COORDINATING CLIMATE CHANGE ADAPTATION AS RISK MANAGEMENT

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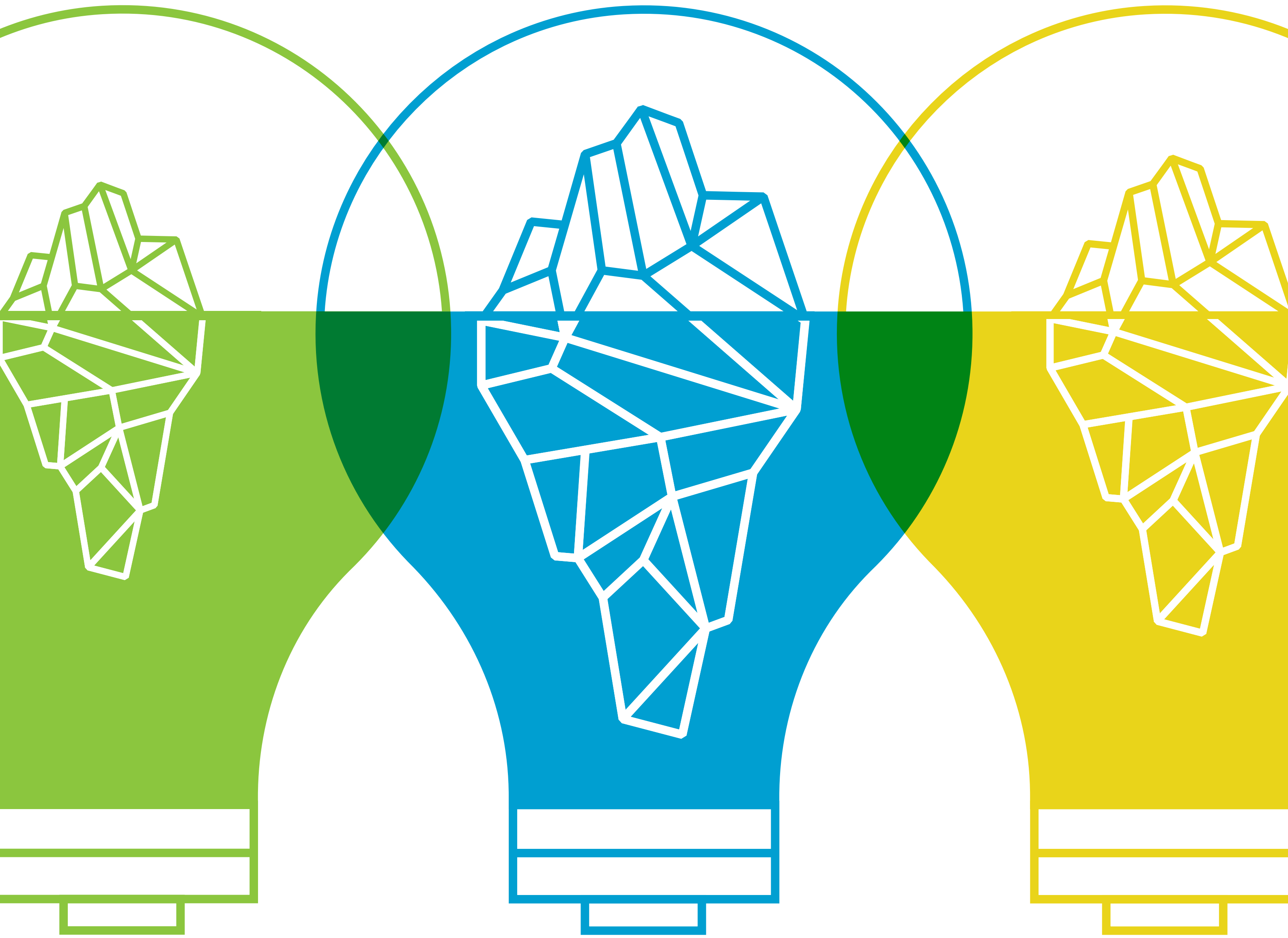

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COORDINATING CLIMATE CHANGE ADAPTATION AS RISK MANAGEMENT

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EDITORIAL
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Editorial: Coordinating Climate Change Adaptation as Risk Management

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Editorial on the Research Topic

Coordinating Climate Change Adaptation as Risk Management

Climate change adaptation is a form of risk management that requires coordinated governance of social, economic, and technological institutions. Risk results from the combined effect of hazards (natural and anthropogenic) and vulnerability—and climate change is already creating pervasive but varying risks in multiple societal and environmental sectors. Therefore, the need for adaptation spans many systems. Policy decisions regarding adaptation measures must be informed by reliable research in science (including the social sciences), technology, and engineering, but that research agenda also must be informed by policy goals and practical constraints.

This Research Topic gathers articles from multiple disciplines that promote research supporting coordinated adaptation strategies to effectively manage climate risk. The collection covers a broad span of topics, demonstrating how widely adaptation will affect social and environmental resources.

Climate change is rife with risks that compound and cascade over time, leading to uncertainties that challenge conventional planning. In their Policy and Practice Review, Lawrence et al. argue that this pervasive uncertainty requires an anticipatory adaptive approach tailored to such a dynamic environment. Using developments in New Zealand's adaptation policy, they show that planning using time-bound methods, such as static lines on maps and zoning, can lock in communities to exposure to risks that are changing in time and space. They identify institutional policy reforms underway moving New Zealand toward a more adaptive direction of climate risk management.

Although public governance institutions are the focus of much adaptation policy analysis, Vandenbergh and Johnson argue in their Perspective that private institutions also will play a significant role. They explain that private governance initiatives that target climate change mitigation have expanded rapidly in the last decade and have been the subject of research in multiple fields, but that private initiatives targeting adaptation have received less attention.

Three articles in the Research Topic focus on ecological risks. In their Policy Brief, Camacho and McLachlan address ways in which current regulatory regimes governing species conservation and control often use terms such as "native" or "invasive" that will not work effectively when climate change disrupts ecosystem and forces species to move. They argue that such species categorizations, as well as the patchwork patter of public and private land ownership over large areas, were developed in a static environment and will become anachronistic and will increasingly challenge regional conservation when the dynamic forces of climate change drive species outside their historical ranges.

In their Review, Bork and Hirokawa shift to consider the ecosystem services that ecological resources provide human communities. They argue that as climate change disrupts ecosystem

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function and structure, local governance of ecosystem management to maintain desired ecosystem conditions will become increasingly important. They review 20 years of U.S. legal literature on local ecosystem governance to identify theoretical arguments for and against local governance, describe ongoing efforts to implement local ecosystem governance, and propose actionable recommendations and critical research needs.

Wildfire risk, both in frequency and scale, is a growing adaptation concern. In their Perspective, Vuorio et al. argue that better policies are needed to reduce vulnerability and fragility of ecosystems and human societies to catastrophic wildfire. They highlight the International Civil Aviation Organization protocols for safety investigations after international fatal aviation accidents, describing how its adaptation to wildfire catastrophes offers a useful framework for establishing international guidelines to reduce risk. In particular, co-operation between aviation authorities has been shown to benefit less developed countries, with the same potential benefit coming from post-wildfire investigations.

Energy transition constitutes a significant component of reducing global risks from climate change, and three articles in this collection explore the risks to and adaptation needs of the energy sector. Ziaja and Chhabra in their Policy and Practice Review investigate the California Public Utilities Commission's 2018 decision to regulate investor-owned energy utilities' climate adaptation activities. The Commission's 2020 regulations were the first of their kind in the country, but their implementation has revealed critical limitations in capacity and the need for more focus on what exactly constitutes an "adaptation measure."

In his Perspective, Monast looks more broadly at Public Utility Commissions (PUC) in the United States, arguing that they can already use their ratemaking authorities to advance climate change adaptation. Discussing how electricity ratemaking is already a form of risk management and reviewing the authorities already available, he argues that PUCs should adopt a risk governance approach, which would both incorporate climate adaptation in ratemaking and help to coordinate adaptation policy across agencies.

