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Editorial

The 'triple whammy' of coasts under threat – Why we should be worried!

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1. Introduction

Many major and mega-cities have developed on coasts worldwide, thereby increasing reliance on coasts for human habitation and infrastructure, commerce and industry (ports and transport), and tourism and recreation (Small and Nicholls, 2003; Defeo et al., 2009; Sengupta et al., 2020; Defeo et al., in revision). This results from the benefits to human welfare, health and well-being by living on or visiting the coast (Barbier et al., 2011; Bindoff et al., 2019). However, all of this produces adverse pressures, superimposed on which are the repercussions of global climate changes. Because of this, we contend, and summarise our concern, that coasts and their ecosystems worldwide are facing three major threats – (1) increasing urbanisation and industrialisation, (2) increasing use of resources such as water, seafood and space, and (3) increasing susceptibility and decreasing resilience and resistance to the effects of climate change and its related stressors (e.g., sea level rise, warming) – this is what may be called a '*triple whammy*' (NB, a '*whammy*' is defined in the Collins English Dictionary as '*something which has a great, often negative, impact*', colloquially as a punch!) (Fig. 1). As such, we emphasise that these three major threats are acting synergistically, impairing the capacity of coastal systems to provide food, protect livelihoods, satisfy recreation, maintain biodiversity and water quality, and afford protection from extreme climate events (McLachlan et al., 2013; Duarte et al., 2020; Grases et al., 2020). Here we aim to present, explain and explore the *triple whammy*.

2. The first 'whammy' - increasing urbanisation and industrialisation

There are a large and increasing number of natural and anthropogenic hazards to coasts worldwide and, if they affect assets and health that we value, these become risks (see the hazard and risk typology in Elliott et al., 2019; Fanini et al., 2020). Therefore, the risks, as the impact to society and its health and well-being, will increase as more people are moving to the coast. These increase the number and intensity of activities, pressures and effects along the coasts and in the seas (Elliott et al., 2017, 2020a). For example, coastal recreation and tourism are increasing, but the benefits of this are becoming outweighed by damage to the features that created the tourism. Sandy beaches attract tourists who then require the infrastructure merely to provide 'sea, sand and sun', which ruins the features which drew the tourists in the first place – hence we could call 'environment-tourism paradox'.

There are increasing demands on the coastal space – either by building on or removing natural habitats, building out into the sea, or concreting the coast to stop the natural evolution of coasts. This has often been erroneously described as 'reclamation', when in fact it is 'land claim' as nothing is being 'reclaimed' from the sea but is claimed for the first time (Wolanski and Elliott, 2015). The management and engineering measures to protect coasts therefore have evolved as four options: 'hold the line', 'advance the line', 'retreat the line', and, as ever, 'do nothing' (Hino et al., 2017; McLachlan and Defeo, 2018; Grases et al., 2020).

As shown the world over, the increasing urbanisation and industrialisation increases contamination of the coastal zone which, if not controlled, leads to biological effects, i.e. pollution per se. Hence this first whammy implicitly covers oil spills as the result of increasing ports and navigation, organic enrichment leading to hypoxia and eutrophication, industrial waste discharges inputting persistent contaminants, and increased litter such as fishing debris and micro- and macro-plastics (e.g. Elliott et al., 2019 and references therein).

3. The second 'whammy' - increasing use of resources

The second part of the triple whammy refers to the greater use of the available resources; this includes occupation and the material use of physical resources (space, water, sand and gravel aggregates for building, etc.), habitats (wetlands, mangroves, saltmarshes, seagrass beds, dunes) and biological resources (fish and invertebrates for food or bait).

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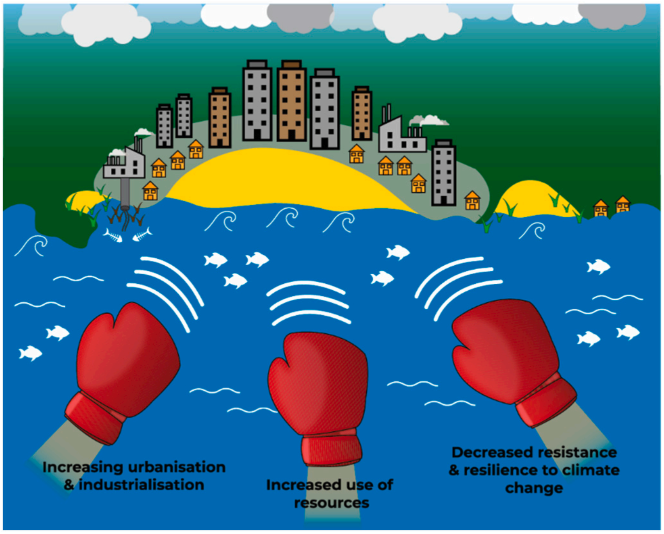

Fig. 1. The '*triple whammy*' for coasts.

