Science in Coastal Adaptation Decision-Making:
Working Effectively with Persistent Uncertainties

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1. Introduction

A remarkable paradox characterizes science in coastal adaptation decision-making: sea-level rise (SLR) is one of the most certain and irrefutable consequences of climate warming, and yet exactly how high it will rise over the 21st century in different locations is ridden with deep and persistent uncertainties. In the first dispensation of the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment trilogy – the Physical Science Basis – the key take-aways for SLR could not be more convincing, nor more eyebrow-raising in their implications (see Box 1; and the chapter by xxx on sea-level rise projections, this volume).

Begin Box 1

Box 1: High-Level Findings from the IPCC Sixth Assessment Report on Sea-Level Rise

- Global mean sea level increased by an average of 0.20 m between 1901 and 2018 at a mean rate of 1.3 mm/year in the first seventy years of that period, an accelerated rate of 1.9 mm/year between 1971 and 2006, then further increasing to 3.7 mm/year between 2006 and 2018. Human influence was very likely the main driver of these increases since at least 1971 (IPCC, 2021:6).
- Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years, driven by accelerating ocean warming (thermal expansion) and ice loss from land (addition of water to the ocean basins) (IPCC, 2021:9). "The rate of ice sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006-2018" (IPCC, 2021:14).
- It is virtually certain that global mean sea level will continue to rise over the 21st century (IPCC, 2021:28), and that the rate of rise will continue to increase.
- "Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets, and global sea level. … In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and will remain elevated for thousands of years," rising "over the next 2000 years […] by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C, and 19 to 22 m with 5°C of warming, and [continuing] to rise over subsequent millennia" (IPCC, 2021:28).
- While far out, difficult to imagine and in many decision-makers' minds irrelevant to today's decisions, there is remarkable confidence in where modern-day SLR is headed, given that "projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods" (IPCC 2021:29).

End Box 1

Despite these stark and mostly high-confidence findings in the IPCC Sixth Assessment Report, a look at the detailed SLR projections over the 21st century reveals only medium and low confidence, confounded by regional divergence from these global estimates. Thus, the challenge that coastal decision-makers must confront. Relative to the baseline established between 1995-2014, global mean sea level in 2100 has at least a 2/3 chance to rise by as much as

- 0.28-0.55 m under the very low greenhouse gas (GHG) emissions scenario,
- 0.32-0.62 m under the low GHG emissions scenario,

- 0.44-0.76 m under the intermediate GHG emissions scenario,
- 0.63-1.01 m under the very high GHG emissions scenario, and
- a small chance it could even go up to 2 m if there is catastrophic ice loss.

Scientific projections of SLR over the past four decades have varied notably, reflecting remarkable advances in observation, modeling and methodology, but also changes in the underlying emissions scenarios and persistent deep uncertainties in scientists' understanding of the fundamental processes driving global sea-level rise (Garner et al., 2018). As a systematic review of the literature reveals, "Results show a reduction in the range of SLR projections from the first studies through the mid-2000s that has since reversed. In addition, [the analysis reveals] a tendency for [IPCC] reports to *err on the side of least drama* [a term coined by (Brysse et al., 2013)]—a conservative bias that could potentially impede risk management" (Garner et al., 2018:1603). That look at the broader literature illustrated that the greatest change and variation has been on the more dangerous *upper* end of projections (Figure 1).

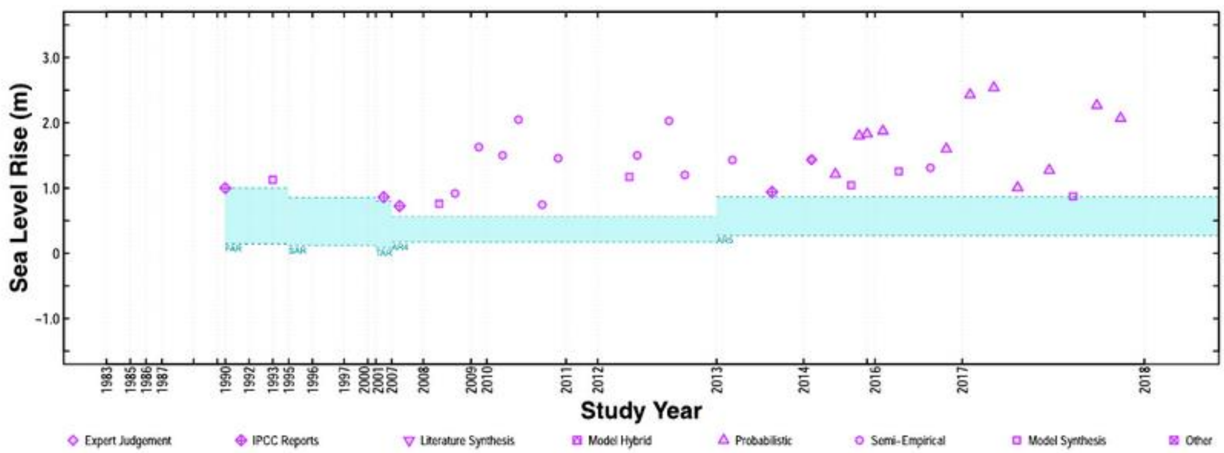

Figure 1: Comparison of upper-range SLR projections illustrates how conservative the IPCC projections (light blue) have been compared to the wider scientific literature (pink symbols). Source: Garner et al. (2018) [need to get permission]

For coastal decision-makers, wide, widening and changing ranges of scientific projections are difficult to deal with given the high-stakes decisions they face. How to decide when faced with questions such as: should further development along vulnerable shorelines be permitted, given the sea-level rise outlook over the long-term even if there is great near-term economic benefit to such development? How can coastal erosion and flooding – some of the greatest risks from sea-level rise and coastal storms – be most effectively managed? Should storm-damaged homes be restored and repaired in place, and if so to what level of protection? How much time can be gained by building nature-based buffers between the sea and coastal structures, and is that worth the investment? What are the costs and benefits of different adaptation strategies? Is relocation from the shoreline necessary and how soon? Different rates of SLR would result in different answers. Some of these responses may later turn out to be maladaptive, i.e., creating lock-ins and/or greater vulnerabilities, either for at-risk human communities, coastal industries and natural systems or for adjacent ones to whom risks have been transferred (Schipper, 2020).