Moving from PUC authority to energy infrastructure, Verchick and Lyster offer a comparative Perspective on building climate-resilient power grids. Dissecting storm- and flood-based power outages and their regulatory aftermath in Texas (United States) and Queensland (Australia), they conclude that both governments could do more to build climate change projections into grid recovery and better fund necessary adaptation measures.

Coasts are the quintessential climate change risk zones. In their Policy and Practice Review, Correll-Brown et al. examine how rising seas are already undermining shoreline management efforts. They investigate the lack of good data regarding how shorelines have already changed in the United States, arguing that the lack of documented change has promoted shoreline management based on a shifted baseline that accepts a degraded coast as normal.

Finally, rounding out the full range of risk that climate change poses, Chen offers a Policy and Practice Review from the financial sector. Specifically, he uses insights from behavioral economics to explore how the uncertainties of climate change can generate perverse decisions in environmental and resource economics, inhibiting effective adaptation strategies.

Individually, the 10 articles in this Research Topic provide a range of lenses through which to explore the concept of climate change adaptation as risk management. Together, they emphasize that much more remains to be done to incorporate a risk management perspective on climate change adaptation—but also that improvements and transitions are available to governments and sectors that wish to better confront the risks that climate change poses.

AUTHOR CONTRIBUTIONS

JR and RC equally drafted and edited this Editorial, which HB reviewed. All authors contributed to the article and approved the submitted version.

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PERSPECTIVE
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Wildfire-Related Catastrophes: The Need for a Modern International Safety Investigation Procedure

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Despite the increased frequency and scale of wildfire-related catastrophes, there has been little or no effective and coordinated international policy to address their highly negative impact. Possibly a generalized approach to respond to such major events could be modeled on existing international safety investigation policies and agreements that already have proved successful. The International Civil Aviation Organization (ICAO) outlines safety investigations after international fatal aviation accidents. Although this well-established safety investigation protocol cannot be directly applied in acute wildfire-related accidents, it can offer a useful framework for establishing international guidelines to reduce risk of future wildfire catastrophes. The co-operation between safety investigation authorities has been shown to be fruitful especially for those less developed countries that have limited resources and experience related to accident investigations. While primarily an adaptive measure that can set practices to reduce vulnerability and fragility of ecosystems and human societies, the same policies could be seen as a climate change mitigation measure, as wildfires can contribute significantly to global CO_2 emissions. Finally, the concept of independent and qualified safety investigations represents the principle of serendipity: disclosing *by accident* something that has not been foreseen. Feedback from reality compensates assumptions and limitations of feedforward analysis of complex systems that can only reveal their dynamics and performance in reality and over time.

Keywords: accident investigation, safety management system, aircraft, COVID-19, wildfire, CO_2-emission

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INTRODUCTION

Large-scale fires, such as those that raged across Australia during the "Black Summer" 2019–2020, can cause destruction both to the local ecosystems and global environment. The risk of wildfires is increasing as climate change progresses (Bowman et al., 2020, **Figure 1**). In addition, human lives have been lost and societies disrupted as a result of such fires. Rainforest fires have occurred periodically in Sumatra, Indonesia since the 1960s (Field et al., 2009), usually during the dry season when fires are set by farmers to clear waste. Although these rainforest fires cannot be considered traditional accidents in all respects, their unexpected overall effects have caused environmental disasters. In 2015 the Indonesian fire season was extremely severe. The CO_2 equivalent biomass

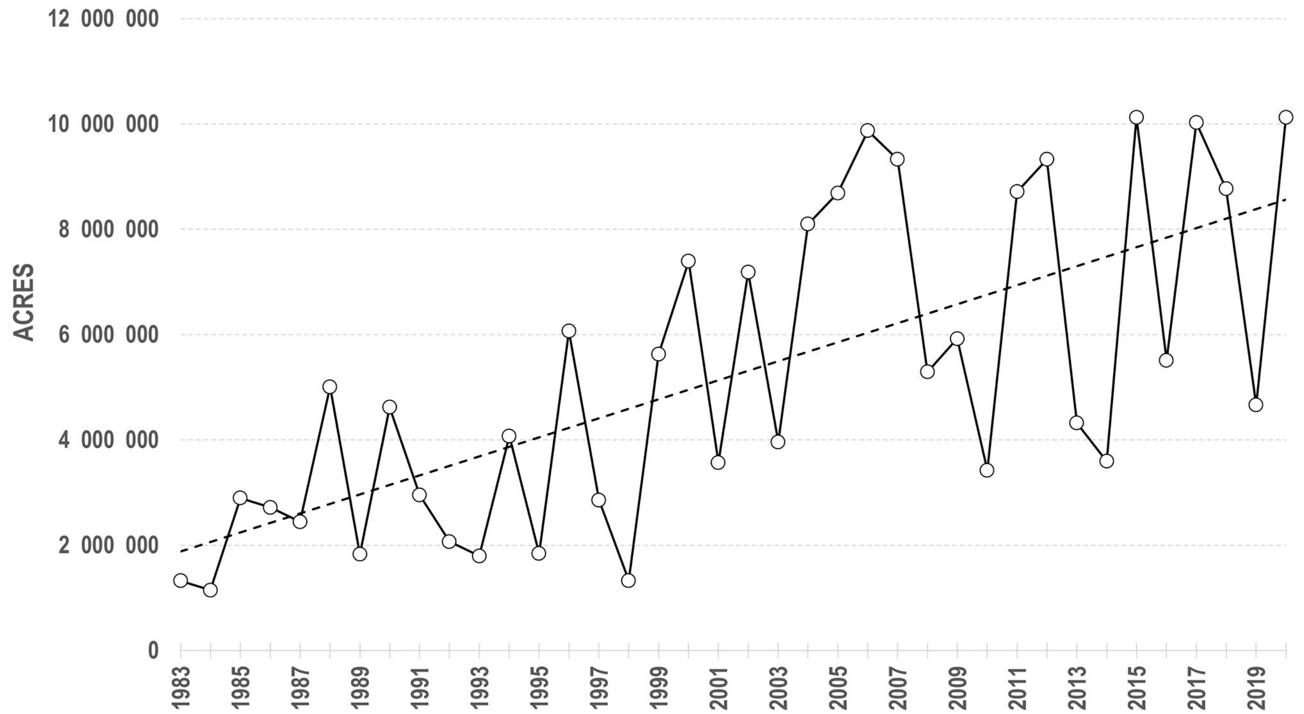

FIGURE 1 | Increasing trend of wildfires in the United States. The graph depicts the total area (in acres) affected by wildfires in the United States between the years 1983 and 2019. Data from the National Interagency Fire Center (www.nifc.gov).

burning emissions were estimated to be equal to the combined fossil fuel emissions generated by Japan and India in 2013 (Field et al., 2016).

In addition to ecosystem disturbance, wildfires can cause colossal economic losses. For example, in 2020 in the United States, there were about 57,000 wildfires compared with 50,477 in 2019 based on the statics provided by the National Interagency Fire Center (Insurance Information Office, 2021). These above-mentioned numbers also reveal that 10.3 million acres were burned in 2020, compared with 4.7 million acres in 2019. The costs of the Australian Black Summer have been estimated to exceed $100 billion, including over $2 billion of smoke-related health costs (Roach, 2020). As a result of wildfires, there are often disruptions in transportation and water and power supply lines. The health effects of wildfires have been clearly established (Stefanidou et al., 2008; Liu et al., 2019; Xu et al., 2020; Yu et al., 2020). Remarkably, during wildfire episodes, the concentrations of the smallest (even submicron-sized) particles were increased (Makkonen et al., 2010). The small particles ($<2.5\,\mu$m) contain toxic trace elements and, as they can penetrate deep into the respiratory system, are the most harmful particles to human beings. A recent analysis of out-of-hospital cardiac arrest data for 5,336 individuals identified through the Cardiac Arrest Registry to Enhance Survival for 14 counties in California (2015–2017) showed that the risk of cardiac arrest increased with fire-related smoke exposure (Jones et al., 2020). Cheong and co-workers reviewed studies that had investigated the acute health impact of the Southeast Asian transboundary haze caused by forest fires and found increases both in the occurrence of acute myocardial infarction and in mortality due to out-of-hospital cardiac arrest (Cheong et al., 2019).