Every human activity has a footprint which then creates pressures- and effects-footprints (Elliott et al., 2020a) and each of these needs to be determined and managed, controlled or eliminated. For example, claiming new (terrestrial) land from wetlands leaves an immediate footprint by removing habitat (Wolanski and Elliott, 2015).

The loss of this space and its habitats leads to pressures (the mechanisms of change) and their footprints (the area covered by the pressures) in removing wetlands, in allowing run-off of effluents and sediment, and removing prey populations and refugia for higher animals, especially the birds and fishes. The resulting effects-footprints include areas where birds and fish can no longer feed, where hydrodynamic patterns are disrupted, where organisms become contaminated and where fish can no longer be exploited either through reduced populations or contaminated catches. As such, human activities on the coast, including the use of coastal resources, are increasing in intensity, and consequently sandy beaches, salt marshes, mangroves, coral reefs, seagrasses are either lost or degraded worldwide (Halpern et al., 2019; He and Silliman, 2019; Sengupta et al., 2020). For example, between 2000 and 2016, 3400 km^2 of mangroves were lost (https://www.nasa.gov/feature/goddard/2020/nasa-study-maps-the-roots-of-global-mangrove-loss) and Hinkel et al. (2013) have predicted that 6000–17,000 km^2 of coastal land will be lost during the 21st century due to erosion and sea-level rise.

4. The third 'whammy' - increasing effects of climate change

The third part of the triple whammy refers to the increasing effects of global climate change-driven stressors (sea-level rise, acidification, storm surges, storminess, warming) on different components of the coastal social-ecological system (SES) (e.g. Elliott et al., 2020b; Defeo et al., in revision). The importance of the SES focusses on the ability of the coast to maintain and protect the natural system, its structure and function and the ecosystem services that it provides, while at the same time delivering the goods and benefits required by society (Elliott, 2011).

Given the changes observed, the coastline is becoming more susceptible to the effects of global climate change – sea-level rise is affecting low-lying areas (e.g. Grases et al., 2020), and the removal of the vegetation (such as protective mangroves, seagrasses and saltmarsh) reduces the buffering of the coastal strip against increasing storminess and climate variability (Barbier, 2015; Elliott et al., 2015; Hochard et al., 2019; Duarte et al., 2020; Sengupta et al., 2020). This lowers the resistance to these global changes (i.e. can the coast withstand them if we remove the protective vegetation?) and decreases resilience (i.e. can the coast recover from them once they occur if we have removed any buffering capacity?).

With regard to the biophysical component of the SES, climate change stressors are altering the biogeochemical and physical properties of water and sediment, as well as the ecological communities having greatly-changed species distributions and abundance thereby altering the structure and functioning of entire ecosystems (Newton et al., 2012). These detrimental effects therefore decrease the ability of coasts to deliver ecosystem services and societal goods and benefits, such as recreation, tourism, fisheries, wildlife habitat and coastal protection.

Climate change and its consequences have produced a conundrum for managers of the coast in that the *causes* are outside the management area and can only be tackled at global level, whereas the *consequences* have to be addressed at the local level. This conundrum has produced what is termed *force majeure* in legal terms in that perhaps a coastal state is not individually responsible for the causes of climate change but it can be held responsible for not addressing the consequences or preparing for the future repercussions due to the loss of resistance and resilience (Elliott et al., 2015; Saul et al., 2016).

5. Cumulative effects of stressors acting synergistically

The stressors from the triple whammy do not act in isolation – some have a cause inside the area to be managed, the so-called *endogenous managed pressures* in which both the causes and consequences can be managed by the coastal authority. In contrast, some of the stressors operate from outside the management area (the so-called *exogenous unmanaged pressures*) and so the causes need wider, perhaps global action, whereas the consequences can and have to be managed locally. Hence all the consequences have to be addressed collectively by holistic management (Newton et al., 2012; Elliott et al., 2020a, 2020b) although as the coastal system is changing naturally, monitoring of anthropogenic changes relies on distinguishing these consequences from those natural changes, the so-called signal-to-noise ratio.