Many coastal managers are stymied by these difficult questions, even though coastal environments, economies and property are already at risk and affected by the impacts of a rising ocean (Fleming et al., 2018, pp.329, 331; Sayers et al. 2022). Decision-makers tend to plan and call for action, but absent adequate investment often still select to delay adaptation action as long as possible, demanding more reliable, locally-relevant data (Moser et al., 2014; Fleming et al., 2018). Others decide to begin adaptation, often selecting a "politically feasible" set of SLR projections, i.e., projections that are most likely to be acceptable to political decision-makers, in order to advance the process at all. Autonomous market responses and distortions can even encourage further high-intensity development at the shorefront (via climate gentrification), rendering the political economy of adaptation even more challenging and creating – ultimately – even greater vulnerabilities (Keenan et al. 2018).

Taking a step back then from the state of SLR science and coastal adaptation in practice[1], a mixed picture of certainties and uncertainties in the scientific, observational, and decision-making realms arises. It inevitably leads to several vexing questions:

- Given scientific certainties and the already observed impacts and trends of SLR (observational certainties), why are we not seeing more action?
- Given the range and types of scientific uncertainties, is action likely or possible?
- Given uncertainties in the decision-making arena itself, does scientific (un)certainty matter at all, and if so, how?

This chapter attempts to address these questions and the paradoxical situation they portray. While anchored in SLR science and coastal planning and decision-making, it asks one central question, albeit with wider applicability, namely: what is the relationship between scientific (un)certainty and action? Section 2 articulates the theoretical expectations one might hold about this relationship in the context of rational decision-making. Section 3 then tests this theory against a number of brief empirical cases, showing how real-life decision-making often does not respond to certain or uncertain scientific understanding as expected. Rather, as Section 4 will show, scientific knowledge (whether certain or not) is transformed into a strategic tool in the political process which then attains importance for or against action. If scientists wish to engage and become players in this process, what options do they have to bring science as effectively as possible into the political process? Section 5 offers a number of answers before concluding with a summary and outlook in Section 6.

2. Scientific Uncertainty in the Rational Decision-Making Paradigm: Theoretical Expectations

Rational decision theory has been developed, critiqued and advanced over the past five decades in a variety of disciplines, including (behavioral) economics, psychology, sociology, law, neuroscience, philosophy, political science, organizational studies, business operations, and planning (e.g., (Jaeger et al., 2001; Brown, 2005; Reyna and Rivers, 2008; Gächter, 2013; Andrews, 2017; Wolbring, 2020). It is beyond the scope of this chapter to review this wide-ranging body of work. Suffice it to say, in its simplest form, rational choice theory assumes

- individuals act rationally in pursuit of their goals (i.e., aligning means and ends logically), and in a risk-averse manner (i.e., maximizing utility, satisfaction or gains while minimizing losses);
- individuals have sufficient and unambiguous information to establish their preferences; and
- those choices can be influenced by incentives.

Because decision-makers often appear to act seemingly against their own stated goals or self-interest, respond counterintuitively to incentives, and/or the information available to them is *not* unambiguous or sufficient (much less complete and certain), much research has gone into understanding the environmental (e.g., organizational, contextual) and internal (cognitive and affective) factors that could explain these empirically observed deviations from theory. The result has been a plethora of alternative models of decision-making in the face of risk and uncertainty.

One logical implication of the basic tenets of rational choice theory, however, is that when decision-makers face a reasonably certain future, they will be in a better position to strategically align means and ends and determine a course of action in ways that maximize gains while minimizing potential losses. In other words, certainty about the future should enable swift and rational action, while uncertainty about future outcomes should stymy it. This does not mean, decision-makers have no tools available to act in

[1] The main focus in this chapter will be on US coastal adaptation. While not directly transferable to other political, socioeconomic, cultural and legal contexts, many insights gained from the US case will resonate elsewhere.

the face of uncertainty, but the theory implies that uncertainty makes it more difficult to act, and it would not be unreasonable to see delays in action, particularly if the gains are unclear and/or the stakes (the potential losses) are high (Kasperson, 2009).

This leads to a simple matrix which relates scientific uncertainty to action (Figure 2). While this caricature does not do justice to the messiness of real-life situations, it helps to structure the discussion below. It suggests that in cases of low levels of uncertainty action is more likely (rational action; dark green), whereas in cases of high uncertainty, no action should be expected (rational inaction; dark red), with the counterintuitive cases being action in the face of high uncertainty (irrational action; light green) and inaction in the face of low uncertainty (irrational inaction; light red).