Thus, natural and human resources continue to be vulnerable to devastating events with serious consequences unless proactive measures are enacted. It is noteworthy that the Australian prime minister Scott Morrison in early 2020 called for a high-level government inquiry into the response to the country's devastating bushfires (New York Times, 2020). Despite the increased scale of fire-related catastrophes and their effect on societies and the environment, there has been no effective and coordinated international policy to address these highly negative impacts. Furthermore, the current international agreements to prevent the increase of atmospheric CO_2 do not consider ecological catastrophes which can contribute significantly to CO_2 emissions (Rogelj et al., 2016). Proactive measures should be enacted.

The first version of Forensic Investigations of Disaster (FORIN) was published in 2010 and the second in 2016 presenting methodological approaches for forensic disaster investigations (Oliver-Smith et al., 2016). It is recognized in the FORIN 2016 edition that there is a need for additional application of the FORIN for disaster risk reduction and climate change adaptation. It highlighted that FORIN can be used to analyse root causes of risk factors helping to provide bases for policies and strategies to decrease future disasters. At this point, however, the guidance has been given at a general level, and there is clearly room for further development.

We propose in this perspective article that international aircraft investigations, which have roots starting from the year 1944 have potentially significant guidance for FORIN incident investigation methodology in several areas (International Civil Aviation Organization, 2016). First and foremost, the most important principle of international aircraft investigation is that it is blame-free (Dekker and Breakey, 2016). Our proposed approach attempts to mollify the blame game. In the current FORIN protocol, there is an effort to start to analyse legal capabilities. In aircraft accidents investigation and legal processes are independent. Secondly, international aircraft accident investigation has a clear protocol by which stakeholders and shareholders participate in the investigation process (International Civil Aviation Organization, 2016). The current forensic investigation of the disaster management system would benefit from an international coalition to address solutions because there may be substantial conflicts of interest with government officials and what could be best practices to reduce future fires. An international approach may mitigate some of the conflicts of interest. Some fire-related issues may prove to be politically complex and challenging, but on the other hand, there is already evidence that progress has also been made in mitigating the impact of wildfires through international cooperation and knowledge exchange (van Lierop and Moore, 2016). This type of guidance is still not yet well-established in FORIN. Thirdly, climate change-related disasters like wildfires are very complex events. Aircraft investigation offers systematic approach techniques to analyse complex interactions (Dekker et al., 2011). In the FORIN protocol, there is an attempt to find the root cause. However, in complex investigations often several causes emerge, and in certain circumstances, it is very difficult to define a single root cause. Fourthly, safety investigation offices need to be juristically independent, and they need sufficient governmental funding (International Civil Aviation Organization, 2016). Both of these conditions are essential to the success of accident investigation. There is also long-term experience of international co-operation between safety authorities in different countries. This relationship can be beneficial for those less developed countries that may have limited resources and experience. These various elements still need to be developed for forensic disaster investigations.

LACK OF SAFETY INVESTIGATION PROTOCOLS AND WILDFIRES

Considering the wildfire events, there is a clear need to develop better outcomes that will identify fragile systems (i.e., the most ones at high risk to suffer from devastating fires), reduce the exposures that impact human health, and also protect from significant resource losses. This kind of a generalized approach for the development of better outcomes could be modeled on other international safety investigation policies and agreements that have proved successful. Currently, for example in Indonesia, the responsibilities for forests are divided between several ministries leading to governmental inactivity in wildfire emergencies (Burki, 2017). In some other countries, such as Australia, major wildfires have led to public inquiry (Inspector-General for Emergency Management, 2020). While one of the aims of the public inquiry is to prevent future catastrophes, as is done in safety investigations, the nature of public inquire is more like a review of events; systematic analysis which could be provided by safety investigation is mostly lacking (Sulitzeanu-Kenan, 2010; Underwood and Waterson, 2013).

Recently, De Sisto and Handmer (2020) suggested the creation of an ongoing and continuously improving learning culture, in which daily based investigative knowledge and experiences are shared at the agency level. Unfortunately, however, such learning mode by co-operation is still missing. One plausible framework is provided by the International Civil Aviation Organization (ICAO): the safety investigations that can be carried out after international fatal aviation accidents, based on the ICAO-approved Annex 13 to the Convention on International Civil Aviation in 1944, and subsequent regular updates (International Civil Aviation Organization, 2016). Indeed, this agreement has demonstrated its effectiveness in improving aviation safety substantially. Therefore, it is reasonable to pose the question of whether international aircraft safety investigation processes would apply to environmental accidents, such as wildfires, and if implemented could they reduce risk and vulnerability to natural resources and human health in those fragile environments where devastating fires are more probable. The overall principle is the same: to prevent similar catastrophes from occurring again and again, or to provide more effective response mechanisms to manage the event and thereby reducing its severity. Importantly, the investigation is carried out not to determine liability, but to develop recommendations of proactive approaches for the prevention of future accidents i.e., learning from previous experience to reduce the risk and vulnerability constructively. These principles have been accepted as a part of European Union directives; thus, international support has been gained (European Union, 2010).

Typically, in aviation accidents, a final report is published within 12 months of the event, but in exigent circumstances, a safety investigation team can report preliminary recommendations much earlier. An example of the recommendations in a preliminary report being expeditiously and widely promulgated was the case of a lithium battery fire in a Boeing 787 aircraft in Boston in 2013. This report led to the worldwide grounding of all Boeing 787 aircrafts to prevent further accidents until the underlying cause was identified and appropriate corrective actions were implemented (National Transportation Safety Board, 2013). We proposed a similar application within the international chemical industry, which lacks a review process despite the occurrence of large-scale catastrophes such as the methyl isocyanate gas leak at a pesticide plant in Bhopal, India in 1984 (Vuorio et al., 2017). Of note, an aviation safety investigation also examines the health issues associated with an accident (International

Civil Aviation Organization, 2012) and thus could address the morbidity and mortality due to methyl isocyanate exposure in Bhopal.

EVOLUTION OF SAFETY INVESTIGATIONS

Safety investigations have seen a gradual evolution in scope and methodology. Safety investigations in aviation were conducted in the United States by the National Transport Safety Board (NTSB) in a multimodal context, based on a legally assured independence from governmental interference (National Transportation Safety Board, 2021). The NTSB conducts its investigative efforts in an independent federal institute, combining all modes of transportation: air, maritime, rail, roads and pipelines. Gradually, the NTSB expanded its scope to victims, family assistance, training of investigators, and event-driven occasionally also to other industrial sectors, such as space and civil infrastructures.

In aviation, the focus during investigations is gradually widening from preventing similar events to improve understanding of the system itself in its behavioral variety, assumptions and limitations, including responding and recovery from destabilizing events. The AF447 case [Bureau d'Enquêtes et d'Analyses (BEA), 2012] revealed fundamental deficiencies in man-machine interfacing, while the B737MAX cases (The House of Committee on Transportation Infrastructure, 2020) disclosed the limitations of certifying disruptive adaptations with derivative certification procedures. Their accidents can be traced back to system properties that did not manifest themselves before as catastrophic and have become foreseeable instead of inevitably being labeled as "emergent" properties. Safety investigations serve the category of "low probability/high consequences" beyond statistical confidence in predicting failure of more frequent, foreseeable events. The concept of independent safety investigations represents the principle of *serendipity:* disclosing *by accident* something that has not been foreseen. Feedback from reality compensates assumptions and limitations of feedforward analysis during the design and certification of complex systems that can only reveal their dynamics and performance in reality (ESReDA, 2020).