Synergistic interactions due to the combination of stressors by definition produce a response greater than expected if there were no interactions; they result in cumulative impacts that often lead to degradation or even collapse of the coastal SES (Halpern et al., 2019; He and Silliman, 2019). In turn, this creates long-term changes that will accentuate the detrimental effects on the coastal SES. For example, sinking coastlines occur through the combined effects of weight of infrastructure (Jakarta, Venice) and rising sea levels, or by the land subsiding through isostatic rebound, especially in areas recovering from the last ice-age (Wolanski and Elliott, 2015). Sandy beaches are constrained or lost due to seaward encroachment by recreational, urban and industrial development on land, while the seaward boundary migrates landwards in response to sea level rise and erosion (Defeo et al., 2009; Hinkel et al., 2013; Wolanski and Elliott, 2015; McLachlan and Defeo, 2018; Grases et al., 2020).

Importantly, and as shown by many papers in this journal, major stressors, implicit in the triple whammy, create a suite of symptoms acting synergistically and so cumulative impacts need urgently to be addressed. This includes, for example, climate change inducing sea-level rise, ocean acidification, species migrations, increased storminess, etc. (Elliott et al., 2015) and organic enrichment from point-source and diffuse sources producing eutrophication which in turn induces water quality barriers, hypoxia, harmful algal blooms, opportunistic benthos, fish kills, etc. (de Jonge and Elliott, 2001).

It is valuable to illustrate the triple-whammy and the knock-on synergistic effects and to show that unless sustainable management is used then both the natural and social systems are degraded; Fig. 2 illustrates this and reflects coastal ecosystems worldwide. The 22-km sandy beach between La Coronilla and Barra del Chuy resorts (Uruguay) is affected by a freshwater canal discharge. Built in the 1920's, the canal was enlarged from 3 km to 68 km between 1979 and