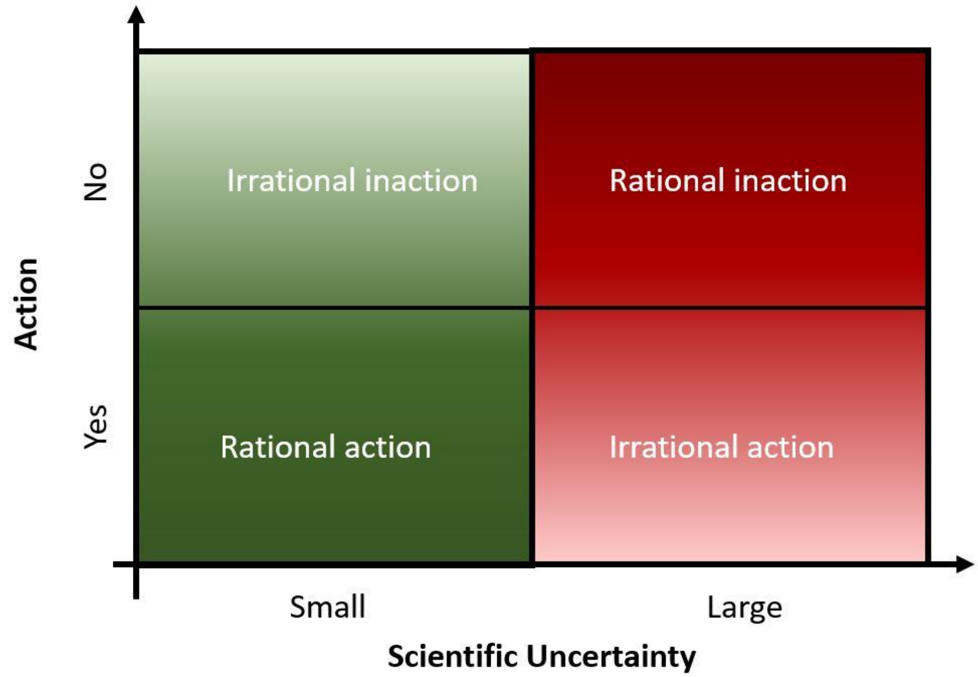

Figure 2: Expected degrees of action in the face of different levels of uncertainty
Source: The author

The next section explores a number of brief cases from around the US to illustrate with empirical evidence how decision-makers do or do not act in accordance with the rational decision-making paradigm laid out here.

3. Testing Theory Against Real-World Cases

3.1 Rational Action

The case of greatest certainty is the one where we can look at 20th century coastal management action in the face of observed (i.e., well-understood) slowly rising sea level and examine the actions that were taken. Before 1972 – the year the federal Coastal Zone Management Act was passed – shoreline development was essentially blind and reactive: development happened, disasters happened, rebuilding happened. But since the passage of the federal act and its state companions in the decades since, the action seen in the face of low rates of SLR is a patchwork of relatively minor adjustments, including flood insurance, elevation of structures, strengthened zoning or building codes, hard and soft shoreline protections (e.g., seawalls, beach renourishment, protections of natural buffers), setbacks and often no action at all until disaster struck. Rebuilding in the same location to the same building standards has been the oft-repeated history of coastal zone management in the US (although the US Federal Emergency Management Agency finally moved to prevent this by administrative action in 2022; see FEMA 2022). In the past, however, this has left many homeowners more vulnerable to the encroaching sea, natural shorelines severely degraded in many places, and countless coastal communities ill-prepared for current and future storms, floods and erosion.

In short, under the assumption of slow SLR (i.e., the certainty that comes from extending known trends into the future), many states and communities took action, albeit only minimally, to adapt. The history of coastal disasters makes the unequivocal case that these actions were insufficient. We have never been over-adapted. Spending too much money for coastal protections that would later turn out to be too much has never been our problem.

By implication, this past experience suggests that there is one uncertainty that coastal decision-makers can safely ignore: the low end of future SLR projections. Decision-makers needn't worry about the most conservative end of SLR projections. Given the physics of ocean warming and accelerating ice loss from land, resulting in the increasing rates of SLR already being observed, there is no reasonable case that can be made that 21st century SLR will be merely an extension of the past. Nor can a good case be made that coastal storms will lessen in terms of intensity or frequency, that El Nino will cease to play a major role along the West Coast of the U.S., that erosion will slow down, or wetland loss come to a halt. Thus, with U.S. coastal communities already not well adapted to current rates of SLR and coastal hazards, more *must* be done. The only question is how much more, which points toward the higher ends of projections, i.e., to the far more uncertain end of the spectrum.

3.2 Irrational Action

The earliest known state-level policy in the United States regulating shoreline development in the face of uncertain SLR was put in place in Maine more than 30 years ago, in 1988. The state passed its so-called Sand Dune Rules, which later were slightly weakened due to property takings concerns but were essentially upheld against these challenges. The law explicitly acknowledges uncertainties in the science and the existence of divergent SLR projections, but drew on expert judgment of the state of science at that time to defend its rule-making and specific choice of one SLR scenario (3 ft. by 2100; later revised under legal pressure to 2ft.) (Moser, 2005). An in-depth examination of that case revealed that the motivation behind the policy had little to do with SLR per se, but with a perceived defacement of the coast from increasing high-density coastal development experienced at that time. Nevertheless, SLR science was used to embolden the case against such development and stands as the earliest example in US coastal policy to put in place a SLR regulation despite uncertain future projections.

A second case comes from California, namely the 2011 amendment to the San Francisco Bay Plan (San Francisco Bay Conservation and Development Commission (BCDC), 2020) (with further, complementary updates in 2019). The policy directing shorefront development along the San Francisco Bay fully acknowledges uncertain SLR projections, particularly beyond mid-century, but does not prohibit new development. Instead, it requires developers to demonstrate resilience until 2050 under all SLR projections, and demands that they present a feasible adaptation plan thereafter, i.e., to make clear how their development will be protected under different SL scenarios. It also places the economic burden of that adaptation on the developer.

3.3 Rational Inaction

The now infamous case of the State of North Carolina "legislating away" SLR might count as a case of rational inaction in the face of significant uncertainty. The state legislature chose to ignore long-term SLR trends, nominally because the "science was bad" and the uncertainties too great to support regulation (Opt and Low, 2017). In 2009, the state Coastal Resources Commission had directed its Science Panel to produce state-level SLR projections to guide coastal regulation, but when those scientific recommendations were delivered a year later, pointing to potentially very high sea levels, the state legislature stipulated that the projections to 2100 could not be applied for such purposes. While well understood as having been politically motivated by development interests, the law did not lay out an adaptation path forward in the face of uncertain albeit potentially very high risk, but instead shaped a path – if only temporarily – that enabled continued coastal development with minimal adaptation in the face of a false sense of certainty (i.e., ignoring the significant rise projected in the latter half of the century).

The only concession made was to require updates on the SLR science every five years. As a result, the Science Panel has updated its projections twice (still only projecting to 2050, but acknowledging that SLR is accelerating) . The state's coastal zone management program is providing technical assistance to local communities wishing to adapt, and the state has advanced comprehensive resilience planning. But the science has still not been deemed certain enough to be used in regulatory and permitting decisions (Allen, 2020).