The NTSB served as a role model for independent investigations, establishing European and other world regional counterparts. Together with its Scandinavian, Canadian and Dutch counterparts, it participated in ITSA, a forum of legally independent, national investigative authorities established in 1993 to learn from each other and to exchange experiences (ESReDA, 2020). A major breakthrough was achieved by posing the question in sharing not what to investigate, but how to investigate. This approach enabled each investigative agency to remain independent from its legal and institutional context and simultaneously achieve a high-level playing field concerning tools, techniques and above all, a common methodology, irrespective of mode, sector or domain. Such a methodology discriminates three phases of the investigative process, each with its specific goals, principles and deliverables. These phases are (ESReDA, 2020):

- *Investigative reconstruction*, based on forensic principles and techniques for collecting raw data, on-site and off-site. This phase makes the step from description to explanation of the event.
- *Analytic interpretation*, mobilizing (multi-)disciplinary knowledge and sectoral, specific expertise and experience enables the step from understanding the event into understanding the system and intervention in the system throughout its life cycle and levels.
- *Adaptive intervention*, based on input from the previous steps, applies engineering design and system change management principles, enabling the transition to sustainable change and feasible and credible safety enhancement.

These steps facilitate insight into the causal relations between events, interrelations between system components and functions and clarify dynamics and time dependence of phenomena. The gradual transition in focus from event to system during the investigation creates oversight over the system architecture, structure, culture and operational processes (Dekker et al., 2011). Identification of change drivers, change agents, and their underlying values and goals clarify the potentials for system change and adaptation. This approach also clarifies the dynamics of a system with respect to the presence of showstoppers, whistle-blowers and change opportunities. It creates opportunities for foresight, predicting future safe performance. In doing so, the legacy nature and specifics characteristics of major systems put high demands and restrictions in developing this methodology for specific applications. Application of this investigative process elevates the investigations from a factor and actor-oriented scope—focusing on performance—to an additional focus on systemic properties and principles, aspects, change vectors, institutional arrangements, values and transition management strategies. A plausibility, feasibility and credibility assessment indicates which safety enhancement options are realistically implementable. Recommendations may focus on optimizing procedures, derivative from existing operational practices, on the introduction of disruptive system adaptations or even on prospective options for changing principles and concepts. Such strategies are case-based, evidence-based and above all, knowledge-based due to the in-depth analysis of the event that triggered a need for safety enhancement. The investigative process bears elements of serendipity: learning by accident something that has not been observed before. Safety investigations represent a specific category of analytical approaches. Generic, statistical analysis of data focuses on trends and patterns, (mono-)disciplinary research provides knowledge and understanding of specific phenomena, specific, conditional analysis of data serves policymaking for specific contexts and target group. Investigations link understanding of events to their systemic context and operating conditions. Safety investigations are the problem providers for knowledge development and system change. The analytic potential of investigations has gradually expanded the interest in understanding the behavior of earthquakes, tsunamis, bushfires and wildlife fires, and other major, low-frequency events without allocating blame and liability (ESReDA, 2020).

COMPARISON OF ADMINISTRATIVE PROTOCOLS BETWEEN AN INTERNATIONAL AIRCRAFT ACCIDENT INVESTIGATION AND THE PROPOSED INTERNATIONAL WILDFIRE INVESTIGATION

Interestingly, some national initiatives regarding wildfires can be traced back to 1910 in the United States, although they were based on an economic rather than an ecological perspective (Silcox, 1910). The investigation of international air accidents began in 1944 with the adoption of Annex 13 of the Chicago Convention by the International Civil Aviation Organization (ICAO) (Stoop and Kahan, 2005). The motivation of the ICAO Annex 13 was to try to prevent similar accidents from occurring again without taking a position on legal liability. Often the safety investigations provide recommendations that suggest enactment of effective legislation addressing the root cause and mitigation of the cause of the event. A criminal investigation, if necessary, is a separate process independent of the safety investigation (Imam and Aspan, 2020). We propose, in an analogous manner, that an international wildfire accident investigation agreement could be developed with an intergovernmental agreement that possibly could be part of the Paris Climate Agreement. Also, guidance provided by the Food and Agriculture Organization (FAO) of the United Nations could be useful to identify the key elements of useful legislation on forest fires (Food and Agriculture Organization of the United Nations, 2009).

At the state level, the ICAO Annex 13 defines those stakeholders who take part in the investigation. Commonly, countries that have been involved in aircraft accident investigations have established accident investigation organizations. In many countries, these organizations are multipurpose; they investigate not only aircraft accidents, but also other major catastrophes that impact society and the environment. The number of permanent staff is rather limited but in the case of an acute investigation (e.g., a critical incident), additional specialists are hired temporarily. From the legal perspective, for example, in the European Union, the ICAO framework is part of the European Parliament Regulation (European Union, 2010), and international cooperation is at the heart of this regulation. During the investigation process, usually the country in which the accident occurred takes responsibility to coordinate the investigation process. The stakeholders (investigators/representatives) will be from the countries representing the aircraft or major aircraft component manufacturers, aircraft registration and deceased passengers. Regarding international wildfire safety investigations, these principles could be adopted as shown in **Table 1**.

The national accident investigation authorities could take on the responsibility of the investigation process also regarding wildfires. This investigation would probably be smoothly undertaken in countries having an established multipurpose accident investigation organization and having traditionally been accustomed to investigating different types of accidents. In countries where safety investigations have mainly focused on accidents involving specific modes of transport, special arrangements for wildfire investigations would be required. An agreement on the investigation of international wildfires, parallel to international air accident investigations, should sanction the participation of representatives from countries affected in the investigation process.

COMPARISON OF TECHNICAL ASPECTS BETWEEN INTERNATIONAL AIRCRAFT ACCIDENTS AND PROPOSED INTERNATIONAL WILDFIRE INVESTIGATIONS

The investigation process in use in aviation has developed based on experience gained over decades. Similarly, the development of a wildfire safety investigation will take considerable time to gather experiences and develop best practices. As a useful example in aviation accidents pre-accident data gathered from flight data recorder and cockpit voice recorder can be used and combined with pilot performance analysis received from airborne image recorders (Li et al., 2020) to assist the investigation to determine the factors to address to reduce risk and vulnerability.

Regarding wildfire safety investigations satellite-based measurement technology can be applied to assist in determining causes of an event, conditions affecting the severity of the outcome in terms of damage to ecosystems and human society as well as potential remediation. Furthermore, this would allow the measurement and analysis of wildfire-caused emissions (Li et al., 2000; Jang et al., 2019; Hislop et al., 2020). The satellite-based emission measurements combined with fire activity and vegetation productivity have been successfully applied internationally in the Global Fire Emission Database (2021). These data provided by the Global Fire Emission Database include (1) burned area (Giglio et al., 2013), (2) carbon and dry matter emissions (van der Werf et al., 2017), (3) fractional contribution of various fire types of total emissions and (4) list of emission factors to compute trace gas and aerosol emissions (Akagi et al., 2011).

DISCUSSION

We propose in this perspective article that wildfire accident investigations could apply safety investigation process principles which potentially can model methodological and legal bases provided by the ICAO Annex 13 based aircraft accident investigation process. It is not, however, possible to "copy-and-paste" this protocol because each system has different requirements and features and much remains to be done in developing a specific international protocol for wildfire safety investigations. However, there are examples of successful forensic investigations of disasters that are related to environmental change caused by humans. One interesting investigation is related to analyzing vulnerabilities in society and the environment that increase climatological hazards (Stonich, 2021). This comprehensive investigative analysis well combines

TABLE 1 | Comparison of administrative protocols between current international aircraft and proposed forest fire accident investigations.

Issue	Existing aircraft accident investigation protocol	Proposed wildfire investigation protocol
International Agreement	ICAO Annex 13 Chicago Convention	Additional protocol of Paris Climate Agreement in co-operation with WHO and FAO
State-level legislation	State-level and alliances-wide legislation	State-level and alliances-wide legislation
Investigation authority	National accident investigation authorities of the country of accident occurrence	National accident investigation authorities with temporarily hired professionals from the country where fire occurs
Stakeholders in the investigation process	Countries representing aircraft or major aircraft component manufacturers, aircraft registration and deceased passengers	Countries representing countries of fire occurrence or countries having environmental and/or health impact due to fire
Investigation	Independent and conducted without prejudice to any judicial action	Independent and conducted without prejudice to any judicial action

WHO, World Health Organization; FAO, Food and Agriculture Organization of the United Nations.

the impact of ecological and political issues on the vulnerability of society.