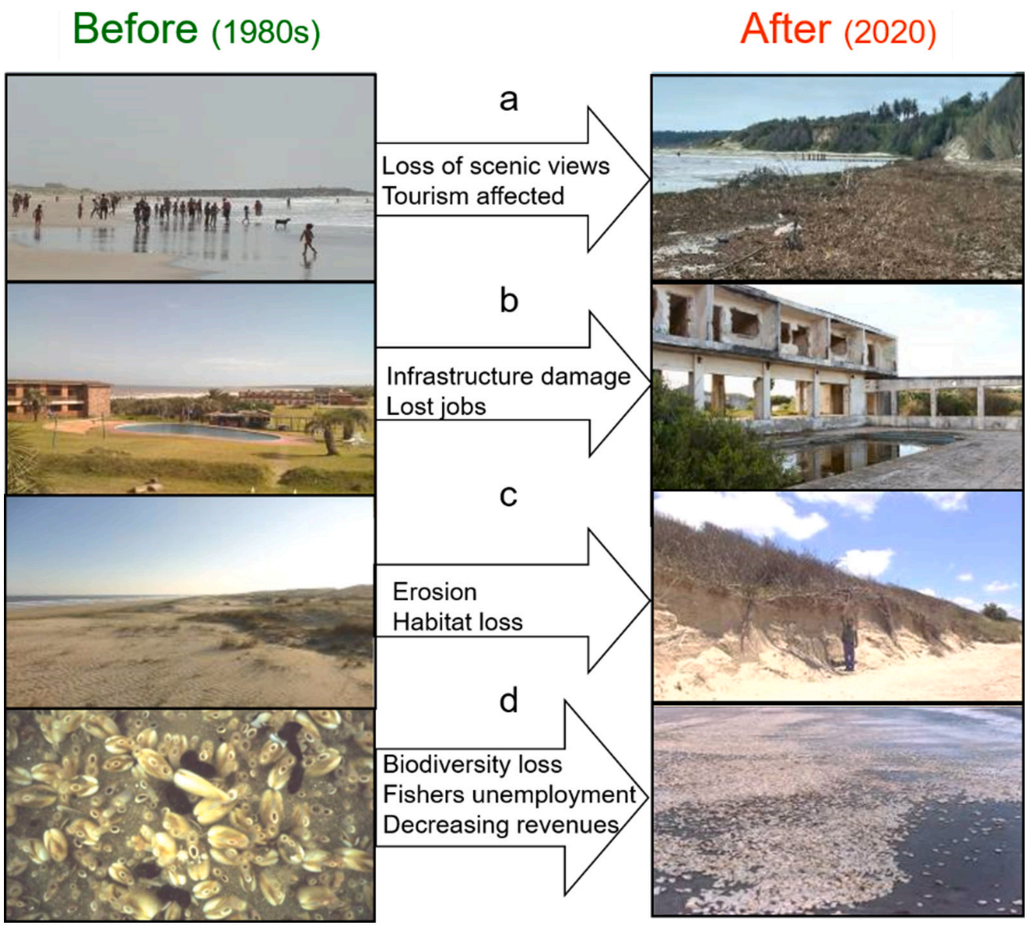

Fig. 2. An example of the triple whammy on the Atlantic coast of Uruguay: the left column shows the state of the coastal system before the expansion of a canal during the 1980s to discharge freshwater from a system of wetlands and increase the surface available for rice crops. The right column shows the present state of the ecosystem, after being hit by the three components of the triple whammy acting synergistically: increasing industrialisation, use of resources and effects of climate change (a–d explanation, see text).

1981, by a top-down government decision to expand the wetland drained surface and increase rice export earnings. Consequently, the canal discharge of up to 89 $m^3 s^{-1}$ includes herbicides and produces a strong alongshore salinity gradient (Jorge-Romero et al., 2019).

La Coronilla previously was a major beach resort, receiving thousands of tourists annually but the number of hotels and visitors has now halved because of the impacts of the canal (Fig. 2a, b). The governance of the whole area, not only the sandy beach but also wetlands and agricultural lands and pastures, has been largely unsuccessful (Jorge-Romero et al., 2019). Climate change is also interacting with this discharge to accelerate deterioration of the SES. The long-term increase in sea-surface temperature and a climate shift from a cool to a warm period in the mid-1990s has impacted this region, which falls within a ‘hotspot’ where warming occurs at several times the average global rate (Ortega et al., 2016). These changes, together with other climate-driven stressors, such as rising sea levels, storminess and erosion rates, have decreased the beach area available for tourism activities and reduced the quality of the habitat for beach fauna (Fig. 2c).

Changes in the biophysical subsystem have further affected the human subsystem of this SES. Indeed, mass mortalities of a cool-water clam that supported a long-established small-scale fishery coincided with the start of the climate shift (Fig. 2d) (Ortega et al., 2016). Mortalities occurred sequentially in a north-to-south direction throughout the species distribution range in South America and followed the poleward movement of the warm-water front. Despite a 14-year fishery closure, with negative socio-economic effects, the stock has yet to reach the former abundance levels, hence denoting a low ecological resilience (Ortega et al., 2016). The coastal changes led to the loss of clams and hence the fishery with resultant employment and economic impacts.

6. The way ahead: final comments and potential solutions?

Defending coasts by hard-engineering (building concrete seawalls) gives confidence to landowners and homeowners on that coast, but this has created ‘coastal squeeze’ whereby sea-level is rising but hard defences prevent coasts from responding naturally by migrating inland. Planting vegetation such as mangroves, seagrass or saltmarsh, by ecoengineering, gives such protection in a more nature-friendly manner (i.e. working with nature and ecosystem-based solutions). However, the increasing need for economic activity such as shrimp-farming, especially in developing countries, is removing such wetlands hence reducing the resistance and resilience of coasts as the third part of the triple-whammy and thereby increasing adverse consequences of sea-level rise, tsunamis and storminess (Wolanski and Elliott, 2015; Barbier, 2015). Hence these actions need to be controlled at national rather than local level by considering the large-scale rather than the small-scale economic consequences.

An increasing amount of assets is at risk from these threats and so if a cost-benefit analysis is carried out to decide what needs to be (or can be) protected, then more protection has to be undertaken – the alternative is not to protect cheaper farmland and so put emphasis on protecting urban areas and industrial areas in the national interest. The conundrum is that a cost-benefit analysis of an uninhabited coastal area would preclude protection, whereas once habitation is allowed on the area then by definition a new cost-benefit analysis would indicate that the area should be protected. It is further emphasised that rich countries have the ability to ‘spend their way out of the problems’, for example by building higher sea walls, whereas low lying, poorer urban areas cannot (Barbier, 2015), e.g., Manhattan in New York will be protected at all costs, whereas the populations of the Sundarbans wetlands in Bangladesh will just have to migrate (as climate-change economic migrants). Hence, will rich countries be able to cope with the problems in the triple whammy but the poor countries continue to suffer?