3.4 Irrational Inaction

A case of irrational inaction (i.e., not adapting in the face of evident risk and agreed-upon science) is the case of Florida permitting the expansion of the Turkey Point nuclear power plant to twice its generating capacity. The power plant, located near Homestead, Florida, some 25 miles south of Miami, is situated at sea level in a high-hazard flood zone. The Southeast Florida Regional Climate Change Compact – a four-county partnership – had previously agreed on SLR scenarios to be used for such decisions, namely 23-61 cm of SLR by 2060 (Moser et al., 2014). While a politically significant step to have a common set of projections across the four-county region, the figures are remarkably low, i.e., not particularly risk-averse or precautionary, when compared to the numbers used in other regions of the world (e.g., the highly precautionary figures (+4.3 m for extreme seawater levels by 2100) used for the Sizewell nuclear power site in the UK; see Wilby et al. (2011). Given the already-existent and clearly growing flood risk under any SLR scenarios to this high-risk infrastructure, relocation to higher ground might be considered a rational choice. However, plant expansion plans were only slightly modified to account for potential flooding of access roads, while the plant itself was not fortified any further in place. Relocation was dismissed as it was deemed too expensive and electricity rate payers were thought to not accept that added cost.

3.5 Implications

A first lesson from these short vignettes is that even with perfect knowledge or well-supported scientific evidence, action is not guaranteed because science does not compel action. Decision-makers' goals, intentions and underlying value commitments (e.g., to growth, development, profit) do. And even when action is being taken, that adaptive action has been generally insufficient – a "fig leaf" that allows decision-makers to say they have taken action, but one that allowed them to side-step political backlash or attacks due to unpopular choices. One critical implication is that focusing only on reducing scientific uncertainties by way of additional research is inadequate at best and will not guarantee that adaptation decisions will in any way be scientifically informed. Differently put, a reduction in scientific uncertainties will not guarantee appropriate, sufficient or timely action to prevent significant losses.

A parallel, second insight from these cases is that uncertainty is not a show-stopper to action. In fact, both certain and uncertain science have been used to justify action. The question, rather, is what is at stake and what motivates people to action and how is science used to bolster the case for or against action?

Finally, and at first seemingly in contradiction to these observations, is that in each of these cases, decision-makers did create or depended on some kind of certainty that allowed them to move forward on the path of action (adaptive or maladaptive) they decided to pursue – just not necessarily scientific certainty. Rather, each describes a case in which decision-makers arrived at a kind of political or psychological certainty by accepting or ignoring, curtailing or selectively using the science. In turn that certainty-imbued science became a strategic tool in the political process. This violates the rational decision-making paradigm, but does not mean science is not relevant to decision-making. It simply tells the wrong story of how that is so.

4. Scientific Knowledge as Strategic Tool in the Political Process

How then does scientific knowledge – uncertain or not – come to matter in the political process? In each of the stories relayed above, more or less uncertain scientific knowledge got transformed into a psychologically "certain" and politically persuasive argument for or against action:

- In the case of rational action in the face of scientifically well-established knowledge of SLR trends, the risks of a rising sea level seem to have been ignored or downplayed (a seeming reduction of uncertainty) to justify continued, if minimally hazard-cognizant coastal development.
- In the case of irrational action, two pathways to action emerged: in one, expert judgment was used to legitimize the selection of one out of several SLR scenarios (again, a seeming reduction of scientific uncertainty to establish regulatory certainty). In the other example, the relatively small uncertainty in SLR in the next few decades was embraced and adaptive action by coastal developers required, with the added stipulation to illustrate both financial capability and flexible yet feasible adaptive pathways over the long-term should sea level be higher than expected over the lifetime of the structure (regulatory and financial certainty).
- In the case of rational inaction, the available science was termed "bad" and unreliable, and thus supported legislators in their ideological desire to ignore its implications (creating a psycho-political certainty). However, the door for future political consideration was left open by demanding periodic science updates.
- And finally, in the case of irrational inaction, an economic and associated socio-political certainty (high costs of relocation and the perceived lack of the public's willingness to foot that bill) won out over another certainty, namely, the already evident and growing risks and clearly established scientific guidance on which science to use in planning and decision-making.

Not only do scientific uncertainties become transmuted into political certainties. Scientific certainties can also be transfigured into political uncertainties to argue against action. Figure 3 illustrates some of the common motivations that drive this transmutation, including personal or political motivation as well as actual or perceived economic benefits from taking action or postponing it, but also reputational, economic or legal liabilities and policy requirements (see also Curry ad Webster 2011).