Safety investigation processes related to forest fire catastrophes are likely to be more complex especially if they are related to additional accidents (Beresford et al., 2021). However, aircraft investigations may be complex in addition to matters relating to the airplane itself. For example, El Al Flight 1862 crashed into the neighborhood of Amsterdam on 4 October 1992 destroying an entire block of flats and killing several people on the ground (Netherlands Aviation Safety Board, 1992).

However, similar overarching quality systems may be applicable, focusing on identifying and implementing solutions based on experience and continuous improvement (International Civil Aviation Organization, 2016; Oliver-Smith et al., 2016). The fundamental elements of the safety (or perhaps mitigation) investigation process are: (1) investigator independence, which requires establishing international agreement to investigate acute environmental catastrophes (International Civil Aviation Organization, 2016); (2) a holistic conceptual process for examining accidents (Dekker et al., 2011); (3) an established, international institutional framework to provide investigator resources for large-scale catastrophes (International Civil Aviation Organization, 2016); and (4) continuous and sustainable training of competent investigators supported by governments (Vuorio et al., 2017).

Although the aviation accident safety investigation protocol cannot be replicated when designing a protocol for acute wildfire-related accidents, it provides a useful framework to establish international guidelines for response and reference to use a similar process to develop approaches to reduce the number and severity of future catastrophes. Transformational rather than incremental changes in current thinking and practice are needed to address the impact of wildfire-related catastrophes on local and global environments, as well as on human, animal and plant health, and to protect the basic functions of society (Kates et al., 2012). Analysis of risk and vulnerability of systems can inform on changes and properties and the emergent consequences could contribute to a better understanding of how and why wildfires develop into disasters (Oliver-Smith et al., 2016).

The implementation of a wildfire investigation procedure could rely on an approach in which the importance of health is integrated into the environmental systemic impact of wildfire (Briggs, 2008). In fact, a recent review shows that there is an increasing interest to develop tools that can take care of health issues in mitigation within the climate change adaptation strategies (Delpla et al., 2021). This inclusion in wildfire-related catastrophes investigations may help to decrease morbidity and mortality, and it certainly can be a force multiplier to promote implementation.

It is noteworthy that, in addition to large-scale wildfires, it is possible to apply aviation accident investigation techniques to other large-scale disasters. The current coronavirus disease (COVID-19) pandemic is reminiscent of previous epidemics that inspired the system of air safety investigations. Dr. John Snow's investigation of the cholera epidemic in London in 1854 provided a basis on how to investigate such devastating events. He was the first to apply the precautionary principle and is considered the father of epidemiology. His example demonstrates the importance of exploring the association between a cause and an effect even without a theoretical understanding of the association (Goldstein, 2012). Since those days, global interactions have become increasingly more complex. The challenge will be to use modern accident investigation procedures to improve global safety systems.

CONCLUSION

Despite the increased frequency and scale of wildfire-related catastrophes, there has been little or no effective and coordinated international policy to address their highly negative impact. Possibly a generalized approach to respond to such major events could be modeled on existing international safety investigation policies and agreements that already have proved successful. At present, there are ongoing interests in the development of forensic disaster investigation protocols. The second edition of FORIN was published in 2016 (Oliver-Smith et al., 2016). Yet, forensic investigations protocols can be considered relatively nascent compared with international aircraft accident protocols which were introduced already in 1944. It could be very fruitful to leverage some of the experiences and practices of the aircraft accident investigation protocols and investigations especially when creating specific protocols for international wildfire-caused disasters.

Such newly created protocols and policies are primarily adaptive measures that can set practices to reduce the vulnerability and fragility of ecosystems and human societies. Since the wildfires contribute significantly to global CO_2 emissions, the same policies can be considered also as climate change-mitigating measures. Finally, the concept of independent and qualified safety investigations represents the principle of serendipity: disclosing *by accident* something that has not been foreseen. Feedback from reality compensates assumptions and limitations of feedforward analysis of complex systems that can only reveal their dynamics and performance in reality and over time.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AV: writing the first draft. AV, PK, AS, BB, JP, and JS: equally contributed to reviewing and editing to produce the final draft. All authors contributed to the article and approved the submitted version.

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Ratemaking as Climate Adaptation Governance

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Electric utilities are directly affected by, and in some cases are a source of, many pressing climate adaptation challenges: wildfires, vulnerable infrastructure, extreme storms, and drought. The state Public Utilities Commission (PUC) is one of the most consequential government agencies guiding the electricity sector's response to climate change. Rate-regulated utilities may not charge ratepayers for new capital investments without PUC approval. When PUCs decide which costs are eligible for rate recovery, they also define which risks utilities seek to manage and which hedging strategies they use to do so. This Article argues that the foundational principles of ratemaking allow the state PUC to manage many aspects of electricity sector adaptation planning, coordination, and implementation. The Article begins with an overview of ratemaking for electric utilities and identifies how the process is an exercise in risk management. The Article then explains how a risk governance perspective can position the PUC to explicitly incorporate climate adaptation into ratemaking procedures as well as help coordinate adaptation policy across multiple agencies.

Keywords: climate adaptation, energy, public utilities, regulation, risk governance

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INTRODUCTION

Electric utilities are directly affected by, and in some cases are the source of, many of society's most pressing climate adaptation challenges: wildfires, vulnerable infrastructure, extreme storms, extreme temperatures, and drought. In most states, ratemaking decisions by the Public Utilities Commission (PUC) directly influence how electric utilities respond. Investor-owned utilities serve almost three quarters of U.S. electricity customers (U.S. Energy Info. Admin, 2019a). These rate-regulated utilities may not charge ratepayers for new capital investments without PUC approval. When PUCs decide which costs are eligible for rate recovery, they also define which risks utilities seek to manage and which hedging strategies they use to do so.

This Article argues that the foundational principles of ratemaking allow the state PUC to manage many aspects of electricity sector adaptation planning, coordination, and implementation. Ratemaking includes many of the characteristics of effective climate adaptation governance: flexible statutory authority for agencies overseeing critical sectors of the economy, the ability to collect and respond to new information, and the ability to direct capital to ensure delivery of essential services. The manner in which PUCs exercise their authority will determine how utilities prepare for, and respond to, a changing climate.

The Article begins with an overview of ratemaking for electric utilities and identifies how the process is an exercise in risk management. The PUC pursues the traditional goals of affordable rates, reliable service, and financial viability for the utility by mitigating certain risks financial and technical risks, and allocating a broader range of risks among utilities, ratepayers, and society. The Article then explains how a risk governance perspective can position the PUC to explicitly incorporate climate adaptation into ratemaking procedures as well as help coordinate adaptation policy across multiple agencies.

RATEMAKING AND RISK MANAGEMENT

The electricity sector's climate adaptation challenges have been in sharp relief in recent years. Catastrophic wildfires have caused severe damage in western states, some of which were ignited by electricity infrastructure. Utilities along the Gulf Coast and East Coast have faced strong hurricanes and historic floods in recent years. In the first half of 2021 alone, record-breaking heat led to rolling blackouts in the Pacific Northwest, a severe winter storm caused widespread power outages in Texas and pushed the state's grid to within minutes of total failure, a megadrought in California threatened hydropower resources and increased the risk of another catastrophic wildfire season, and the Atlantic hurricane season was off to another early start (Cappucci, 2021; Douglas, 2021; ERCOT, 2021; Patel, 2021; Singh, 2021). These are immediate operational threats for the nation's complex electricity system, and highlight the direct link between electricity decision-making and the economic and social risks presented by a changing climate. Ratemaking by state PUCs will play a pivotal role guiding utilities' responses.

