oceanic dinoflagellates (*Dinophysis*, *Karenia*, *Gymnodinium*) in embayments also contribute to the extension of HABs in some areas. Large oceanic current systems transport the N-fixing cyanobacterium *Trichodesmium* from tropical oligotrophic regions to W. Florida waters, enriched with Saharian iron dust, where it blooms. Some HABs have specific life cycles including resting stages for diatoms (spores), dinoflagellates (cysts) and cyanobacteria (akinetes). These resting stages provide these algae with a competitive advantage over populations that cannot survive in poor conditions.

Climatic and hydrological changes affect nutrient delivery and processing e.g. the input of micronutrients and freshwater from rainfall and river flow, flooding after hurricanes and tropical storms also favor HABs growth and persistence. Certain PSP and CFP producers (dinoflagellates) have increased significantly under large-scale changing climatic conditions in temperate environments (Kattegat, NW Spain, SW Portugal) and in the Indo-Pacific, respectively. Some of these blooms have been linked to the North Atlantic Oscillations (NAO) and to El-Niño events that affect local climate in wind-driven upwelling systems.

Despite the importance of natural events in algal bloom formation, many examples relate HABs to anthropogenic activities since World War II. Red tides (dinoflagellates) in Asia e.g. the mouth of the Yangtze Estuary in China and the Seto Inland Sea in Japan are related to the parallel increasing population density and nitrogen (N) and (P) loadings. Nutrient-enriched conditions in brackish coastal bays and estuaries have been correlated with high abundance of diatoms (central California, Louisiana in the

US), dinoflagellates (off the coast of North Carolina-US, Northern Adriatic, Aegean and Black Sea), and halotolerant cyanobacteria (Baltic Sea, Brazil, Australia) but the direct cause of this relationship is not fully understood. In tropical regions, eutrophication of reef communities often lead to the overgrowth of macroalgae on corals and high coral mortality that favor the bloom of benthic dinoflagellates (CFP producers). Both elevated N and P concentrations and silicon limitation can favor the dominance of HABs e.g. the haptophyte *Phaeocystis* in the North Sea. Declining silicon input to coastal zones and estuaries is often due to damming of rivers and give a competitive advantage to marine haptophytes and dinoflagellates over diatoms. The residence time of the water in freshwater systems is increased by the construction of the dams. This allows for the development of freshwater diatom blooms. The Silicon-rich frustules of the diatoms are not remineralized as rapidly as organic matter and so dams effectively retain Silicon upstream. The ratio of Silicon to Nitrogen therefore decreases and estuarine and coastal diatoms may have insufficient Silicon to divide. The communities of phytoplankton organisms may therefore shift so that diatoms are replace by non-silicon requiring organisms such as dinoflagellates and this may significantly alter the food web.

Many potable water reservoirs are under the pressure of expanding population, and are negatively impacted by both sediment erosion i.e. reduce water flow and elevated N and P loading that will stimulate noxious cyanobacterial blooms. Similar trends are reported for river systems with weir pools. Many HABs have characteristic modes of nutrition from autotrophy to heterotrophy i.e. can use organic carbon, nitrogen and phosphorus (mixotrophy, osmotrophy). Recent studies have shown that the increase in organic nutrients could benefit certain HABs (dinoflagellates, prymnesiophytes). The global nitrogen-based fertilizer usage has shifted toward urea-based products and is expected to continue. Thus, significant amounts of urea are transported to estuarine and coastal waters with the potential for increasing eutrophication of these sensitive areas. Since urea is also one very important nitrogen substrate for some HAB species, the global increase of PSP outbreaks is comparable to the increase of urea use for 1975-2005. Aquaculture sites are also a large source of nutrient from animal excreta, rich in N and P, to coastal sediment. Their contribution to HAB formation will depend on the hydrology of the system e.g. HAB proliferate in calm areas.

Among the natural marine environmental contaminants that are health risks, HABs are most prominent. However, the relative effects of natural versus anthropogenic factors on harmful algal blooms cannot yet be resolved.

Dead zones

Once the consequences of eutrophication are felt in coastal waters there is little that can be achieved to redress the situation by ecological engineers. The scale of coastal waters and their open boundaries make management difficult or impossible. Examples of this are the dead zones of hypoxic and anoxic waters in the Gulf of Mexico and the Black Sea. Only the surface waters of the Black Sea remain oxic and most of this deep basin is anoxic. Two-thirds of the continental USA agricultural lands drain down the Mississippi into the Gulf of Mexico. The runoff of excess fertilizers increases nutrient inputs ands also causes imbalances in the nutrient ratio. The plume of the Mississippi can be seen from satellite imagery but the effects of the nutrients are more widespread and can be detected through remote sensing by the high chlorophyll concentrations from the phytoplankton blooms. This excessive production unbalances the ecosystem and the microbial decomposition of the increased organic matter depletes the water of oxygen leading to hypoxia and even anoxia. The effect is particularly marked during the summer months when the waters are warm and saline therefore oxygen is less soluble. No effective ecological engineering measures are possible offshore to counter this effect that in some years covers a very large area of the Gulf of Mexico leading to the loss of valuable fisheries. However, the summer is also the hurricane season in the Gulf of Mexico and the turbulence and mixing caused by large and frequent storms can at times break up the "Dead" zone.