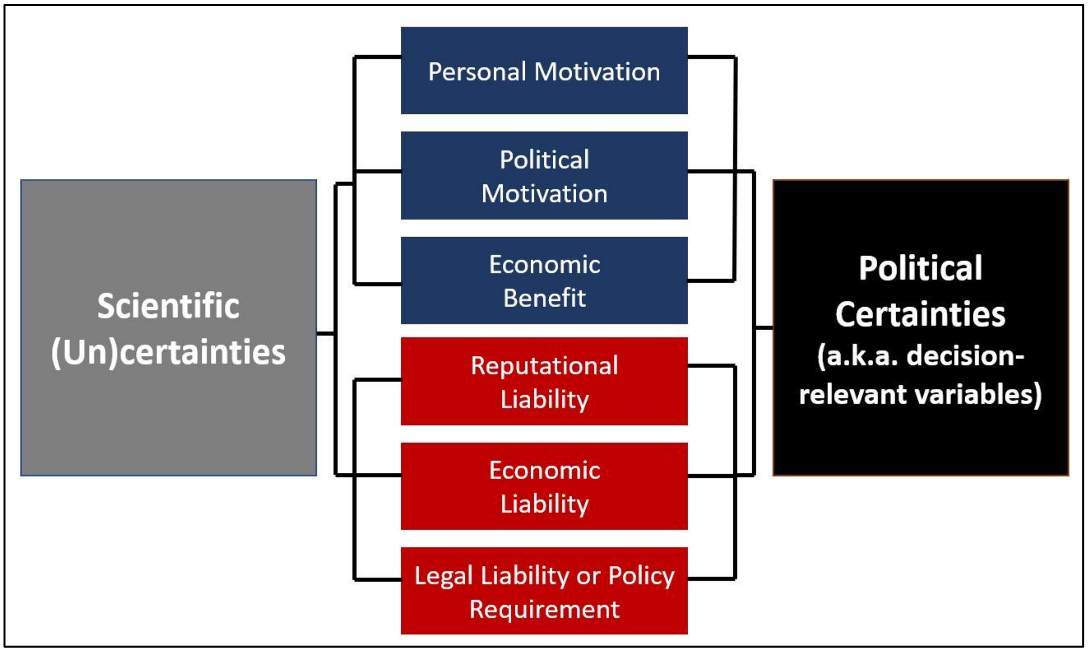

Figure 3: The transmutation of scientific (un)certainties into political certainties
Source: The author

These observations clearly help to better understand why actions and inactions are being observed against the spectrum of scientific (un)certainties. They tell an empirically more accurate, more nuanced and thus more persuasive story. This alone, however, would paint a picture of science essentially being no more than a political football (incidentally, a bias some scientists hold and actively use to stay a long way away from political engagement). Clearly, such a story would still be inadequate because it diminishes scientists' agency to simply being servants to a process they cannot influence and which reduces them to one-way information-delivery "automatons", rather than actors who themselves can act strategically and ethically in their engagement with information users.

Differently put, for scientists to ignore the political needs of decision-makers and the range of motivations that underly their choices (as depicted in Figure 3) is no better than politicians ignoring scientific facts just because they are inconvenient. The task for scientists instead is to become smart and practiced in learning about these political (and underlying social and psychological) motivations and learning to work with them. As they learn about these underlying decision drivers, scientists can play more effective roles as issue advocates (more activist) or honest brokers (less activist) (Pielke 2007). In the former case, they may help advocate for flexible adaptation actions that reduce risk, minimize losses, benefit at-risk communities and natural habitats, preserve positive choices for future generations while protecting and restoring the life support systems on which humans depend. In the latter case, they may simply choose to lay out the choices more clearly without taking any side as to what decision-makers should choose.

Incidentally, doing so involves learning some of the very lessons that have led to modifications of the all-too-simplistic rational decision-making paradigm (Samson, 2014) (Table 1).

Table 1: Social-Science Insights that Have Modified the Rational Decision-Making Paradigm

Biases and heuristics	People employ biases and heuristics in forming judgments in the face of uncertainty (Tversky and Kahneman, 1974)
Mental models & confirmation bias	People process information through preexisting mental models and exhibit confirmation bias which makes uptake of new information that challenges people's beliefs and values more difficult (Plous 1993; Johnson-Laird, 2010);

Slow vs. fast information processing	People process information not just carefully, analytically and systematically ("slowly") but also affectively and intuitively ("fast") (Kahneman, 2013)
Choice framing	People respond differently to different kinds of uncertainties and framings of choices (Levin et al., 1998; Ho and Budescu, 2019)
Trust in information sources	People do not process all information equally, but tend to pay more attention to information from trusted sources (Sarathchandra and Haltinner, 2020)
Denial of existential threats	People avoid and deny information that signals existential threats (Wullenkord and Reese, 2021)
Context-dependence of decision-making	People make decisions that don't just depend on the information they receive, but the environment and context in which they make them (Gigerenzer and Goldstein, 1996)
Context-dependent valence of values	People hold multiple values with different, often context-dependent valence as they choose among options and those preferences don't stay the same over time (Thaler, 2015)
Loss aversion	People care more about losing something they have than gaining something they don't yet have (Kahneman and Tversky, 1979)
Social norms	People are often more influenced by social norms than economic norms (Kinzig et al., 2013)
Emotions and values	People make better choices when factual information is linked to emotions and values (Reyna, 2021)

Which of these influences matter most at any one time and with different decision-makers cannot be predicted. The important take-away is that these psychological influences *always* come into play. The purely "rational" (emotion-free) decision does not exist, and is in fact not desirable (Reyna 2021). Drawing on these insights, however, suggests scientists have significant power in shaping how information is delivered and heard, how decision options are framed, and how scientists can help decision-makers make adaptation decisions without risking their political survival. It changes scientists from being deliverers of information to being sophisticated partners in a transaction, which makes the uptake of (uncertain) science in adaptive decision-making more likely.

5. Opportunities for Science to Shape Coastal Adaptation Decision-Making

Returning to the practical, what are some concrete ways then for scientists to help inform and shape coastal adaptation decision-making in the face of scientific uncertainty? The proposed entry points discussed below illustrate not only ways in which scientists can help inform decision-makers' understanding of risks, uncertainties and the options, values and preferences they have, but also the necessity of relationship building, continuity of engagement, and reflexivity (on all sides) to grapple with the inherently non-scientific, normative dimensions of decision-making.

5.1 Help in Prioritizing Risks

With climate change impacts emerging faster and faster, and many of them creating a sense of foreboding and overwhelm, busy decision-makers first need help with not just identifying the entire universe of possible risks, but which ones to focus on first. Breaking down overwhelmingly large (and profoundly threatening) problems into a series of tractable ones makes it more likely to get publics' and decision-makers' attention. Pragmatically, often this means tying climate change and adaptation to an existing problem that already has their attention. For example, as coastal managers update existing road or water infrastructure in coastal areas, careful consideration of sea-level rise (and other climate change impacts) projections and an appropriate economic analysis of adaptation options (e.g., robust decision-making under deep uncertainty) can help meet multiple objectives while minimizing risks for decades. Linking to such immediate needs helps planners, stakeholders and elected officials with limited attention spans to focus on adaptation; it is also often where there are resources to address the growing risks from climate change.