Ratemaking reflects a century-old compromise. States grant electric utilities exclusive licenses to sell electricity to retail customers within their respective service territories. In exchange, the PUC ensures that a monopoly utility's rates are reasonable and utility investments produce tangible benefits for ratepayers. Rates must also allow a utility the opportunity to earn a reasonable return on investments and attract capital to meet future electricity demand (Bluefield Water Works, 1923).

State laws generally require that electricity rates be "just and reasonable," that utilities choose the least cost option for providing reliable electricity, and that utilities may only recover costs that are prudently incurred (Cal. PUC). PUCs have broad discretion when applying these principles. Historically, commissions apply the concepts narrowly, focusing on fuel costs, available technologies, and changing electricity demand due to population growth, but ignoring other factors with direct impacts on costs and reliability. For example, least cost can depend upon the time horizon under consideration, as regulatory changes can increase costs significantly, but commissions are typically reluctant to approve higher costs to mitigate regulatory risk (Monast, 2015).

PUCs set rates through quasi-judicial processes, hearing evidence about a utility's costs presented by parties and seeking a balance that ensures reliable service, keeps rates affordable, and allows utilities to earn reasonable returns sufficient to compensate investors and attract capital for future needs (Swanson Katz and Schneider, 2020). In some states, PUCs use a similar process to evaluate utilities' integrated resource plans that assess future generation needs and investment options (Wilson and Biewald, 2013). In between formal rate cases, PUCs hold proceedings to consider such issues as whether capital expenditures are prudent and thus eligible for a rate of return for utility shareholders, whether to adjust allowable fuel charges, and whether to approve rate increases due to new regulatory requirements.

Balancing the multiple goals of ratemaking is an exercise in mitigating and allocating risk. The process mitigates financial risk to investors by protecting utilities from competition and providing a high degree of certainty regarding returns. Ratemaking mitigates financial risk to ratepayers by preventing the utility from using its market power to drive up costs and by controlling which costs monopoly utilities may pass on to customers. Allowing the utility to earn a competitive rate of return for shareholders and allowing it to charge customers for capital investments helps mitigate reliability risk by facilitating system planning and infrastructure investments.

The process also allocates risks among utilities, ratepayers, and society. Ratepayers are often responsible for compensating utilities for their investments even if the investment becomes uneconomic before it is fully amortized (Webb et al., 2020). This provides a high degree of certainty for investors and lenders, helping the utility raise capital and keep borrowing costs low, but it does not remove the risk altogether. In exchange for the investor certainty and low borrowing costs, ratepayers bear much of the financial risk once a PUC incorporates a capital expenditure into utility's rate base, insulating the utility from changing market conditions. Similarly, ensuring that a utility may pass reasonable fuel costs to ratepayers helps insulate the utility from price fluctuations but may expose ratepayers to those same risks. A PUC's focus on low-cost investments may also prioritize generation options with greater public health and environmental impacts, thus keeping electricity rates lower but shifting costs and burdens elsewhere in the economy[1].

RATEMAKING'S ADAPTATION GOVERNANCE POTENTIAL

Embracing the risk governance role of the PUC is the key to facilitating a more comprehensive response to climate change. The traditional approach to risk and ratemaking evolved based on predictable weather patterns, stable electricity demand growth, and a limited set of choices for generating electricity. Recurring threats to infrastructure caused by droughts, fires, storms, and extreme temperature swings have direct impacts on system reliability and rates. Viewed in this light, climate adaptation risks are similar to the risks typically addressed through the ratemaking process. The PUC's flexible statutory

[1]For a more thorough discussion of the risk allocation, risk mitigation, and risk creation roles of ratemaking, see Monast (2021). Precautionary Ratemaking. *UCLA Law Review* 69: in press (http://ssrn.com/abstract=3898844).

authority allow it to consider whether, and how, to mitigate and allocate risks created by these emerging threats.

The multiyear drought in the western U.S. in an informative case study in climate risk and PUC authority. The increasing population living near wildland vegetation make wildfires more likely, more deadly, and more expensive (Radeloff et al., 2018). Existing power lines through a dry forest heightens the likelihood of fire even if the utility performs regular maintenance and vegetation management along rights-of-way. Depowering transmission lines helps protect the public during periods of extreme risk, but recurring power shutoffs are a drastic shift for the utility's obligation to provide reliable power and creates additional public safety risks[2]. Other options, such as shifting to a more distributed electricity grid that does not rely upon vulnerable transmission lines or burying power lines in high-risk areas, can mitigate reliability and public safety risk but may be cost prohibitive. Further complicating matters, risk mitigation by electric utilities cannot eliminate other sources of wildfire risk (Baker, 2017). Lightning strikes and human activities such as campfires, burning brush, and fireworks can also cause devastating fires.

Prioritizing long-term risk mitigation rather than low electricity rates in the near-term can expand the types of investments appropriately included in electricity rates, allowing consideration of more costly investments to hedge against the potential for widespread infrastructure damage or threats to public safety. A risk governance approach can also determine which risks to mitigate, which to address outside the ratemaking context, and which to accept.

PUCs already engage in adaptation-related risk management to varying degrees, but they may not refer to it as such. For example, PUCs approve costs for storm preparation and recovery, and many states authorize investments to redesign infrastructure in areas prone to hurricanes and floods (U.S. Dept. of Energy, 2010). Enhanced vegetation management to reduce fire risk and winterizing power plants in areas that have not historically been vulnerable to severe cold spells help increase resiliency to extreme weather events.

There are important limitations with a case-by-case approach to extreme weather, fires, and other natural disasters. Focusing on immediate needs may continue path dependency based on existing system design, locking in infrastructure costs and overlooking higher cost options with greater risk mitigation potential. For example, improved vegetation management may help reduce the chance that transmission lines will spark wildfires, but a more decentralized system with less dependence on transmission lines through fire prone areas may have greater risk reduction benefits and enhance reliability during wildfire season.

[2]For example, power shutoffs by PG&E in 2019 affected millions of customers and provided little warning (MacMillan and Siddiqui, 2019). Residents who depend on electricity to operate oxygen machines and other life-saving electronics had limited time to relocate or buy generators (Chabria and Luna, 2019). The power outage also caused 874 cell towers to shut down, creating additional public safety risks (CBS SF Bay Area, 2020).

Furthermore, a case-by-case, or disaster-by-disaster, approach may also fail to consider near-term responses in the context of other policy and technology changes that may also increase costs. Climate change is only one of the factors complicating electricity sector planning. Utilities and regulators are navigating changes in energy economics and technologies. Older coal and nuclear plants are retiring, the pace of electric vehicle adoption is uncertain, and advances in storage technologies could fundamentally change the role of renewable energy (Diaz, 2021). More states are also adopting aggressive decarbonization goals, which will require resources and will affect the price of electricity (U.S. Energy Info. Admin, 2019b). A broader risk management view of ratemaking can seek to optimize adaptation-focused investments with these other changes affecting electricity grids.

Some PUCs take a more comprehensive approach to climate-related risk assessment. The California PUC, for example, requires the state's investor-owned utilities to conduct regular vulnerability assessments of their infrastructure, operations, and services, as well as the communities they serve (California PUC, 2020a,b). However, these broader PUC-directed risk assessments are also inherently limited[3]. Many of the risk drivers are beyond the reach of the PUC and balancing risk tradeoffs often requires a wider range of expertise and resources than are typically found at PUCs or the utilities they oversee.

Nonetheless, PUCs can contribute to adaptation governance even where they do not have direct authority. Climate adaptation requires weighing the longer-term solutions within the direct control of the electricity sector, as well as balancing the cost of these adaptation measures with the broader needs of the electricity sector and society. There is no single federal or state regulator that considers electricity sector risks and tradeoffs in a comprehensive manner. The Federal Energy Regulatory Commission focuses on interstate electricity markets and infrastructure. Regional transmission organizations (RTOs) and independent system operators (ISOs) manage wholesale electricity markets in many states. State and federal environmental regulators focus on public health and environmental impacts. Local planning authorities may oversee aspects of infrastructure siting and safety, but their authority may be limited by geography or the scope of their jurisdiction.