Ecological engineering of coral reefs

Coral reefs can be severely degraded with much smaller levels of eutrophication than those needed to impact open waters. As detailed in chapter 44, coral reefs have a rich biodiversity and they greatly benefit humanity by building islands and atolls, inhibiting coastal erosion, and supporting fisheries and tourism. The destruction of coastal coral reefs is increasing worldwide (e.g. up to 50% in the last 15 years in some Asian countries). There is not one country in the world that has put in place a sustainable coral reef management policy because human activities on land are not incorporated in coral reef management policies. The present coral reef strategy principle relies on drawing a line around selected coral reefs and naming them marine parks or marine protected areas. Corals and its fisheries are protected inside that line. It ignores the fact that the land and the coral reef are ecologically connected through the rivers. As a result this management practice invariably fails where the corals are impacted by rivers that are impacted by human activities in the catchment.

The health of coral reefs fluctuates naturally in time. Historically coral reefs have been impacted by natural disturbances such as tropical cyclones and river floods; if good water quality prevailed after these occasional disturbances, reefs have invariably recovered. Nowadays coral reefs are subject to direct human impacts from land runoff from river catchments impacted by human activities; this results in an increase in suspended sediment and nutrient concentration during the recovery period after a natural disturbance, and from global warming that generates increased bleaching events in summer. Coral reefs are weakened, more frequently diseased, and unable to recover between disturbances, they are thus commonly slowly dying out from failure to recover from disturbances.

The physical forcings of coastal coral reefs are river floods and tropical cyclones that are natural disturbances, and the oceanography that enables the exchange of coral planulae between reefs. The biological forcing is mainly the competition for hard substrate space between the coral and the algae. The recruitment of juvenile coral decreases with increasing algal cover on the hard substrate. Human activities on land increase the suspended sediment and nutrient load, and thus help the algae. Algae are preyed upon by herbivorous fish that is preyed upon by carnivorous fish. The harvesting of herbivorous fish by people also helps the algae. The coral is preyed upon by the crown-of-thorns starfish (COTS), whose population dynamics also appears to be helped by human activities on land resulting in increased nutrient that promotes the plankton that supports the drifting COTS larvae. Additionally global warming results in an increased mortality of adult corals, or poor health making them more susceptible to diseases or to be attacked by borers.

An ecohydrology model was built that incorporates all these processes. It was applied to the Great Barrier Reef and successfully verified against twenty years of data. The model suggests (Figure 1) that the biodiversity of the Great Barrier Reef is already seriously impacted by human activities and may progressively over a period of tens of years degrade to end up being mainly an algae-covered substrate, thus becoming an algae-dominated reef most degraded coastal reefs in East Africa, South East Asia, and Micronesia. Thus the Great Barrier Reef, the largest coral reef ecosystem on earth, may become another casuality of the lack of recognition of the need to adopt ecohydrology as a guiding principle in managing human activities. The model suggests that much-improved land-use practices will enable some regions of the Great Barrier Reef to recover, even with global warming. However, the model suggests that if global warming proceeds unchecked only biological adaptation –about which no information is yet available - may prevent a collapse of the Great Barrier Reef health by the year 2100.

Conclusions

Coastal waters are increasingly degraded world-wide through human activities on land. Because coastal waters have open boundaries to the ocean, there are no simple local engineering solutions to maintain or restore their ecosystem health and the ecological services that they provide. In coastal waters, further applications of ecohydrology are the use of macrophytes to enhance the internal consumption rate, and benthic suspension feeders, such as bivalve molluscs, sponges, tunicates, and polychaetes, to filter and pelletize excess nutrients and plankton. As detailed in chapter 55, attempts to restore coastal water quality by planning to restore seagrass beds and coral reefs are bound to fail until the land-use practices that degraded these habitats in the first place are modified.

The only ecologically sustainable management strategy for coastal waters is adopting ecohydrology as the guiding principle for managing human activities on land while at the same time protecting fisheries, implementing a fisheries buy-out programme, and using engineering and technology to treat sewage and storm water. Ecohydrology science offers a number of solutions, including top-down and bottom-up ecological manipulation and the creation and restoration of wetlands to help restore the health of rivers and estuarine waters. This ecological engineering approach can be combined with some technological fixes, such as the creation of freshets and smarter land-use. This necessitates changing present governmental practices based on political geography or specific activities (e.g. farming, water resources, fisheries, urban developments). Generally, the political geography limits or the usage units do not coincide with the basin boundaries. The ecohydrology approach also necessitates a high level of collaboration amongst stakeholders in order to develop best practice. Without these changes, estuaries and coastal waters will continue to degrade worldwide, whatever local integrated coastal management plans are implemented.