This may still not reduce the universe of possible climate change impacts enough to help with focus. Where then are the most meaningful points of intervention? (Walker et al., 2010) proposed a triage approach distinguishing three categories of situations:

1. No matter the climate scenario, impacts will be minimal;
2. No matter what we do, losses will be severe, irreversible; and
3. Adaptation promises to make the greatest difference on impacts.

It is only in that third category where questions of risks, benefits, and harms (and associated uncertainties), the relevant actors/affected parties to involve, scope, scale, urgency/timeframe, and the feasibility of adaptation actions need to be addressed. Thus, rather than delivering all-encompassing climate impacts or risks assessments, scientists can be most helpful to decision-makers if they go a step further and identify this third space where adaptation could make a real difference. This opens the door to being decision-relevant.

5.2 Address What is Unique about Adaptation

In the next instance, scientists can be helpful in elucidating aspects that are unique about adaptation. While many decisions entail uncertainty, many adaptation decisions have to contend with *deep uncertainty*, *indirect costs and benefits*, and with *long time horizons* at once.

Importantly, there are not only scientific or predictive uncertainties to worry about, but also values uncertainties (Moser, 2005; Bammer and Smithson, 2008). Regarding values uncertainties, a unique challenge in adaptation is that what and how much society values something currently vs. in the future is not necessarily the same. This may affect what gets protected now vs. what is still seen as worthy of protection later, how much society is willing to pay for something now vs. later and so forth. Often, there is ambiguity in individuals' values and the sum of individual values is not necessarily the same as collective values due to competition among the values we hold. Typically, these value uncertainties are hidden in model assumptions and not made visible or understandable to decision-makers. Thus, rather than glossing over or trying to resolve all these uncertainties, it is often more important for decision-makers to understand the role and implications of different values so they can arrive at their own judgment. Scientists can further help decision-makers and stakeholders with different values identify their own implicit assumptions and facilitate deliberate reflection and deliberation on these values.

Another (not-entirely unique but nonetheless crucial) feature of adaptation is that the cost of anticipatory adaptation is born now, even if its ultimate benefits are only reaped in the future. As with greenhouse gas emissions reduction, decision-makers will be keenly interested in a) distributing the cost not just across societal group in the present but also over time, and b) favor adaptation options that have near-immediate (co-)benefits. In many ways, however, this uneven distribution of costs and benefits gives adaptation often the character of public goods, provided best by institutions with a responsibility towards the collective, rather than by private actors, seeking profit maximization. Given limited public funds to date for adaptation, there has been a growing interest in involving the private sector in financing adaptation. In some instances, this may open up greater pools of resources, but may also require improved support from the scientific community in placing economic value on non-monetized risks and benefits, and help with comparing costs and benefits across typical disciplinary and governance silos.

Finally, adaptation must contend with the necessarily long-term planning horizons for future climate risks versus short-term planning cycles. In many instances, existing institutions (much less current decision-makers) may not have the longevity required to sustain and/or repeat adaptation efforts into that long-term future. Scientists must help facilitate conversations about how to chart that path, help identify ways for decision-makers to feel comfortable and able to make commitments over time, and help them find feasible near-term and interim steps that maintain long-term flexibility. The important work on adaptation pathways and robust decision-making in the face of deep uncertainty (see chapters by Lempert and Brown) provide tools to do so.

5.3 Help in Choosing Adaptation Options

Having identified risks where adaptation can make a real difference and having recognized the unique challenges decision-makers face, scientists can then support the adaptation process by making it possible for stakeholders and decision-makers to choose among different adaptation options. Not only do people need to understand the pros and cons and costs and benefits of different adaptation options, then need guidance in working through these decisions.

A first useful step then is that the adaptation options considered must be assessed as to whether and how they address the unique aspects of adaptation (Table 1).

Table 1: Preferable Adaptation Options that Address the Unique Features of Adaptation

Adaptation options that address deep uncertainty issues	Adaptation options that address indirect benefit issues	Adaptation options that address long time horizons
- Have net benefits, regardless of future climate - Include the possibility of low-cost safety margins - Can easily be changed, avoid lock-in - Fit with short-lived planning horizons, allowing repeats - Simplify or streamline decision-making complexity - Build toward wider range of variance, not average - Include inbuilt mechanisms for routine, periodic review	- Involve mechanisms that lower direct costs to actors now, spread to or share costs with future actors - Involve mechanisms that provide near-term benefits and address trade-offs - Facilitate cross-sector alignment and thus enable sharing of costs and benefits - Lower transaction costs now, e.g., by allowing more frequent, smaller decisions resulting in learning and familiarity; or through "mainstreaming"	- Identify options to fill the institutional gap - Involve mechanisms that bridge short-term horizons - Require periodic revisiting of decisions - Build in monitoring and evaluation and establish agreed thresholds which – when reached – trigger subsequent adaptive action

Source: Adapted from Walker et al. (2010)

In addition, adaptation decisions must also consider issues like safety of operation, ease of implementation, and other implementation issues. Clearly, the decision for or against different adaptation options involves profound values choices. Scientists – using structured decision-making processes – can help planners, decision-makers and stakeholders make the criteria transparent and then deliberate the values-side of their choices (Gregory et al., 2012). This may entail explicitly exploring visions of the future, including the desirable, plausible/constrained, and possible futures. But it also means listening carefully and helping to surface implicit values in how people discuss these futures and choices. This empowers all involved in the decision-making process and enables them to participate more effectively. But it also helps to improve the quality of decisions itself, i.e., by helping to refine the problem definition, clearly elicit and discern the objectives, define a range of alternatives that are linked to those objectives, then help assess the consequences of pursuing any one of the alternatives, and confronting tradeoffs (and possible synergies).

Notably, in none of these instances are scientists unduly influencing or making any of these choices for the decision-makers, i.e., they remain objective in the sense of not imposing their values on a decision.