PUCs can help fill the gap by requiring utilities to expand the scope of their integrated resource plans and vulnerability assessments. These are recurring risk assessments that can inform climate adaptation planning across multiple agencies. Broader risk assessment can change the financial calculus for some investments. They can also examine the adaptation benefits of different grid options, as well as the economic and social impacts if the electricity system fails to mitigate certain risks and how those impacts may be borne in other ways. The PUC could use these processes to assess risks

[3]Ziaja, S., and Chhabra, M. (2021). *Climate Adaption for Energy Utilities: Lessons Learned from California's Pioneering Regulatory Actions* (article to be published as part of the Frontiers in Climate, Coordinating Climate Adaptation collection).

beyond its immediate jurisdiction, particularly if those risks have implications for electric utilities and their customers. The PUC, or another designated state agency, could then use the risk assessments to develop multi-agency responses and identify policy priorities.

A PUC-led approach to climate adaptation governance is not a substitute for new state and federal policies designed explicitly to address climate change mitigation and adaptation. Effective multi-agency coordination would presumably require additional resources for the risk assessments and ideally would not rely on utilities conduct the assessments themselves. However, in the absence of new policies and government funding, the PUC is an agency that is already making decisions about climate adaptation. Recognizing the PUC's risk governance role would help explicitly incorporate the electricity sector's adaptation needs into the ratemaking process.

CONCLUSION

The state PUC is one of the most consequential government agencies guiding a utility's investments, and thus a state's energy mix. The PUC decides which costs a utility may recover from its customers, the rate-of-return a utility's shareholders may earn, and the expenses that qualify for the rate-of-return. Whether or not PUCs characterize their ratemaking decisions as adaptation policy, their actions dictate how utilities prepare for, and respond to, a changing climate. Most state PUCs approach climate risk using a narrow economic lens, focusing on near-term threats that could have direct impacts on electricity rates, system reliability, or the financial viability of the utility. This is not the formula to adapt to climate change while also maintaining an affordable and reliable electricity grid. Recognizing the link between climate risk and the PUC's traditional roles allows commissioners to take a more comprehensive approach to the risks within their direct jurisdiction and help facilitate adaptation responses across multiple agencies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Trends in Local Ecosystem Governance

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The physical and biological factors that together determine ecosystem structure and function will be subject to enormous pressures under future climate regimes. These pressures will impact ecosystem processes and services, ranging from impacts on biodiversity to loss of essential ecosystem benefits. Ecosystem management to maintain desired ecosystem conditions will become increasingly important. Existing governance structures are insufficient to provide the necessary guidance for these management efforts. The legal literature is increasingly focused on local ecosystem governance as a viable option to fill this governance gap. For example, increasing recognition of the value of ecosystem services to local communities has driven increased efforts to protect those services through local ecosystem initiatives. The local ecosystem governance scholarship is diffuse, making the literature difficult to access. Based on a review of the legal literature on local ecosystem governance over the last 20 years, this article marshals the theoretical arguments for and against local governance and identifies ongoing efforts to implement local ecosystem governance. The article also identifies both emerging challenges to local ecosystem governance and potential ways to address those challenges. From this review emerges actionable recommendations and critical research needs to improve local ecosystem governance.

Keywords: ecosystem, governance, local, collaborative, watershed, ecosystem services

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INTRODUCTION

Ecosystems consist of the organisms in a given space interacting with their physical environment (Odum and Barrett, 2005). Ecosystems are nested units, defined based on characteristics of interest, so they can be very small, like the gut biome of an individual person, or very large, like the arctic tundra. The characteristics of a given ecosystem—the particular mix of species, in their particular abundance, the system's overall productivity and resilience—depend on a host of factors. These primarily include the physical characteristics of the system like climate, disturbance regime, or soil chemistry, and the species availability and interactions between the species (Stokstad, 2009). For example, the mix of trees growing in a forest depends on the region's physical characteristics, on the species available to colonize the forest, and on interactions between the trees and other living organisms in the forest. Altering any aspect of the physical or biological components is likely to change the characteristics of the resulting ecosystem. Our world's changing climate will alter core aspects of virtually every ecosystem on the planet (Ruhl and Salzman, 2010); existing climate change has already altered 82% of core ecological processes worldwide (Scheffers et al., 2016). These changes will play out in untold ways across ecosystems everywhere.

Ecosystem changes create significant risks. Humans are part of ecosystems and rely on ecosystems both for necessary goods, like lumber or fish or oxygen, and for necessary services, like flood control, carbon sequestration, aesthetics, and support of biodiversity (Guswa et al., 2014). Ecosystems also provide nonmarket value, often deeply tied to the nature of a location, like California's coastal redwoods or the Great Smoky Mountains in Tennessee. Research suggests that the ecosystems of the future are unlikely to resemble the ecosystems that support existing society. The looming changes create significant risks for the individuals, communities, and whole countries that have built a way of life and the infrastructure to support it based on characteristics of existing ecosystems (Rolland et al., 2014). The increased disaster risk brought about by climate change, through increased severe weather events, sea level rise, and changed precipitation patterns, will further aggravate these impacts (Munang et al., 2013; Rolland et al., 2014). Ecosystem shifts will be a core challenge of climate change, and mitigating that challenge will require increasingly active management of ecosystems to preserve desired traits in existing ecosystems and to guide development of new ecosystems (Bork, 2021). In this context, ecosystem governance or ecosystem management means management of the whole ecosystem using a systems approach, not focused on a single species or single ecosystem benefit or other single aspect of the environment (Angelo and Glass, 2021).

Over the last 20 years, legal academia has developed a rich and diverse local ecosystem governance literature. For this review, which is largely focused on literature addressing local ecosystem governance in the United States, we define local ecosystem governance as generating shared vision for and exercising power over part or all of an ecosystem at a sub-national and generally sub-state scale, although we also include regional governance of ecosystems that cross state lines (Humby, 2014). The local ecosystem governance literature addresses ecosystems on state, tribal, and federal public lands and on private lands; most ecosystems span many property and jurisdictional boundaries. Law writers have addressed local ecosystem governance primarily in public land articles (e.g., Keiter, 2005; Colburn, 2006; Griffith, 2020), in articles addressing climate mitigation (e.g., Bianco et al., 2020) and adaption (e.g., Ruhl, 2010), in the new governance/resilience literature (e.g., Wiersema, 2008; Holley, 2010a; Arnold and Gunderson, 2013; Craig and Benson, 2013; Arnold, 2015), and in broader pieces about the future of environmental law in the anthropocene (e.g., Camacho, 2010; Bork, 2021). Many articles address local governance in an ancillary way or as part of a broader investigation, and far fewer articles take on local governance as a primary focus (examples include Hirokawa, 2011b; Salzman et al., 2014).

As this broad literature base suggests, local ecosystem governance has emerged as a go-to suggestion to address myriad ills in environmental decision-making. In many cases, it appears to be a plausible solution to intractable problems. Further, local cost/benefit analysis coupled with a robust understanding of ecosystem services can produce decisions that reflect local values while also protecting regional interests. Local governance is not a panacea, however (Porras, 2009), and the literature has been less successful in discerning exactly when and where it should be deployed. More broadly, although authors have been promoting local governance for many decades, local ecosystem governance has seen only limited adoption in practice. There is an implementation gap.