Given the above, there is the need to address the 'triple whammy' at global as well as local scales and there the need to break such a cycle by not allowing development on vulnerable coasts. Indeed, where coastal defences become prohibitively expensive, then a recently adopted management measure is to prevent building in the 50 or 100-year erosion-risk region. However, if society demands access and development even on vulnerable coasts, then policy makers and politicians may find it difficult to stop those societal wishes.

Each of the elements of the 'triple whammy' can be translated into the way specific pressures (as the mechanisms of change) are caused and these pressures then need quantitative, SMART (specific, measurable, achievable, realistic, time-bounded) indicators to determine the efficacy of management actions (Elliott et al., 2020b). Table 1 suggests indicators (and their units) which could quantify the magnitude of the triple whammy (i.e. the size of the shock experienced in an area over a given time). Furthermore, decisions on protecting the coast, and hence the solutions, have to satisfy ecological, economic, technological, societal, administrative, legislative, political, ethical (moral) and cultural aspects, and be communicated effectively to stakeholders (Elliott et al., 2020b).

We hope that we have shown that the triple whammy is a real phenomenon and so there are difficult questions to be asked and decisions to be made – for example, what coasts should we protect for nature and what are to be sacrificed for industry and urbanisation, and when should or should not we protect a coast? We have to ask which resources are to be exploited for the good of society, even if in the short term, and which resources are to be left for future generations? We know that the ecological and human systems can adapt to the threats, either by the species changing distributions or acclimating to new conditions, or humans moving away from hazards or creating structures to protect themselves from harm. But we should question when should or should not we intervene, and when must we work with nature and when should we try to stop nature 'acting naturally'? Such decisions will include not only stopping development and building on coasts but, because of the costs, perhaps stopping defending coastlines.

Therefore, we will have to decide when to allow people to live on a favoured piece of coast and when to tell them to move inland – will the planning authorities do this or will it be left to the insurance companies ('*you can live on the coast if you want but we will not insure your house against erosion and flooding*!')? As a stark example of this, the occupants of the village of Fishbourne in the UK have been told that their village will not be protected against flooding and so they will probably have to vacate the village by the middle of the century (Buser, 2020) – again making the residents climate-change economic migrants?

Finally, we emphasise that the interactions among these threats of the triple whammy, as well as the mechanisms operating behind them, are still poorly understood and require research; for example, do the relative amounts of these threats differ with geographical areas even though all of these whammies affect all areas to a lesser or greater extent? This is despite the future of the coast and our occupation of it requiring an increased understanding. We need further studies on the natural and human adaptation to the changes that we mention, for example whether and by what amount the ecology and society will adapt to changing climate conditions. Hence, we need more research and communication to overcome uncertainty but we can be certain of one thing - that the problems are not going to go away but will get worse with time unless we act quickly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 1
How to measure a coast has been '*triple-whammied*!': suggested indicators of the 'triple whammy' to be applied to a given geographical area and over a defined period.

Element of 'triple whammy'	Pressure indicator	Suggested units
Increasing urbanisation and industrialisation	Urban area size increasing	ha·decade^{-1}
	Population increasing	population·decade^{-1}
	Increasing industrialisation (size)	Area occupied: ha·decade^{-1}
	Increased effluent discharges (content and concentration of contaminants)	Number of discharges·decade^{-1}; increased loadings·decade^{-1}
Increasing use of resources:	Wetland space diminishing	ha·decade^{-1}
	Terrestrial space increasing	ha·decade^{-1}
	Energy usage increasing	GigaWatts·decade^{-1}
	Water use increasing	MegaLitres·decade^{-1}
	Wetland vegetation area diminishing	ha·decade^{-1}
	Dune area decreasing	ha·decade^{-1}
	Animal resources (e.g. fishes and shellfish) decreasing	Yield (tonnes·decade^{-1})
Increased susceptibility & decreased resistance & resilience to climate change	Sea level rising relative to land level	mm·decade^{-1}
	Storminess and extreme events increasing	1-in-100 yr events·decade^{-1}
	Warming and heatwaves increasing	°C·decade^{-1}; 1-in-100 yr events·decade^{-1}
	Onshore winds increasing	1-in-100 year events·decade^{-1}
	Acidification increasing	pH units·decade^{-1}
	Salinisation developing further	Groundwater salinity psu·decade^{-1}

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