This solution is easy to preach and a nightmare to implement, mainly for political and socio-economic reasons. Worldwide the implementation of this science-based strategy will most likely stall until a political solution is found to regulate human activities on land. Indeed local farmers, fishermen and urban developers are often at odds with the imposition of land-use, water resources and fishery management rules that they claim jeopardize their ability to earn a living.

The coastal waters ecosystem modeler is faced with complex processes and feedback processes between the physics and the biology, which often cannot be fully quantified because the data are inadequate. Models should not be seen as able to replace reality and the need for field observations.

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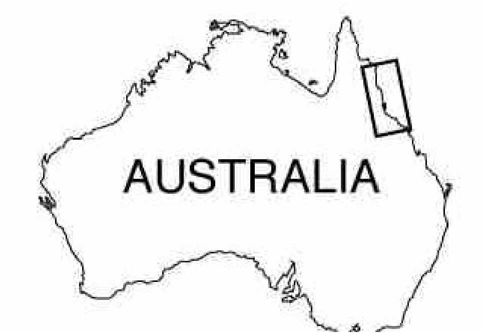
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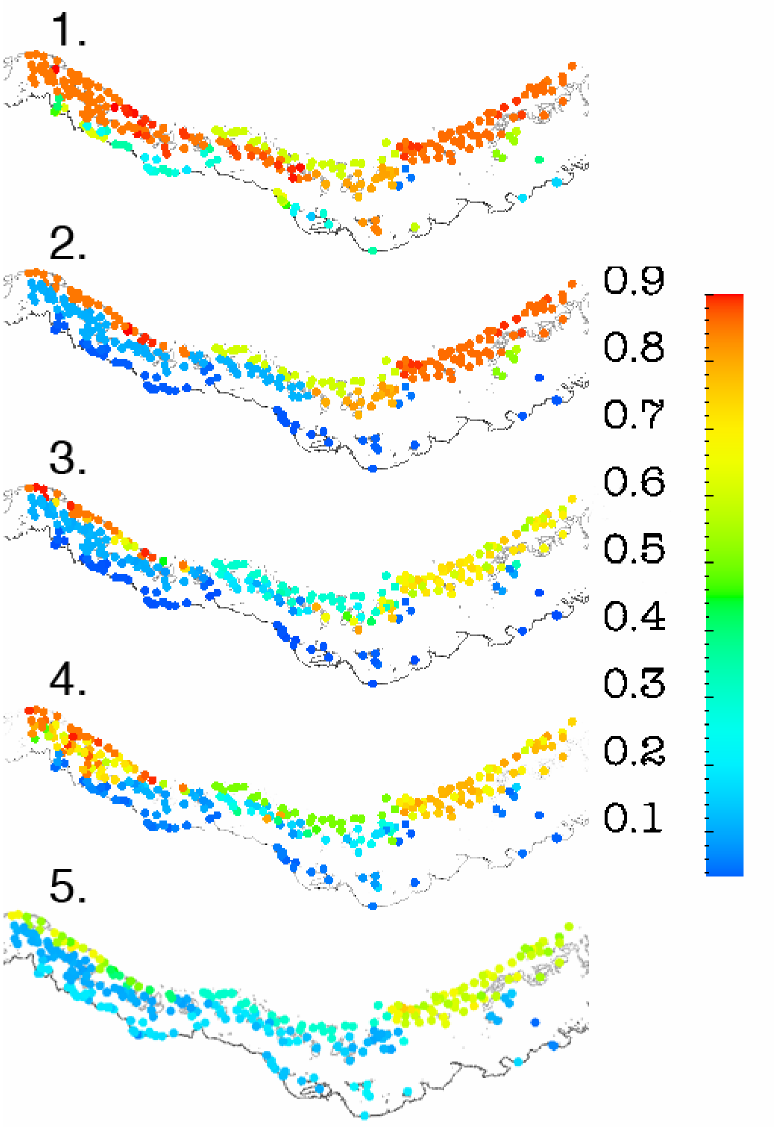
1.
2.
3.
4.
5.
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Figure 1. Location map of the 400-km long central region of the Great Barrier Reef. Predictions of the coral density in the same region for (case 1) no human impact, (case 2) present conditions with land-use, (case 3) existing land-use practices and with global warming in the year 2050 following the IPCC scenario A2, (case 4) halving of the nutrient and sediment runoff from land-use and with global warming following the IPPC scenario A2 in the year 2050, (case 5) same scenario as for case 4 in the year 2100. The colour bar shows the coral density as a fraction of the hard substrate area for each of the 261 reefs in the model domain (eg 0.3 = 30%). Adapted from Wolanski and De’ath (2005).