Scientists – as citizens – have no more a voice than other citizens. Rather, to be useful and decision-relevant, scientists assist better decision-making. They do so not only by conducting research to answer decision-relevant questions but by helping to facilitate a process in which all voices are heard and given appropriate consideration so that the decision and its consequences become clearer to all involved. They support joint fact-finding and knowledge co-production, and assist in making risks, uncertainties and decision consequences meaningful (Hilger et al., 2021).

6. Summary and Outlook

This chapter examined the ways in which uncertainties in and beyond sea-level rise science can, but does not necessarily, delay coastal adaptation action and how scientists can work more effectively with coastal practitioners and communities to make uncertainties intelligible and decision-relevant, while still facilitating action. The argument launched from a review of an outdated way of thinking wherein scientific uncertainty is thought to be "the problem", i.e., the reason for delayed decision-making, resulting in an assumption that uncertainty needs to be reduced in order to see "right action." With limited empirical evidence to support this simplistic assumption, the chapter then proposed an alternative paradigm that more adequately captures the role of (uncertain) science in decision-making. It showed how scientific uncertainty is transmuted in the political process into a "political certainty" so that it can bolster the case for action or inaction, as the case may be. In this sense uncertainty becomes "politically constructed." Importantly, however, scientists are not just powerless bystanders to this process but can actively "co-construct" the meaning, importance and interpretation of uncertainty. While more science may be useful, and some scientists are better at advancing the knowledge frontier than public deliberation of adaptation options, this recommendation shifts the attention from "doing more science" to "working effectively at the science-policy interface."

The chapter argued that there are not only uncertainties in all dimensions of climate risk assessment and coastal impacts research, but also in all aspects of coastal adaptation decision-making and risk governance (Moser, 2005; Renn, 2008). Scientists must learn to navigate this complex territory with greater sophistication, drawing on what is understood about how people process information, form judgments, and make decisions in the real world. With that understanding, scientists can more usefully support coastal decision-making by helping to identify coastal adaptation priorities, address the unique aspects of adaptation, and identify and assess possible adaptation options suitable in different coastal contexts. At minimum, the shift that the chapter proposes is thus one from a "scientifically rational" decision-making paradigm to a "politically rational" one. Maybe more important even is the move away from seeing (or drawing) a sharp line between the scientific and the decision-making processes to seeing the two as transactionally and relationally intertwined. It asks that both scientists and decision-makers get better at working with each other. Then uncertainty can no longer been seen as being inherently important to decision-making, but as a condition that attains co-created political significance. In short, no knowledge is inherently valuable; no knowledge is inherently "certain enough" for action; and no uncertainty is inherently decision-relevant or decision-limiting. Instead, all forms of knowledge can attain value in someone's eyes, in some contexts; all knowledge can be "good enough" to act on; and all certainties and uncertainties can be made decision-relevant.

This implies – for both the coast and for other sectoral contexts – not only a different kind of training of scientists and decision-makers to build the necessary skill. It also demands doubled efforts in strengthening, normalizing and institutionalizing science-policy interactions. In the face of accelerating climate changes, there is no time to lose in making sophisticated science-policy interactions commonplace so that trust and familiarity are established as the foundational conditions for the difficult choices coastal communities now face in an always-uncertain and increasingly high-stakes environment.

7. **References** [35]

Allen, J. (2020). NC's First Sea Level Rise Report, 10 Years On. *Coastal Review* June 24, 2020, available at: https://coastalreview.org/2020/06/ncs-first-sea-level-rise-report-10-years-on/.

Andrews, C.J. (2017). "Rationality in Policy Decision Making," in *Handbook of Public Policy Analysis: Theory, Politics, and Methods,* eds. F. Fischer, G.J. Miller & M.S. Sidney. (New York: Routledge (CRC Press, Taylor & Francis Group)), 161-172.

Bammer, G., and Smithson, M. (2008). *Uncertainty and Risk: Multidisciplinary Perspectives.* London: Earthscan

Brown, R. (2005). *Rational Choice and Judgment: Decision Analysis for the Decider.* Wiley.

Brysse, K., Oreskes, N., O'Reilly, J., and Oppenheimer, M. (2013). Climate change prediction: Erring on the side of least drama? *Global Environmental Change* 23(1)**,** 327-337. doi:10.1016/j.gloenvcha.2012.10.008.

Curry, J.A. and Webster, P.J. (2011). Climate science and the uncertainty monster. *Bulletin of the American Meteorological Society,* 92, 1667-1682.

FEMA (Federal Emergency Management Agency (2022). Partial Implementation of the Federal Flood Risk Management Standard for Public Assistance (Interim). FEMA Policy 104-22-0003. Washington, DC: FEMA. https://www.fema.gov/sites/default/files/documents/fema_fp-104-22-0003-partial-implemetnation-ffrms-pa-interim.pdf.

Fleming, E., Payne, J., Sweet, W., Craghan, M., Haines, J., Hart, J.F., et al. (2018). "Coastal Effects," in *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II,* eds. D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock & B.C. Stewart. (Washington, DC: U.S. Global Change Research Program), pp. 322–352.

Gächter, S. (2013). "The Handbook of Rational Choice Social Research," in *1. Rationality, Social Preferences, and Strategic Decision-making from a Behavioral Economics Perspective,* eds. W. Rafael, A.B.S. Tom & N. Victor. Stanford University Press), 33-71.

Garner, A.J., Weiss, J.L., Parris, A., Kopp, R.E., Horton, R.M., Overpeck, J.T., et al. (2018). Evolution of 21st century sea level rise projections. *Earth's Future* 6**,** 1603–1615. doi:10.1029/2018EF000991.

Gigerenzer, G., and Goldstein, D.G. (1996). Reasoning the fast and frugal way: Models of bounded rationality. *Psychological Review* 103**,** 650-669.

Gregory, R., Falling, L., Harstone, M., Long, G., McDaniels, T., and Ohlson, D. (2012). *Structured Decision-Making: A Practical Guide to Environmental management Choices.* West Sussex, UK: Wiley-Blackwell.

Hilger, A., Rose, M., and Keil, A. (2021). Beyond practitioner and researcher: 15 roles adopted by actors in transdisciplinary and transformative research processes. *Sustainability Science* 16(6)**,** 2049-2068. doi: 0.1007/s11625-021-01028-4.

Ho, E.H., and Budescu, D.V. (2019). Climate uncertainty communication. *Nature Climate Change* 9(11)**,** 802-803. doi:10.1038/s41558-019-0606-6.

IPCC (2021). "Summary for Policy Makers," in *Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou. (Cambridge, UK: Cambridge University Press), 41 pp.

Jaeger, C.C., Renn, O., Rosa, E.A., and Webler, T. (2001). *Risk, Uncertainty, and Rational Action.* London: Earthscan.

Johnson-Laird, P.N. (2010). Mental models and human reasoning. *Proceedings of the National Academy of Sciences* 107(43)**,** 18243-18250. doi:10.1073/pnas.1012933107.

Kahneman, D. (2013). *Thinking, Fast and Slow*. New York: Farrar, Straus and Giroux.
Kahneman, D., and Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica* 47(2)**,** 263-291.
Kasperson, R.E. (2009). "Coping with Deep Uncertainty: Challenges for Environmental Assessment and Decision-Making," in *Uncertainty and Risk: Multidisciplinary Perspectives*, eds. G. Bammer & M. Smithson. (London, Sterling, VA: Earthscan), pp. 337-347.
Keenan, J.M., Hill, T. and Gumber, A. (2018). Climate gentrification: From theory to empiricism in Miami-Dade County, Florida. *Environmental Research Letters* 13(5), 054001.
Kinzig, A.P., Ehrlich, P.R., Alston, L.J., Arrow, K., Barrett, S., Buchman, T.G., et al. (2013). Social Norms and Global Environmental Challenges: The Complex Interaction of Behaviors, Values, and Policy. *BioScience* 63(3)**,** 164-175.
Levin, I.P., Schneider, S.L., and Gaeth, G.J. (1998). All frames are not created equal: A typology and critical analysis of framing effects. *Organizational Behavior and Human Decision Processes* 76**,** 149-188.
Moser, S.C. (2005). Impact assessments and policy responses to sea-level rise in three US states: An exploration of human-dimension uncertainties. *Global Environmental Change Part A* 15(4)**,** 353-369.
Moser, S.C., Davidson, M.A., Kirshen, P., Mulvaney, P., Murley, J.F., Neumann, J.E., et al. (2014). "Ch. 25: Coastal Zone Development and Ecosystems," in *Climate Change Impacts in the United States: The Third National Climate Assessment*, eds. J.M. Melillo, T.T.C. Richmond & G.W. Yohe. (Washington, DC: U.S. Global Change Research Program), pp. 579-618.
Opt, S., and Low, R. (2017). Dividing and Uniting Through Naming: The Case of North Carolina's Sea-Level-Rise Policy. *Environmental Communication* 11(2)**,** 218-230. doi:10.1080/17524032.2016.1157507.
Pielke, Jr., R. A. (2007). *The Honest Broker: Making Sense of Science in Policy and Politics*. Cambridge: Cambridge University Press.
Plous, S. (1993). *The Psychology of Judgment and Decision Making*, McGraw-Hill
Renn, O. (2008). *Risk Governance: Coping with Uncertainty in a Complex World.* London: Earthscan.
Reyna, V.F. (2021). A scientific theory of gist communication and misinformation resistance, with implications for health, education, and policy. *Proceedings of the National Academy of Sciences* 118(15)**,** e1912441117. doi:10.1073/pnas.1912441117.
Reyna, V.F., and Rivers, S.E. (2008). Current Theories of Risk and Rational Decision Making. *Dev Rev.* 28(1)**,** 1-11.
Samson, A. (ed.). (2014). *The Behavioral Economics Guide 2014: Introduction to Behavioral Economics.* London: Behavioral Science Solutions Ltd.
San Francisco Bay Conservation and Development Commission (BCDC) (2020). San Francisco Bay Plan. San Francisco, CA: BCDC.
Sarathchandra, D., and Haltinner, K. (2020). Trust/distrust judgments and perceptions of climate science: A research note on skeptics’ rationalizations. *Public Understanding of Science* 29(1)**,** 53-60. doi:10.1177/0963662519886089.
Sayers, P., Moss, C., Carr, S. and Payo, A. (2022). Responding to climate change around England's coast-The scale of the transformational challenge. Ocean & Coastal Management 225: 106187. doi:10.1016/j.ocecoaman.2022.106187.
Schipper, E.L.F. (2020). Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth* 3(4)**,** 409-414. doi:10.1016/j.oneear.2020.09.014.
Thaler, R.H. (2015). *Misbehaving: The making of behavioral economics.* New York: W. W. Norton & Company.
Tversky, A., and Kahneman, D. (1974). Judgments Under Uncertainty: Heuristics and Biases. *Science* 185(4157)**,** 1124-1131.
Walker, W.D., Liebl, D.S., Gilbert, L., LaGro, J., Nowak, P., and Sullivan, J. (2010). "Adapting to climate change: Why adaptation policy is more difficult than we think (and what to do about it)",

in: *WICCI Working Group Reports.* Madison, WI: Wisconsin Initiative on Climate Change Impacts (WICCI).
Wilby, R.L., Nicholls, R.J., Warren, R., Wheater, H.S., Clarke, D. and Dawson, R.J. (2011). Keeping nuclear and other coastal sites safe from climate change. *Proceedings of the Institution of Civil Engineers-Civil Engineering*, 164, 129-136.
Wolbring, T. (2020). Rationality, strategic interactions, and theories of middle range. *Social Science Information* 59(4)**,** 569-574. doi:10.1177/0539018420964390.
Wullenkord, M.C., and Reese, G. (2021). Avoidance, rationalization, and denial: Defensive self-protection in the face of climate change negatively predicts pro-environmental behavior. *Journal of Environmental Psychology* 77**,** 101683. doi:10.1016/j.jenvp.2021.101683.