In spite of the promise of local governance, the diffuse nature of the literature in this area frustrates attempts at understanding the state of the art in the legal scholarship. It can also make accessing and understanding the primary pro and con arguments difficult, obscuring the many areas of broad consensus and the remaining areas of disagreement and leading to wasted research and writing effort. Legal scholarship in this area has also generally not been in dialog with the local environmental governance literature outside of the legal academy. For example, literature reviews in other disciplines that focus on ecosystem management, panarchy and ecosystem management, or governance of social-ecological systems often largely omit the legal literature (e.g., Folke et al., 2005; DeFries and Nagendra, 2017; Garmestani et al., 2020). Here, we seek to distill the legal literature on local environmental governance into a cohesive whole to both consolidate existing scholarship and to make this research more accessible outside the traditional legal literature channels. To maintain this focus, the review necessarily omits relevant work in many other fields, from conservation biology to land use planning, as beyond the scope of this review. We also omit or only briefly mention other topic areas that bear on local governance in the interest of providing a more complete review of the work directly on point; in most cases we provide citations to works that explore these other areas more fully. Finally, this is not a critical review; instead, we identify the many areas of broad agreement and disagreement about the promise and perils of local ecosystem governance and target several areas for additional research to advance this aspect of environmental law.

METHODS

This review focused on the local ecosystem governance literature published in U.S. law reviews from the year 2000 to March 2021. As noted above, we thus excluded articles in journals in other fields, informally published whitepapers, monographs, and books, among other media. A review of the older literature on this topic was done in Fischman and Hall-Rivera (2002), and the term "local environmental law" was coined in the early 2000s (Nolon, 2003b), so drawing a hard line beginning with the year 2000, while somewhat arbitrary, has some foundation in the literature. Moreover, our research suggested that significant pre-2000 works were generally reflected in the literature we did review. We also note that Salzman et al. (2014) have reviewed the urban ecosystem services literature. Our review did not specifically address the literature on sustainable building practices or other built environment approaches that integrate ecosystem management principles into construction and site design methods, in large part because the literature on green building is not typically framed in ecosystem management terms. We note that keeping human values relevant in ecosystem management has the potential to collapse the distinction between human needs in particular places and ecosystem functionality (Spyke, 2001; Beatley and Collins, 2002; Beatley, 2009).

We performed Westlaw searches using the terms "Local Ecosystem Governance," "Environmental Governance," "Ecosystem Governance," and the combined search "local government," and "ecosystem management." We limited results to articles appearing in law reviews since the year 2000, and then reviewed all of the search results. While reviewing the selected articles, we examined their bibliographies in order to find additional relevant articles within the relevant time frame that our initial search parameters missed, again excluding non-law review publications. This approach is unlikely to produce an exhaustive list of all law literature that addresses local ecosystem governance; many articles mention it only briefly or in a tangential way, and some of those articles may escape our search approach. Nevertheless, it should provide a fairly comprehensive list. We reviewed over 140 articles, giving us a broad view of the law review articles addressing local ecosystem governance between 2000 and March 2021. Importantly, this approach is likely to capture all of the major trends and areas of agreement or disagreement within the field (Humby, 2014).

RESULTS AND DISCUSSION

We present the results of our literature review as a nested series of questions and answers. This allows for the easy evaluation of major areas of agreement and disagreement and provides a readable way to organize the voluminous legal literature on local ecosystem governance.

Why Use Local Approaches for Ecosystem Governance?

The literature clearly is unified in suggesting that the impacts of climate change require a reordering of humanity's relationship with nature. This requires decision makers to answer a host of new questions, including what aspects of ecosystems should be protected and what costs are acceptable when managing those ecosystems (Doremus, 2000). The literature is in substantial agreement that answering these questions will require new forms of governance (e.g., Colburn, 2006; Adler, 2007; Wiersema, 2008; Craig and Benson, 2013; Baker, 2015; Benson, 2015; Biber, 2017; Hirokawa, 2017). Most commentators agree that answering these questions should take place, at least in part, at a sub-national level, and often at a local level, although views on the appropriate sub-national governance unit vary significantly (Tarlock, 2002; Colburn, 2006; Salcido, 2012; Hirokawa, 2017; Bork, 2021).

The literature reflects a broad consensus that local approaches are indeed promising, but the reasons vary widely. Many authors evaluate the promise of local approaches based on the likelihood of achieving particular outcomes, either the traditional positive environmental outcomes (greater protection of native or total biodiversity, increased protection of relatively intact ecosystems, decreased carbon emissions, protection of historic baselines or otherwise valued conditions, etc.) (Tarlock, 1993; Nolon, 2012, 2016; Roesler, 2015) or outcomes that reflect a more complicated view of positive environmental outcomes (e.g., resilient ecosystems or reconciled ecosystems) (Ruhl, 2010, 2011; Arnold, 2014a, 2015). Many other authors take a positive view of local governance for process-based reasons, thinking them more likely to result in consensus decisions or more likely to produce community support for resulting decisions, to improve democratic functioning and civic engagement, or to better integrate the real costs and benefits of environmental decisions, among many other process-based views. A third category blends the first two: many authors suggest that local governance will produce better decision-making processes, which will, in turn, result in decisions with substantively better environmental outcomes. With these three broad groupings in mind, we examine the most common justifications for local ecosystem management below.

Place-Based Considerations

Many commentators argue for local ecosystem governance based on what might be termed "place-based considerations." These considerations go under many names, including bioregionalism (i.e., Doremus, 2001; Nicholson, 2010; Wilson, 2020), bioregional federalism (Nicholson, 2010), ecoscapes (Telesetsky, 2012), and place-based environmental law (Beatley and Collins, 2002; Hirokawa, 2017; Rosenbloom and Hirokawa, 2019). Although the terms have some subtle distinctions, we group the concepts together here because they offer many of the same arguments for local governance. We use the term place-based in this context, both because it is a broader category that may include both bioregionalism and ecoscapes (Adler, 1999; Telesetsky, 2013), and because it appears to have been embraced more broadly, based on Westlaw search results for all three terms.

Emotional and Experiential Attachment

The place-based arguments focus on two aspects of a sense of place. The first is psycho-emotional and experiential, relying on a human tendency toward emotional attachment to specific locations (Nolon, 2002a; Telesetsky, 2012; Hirokawa, 2017; William et al., 2020). People form emotional ties to the real places they inhabit, and they will be more likely to consider the benefits of environmental protection in political decisions affecting those places (Spyke, 2001; Nicholson, 2010). Even in cities, commentators suggest that a place-based urban land ethic will encourage people to better care for the land and engage governance through collective mindfulness and stronger connections between people, their environment, and their government (Berry, 2014). The place-based argument suggests that these ties increase support for environmental protection because people are willing to accept some costs and inconveniences for the sake of protecting, preserving, or enhancing a place of particular personal importance (Doremus, 2000; Hirokawa, 2017). As a corollary, Carpenter argues that federal law can supplant local environmental ethics, so that local people and government structures feel no need to take on environmental issues like endangered species, which are generally addressed by the federal government (Carpenter, 2011). Finally, place-based advocates suggest that local governance improves social commitment to environmental policies, with concomitant improvements in citizen monitoring of government follow through on environmental promises (e.g., Salcido, 2012;

Telesetsky, 2012; see more discussion in the section Improving Governance Processes).

Local Knowledge

The second aspect of the place-based arguments focuses on local knowledge. These arguments concern knowledge of local ecosystems, or, less frequently, local values, and the local social-ecological system (the way that the ecosystem and the local communities interact) (Spyke, 2001; Adler, 2005; Arnold, 2010; Hirokawa, 2017). This knowledge is vital for effective governance, the argument goes, because communities inherently interact with and shape their local environments.

One consistently referenced (but not fully explored) reason for promoting local ecosystem management concerns variation in ecosystem features across the nation. Variation in ecological systems make rational, one-size policies very difficult (Adler, 2005; Hirokawa, 2017) and also may undermine the effectiveness of federal environmental programs (Rosenbloom and Hirokawa, 2019; Bork, 2021). Importantly, because of the broad variation in local ecosystem circumstances, local ecosystem governance is an exercise in customizing successful approaches from other jurisdictions and innovating new ones, prompting Fox (2017) to assert that "innovative environmental protection may currently be more likely to occur at the local level than at any other." Local approaches can be customized to account to local variation in a way that blanket approaches cannot.

In terms of local values and social-ecological systems, people who live in a place experience that location differently than those who would regulate from afar, which in part explains why different levels of government regulate ecosystems so differently (Hirokawa, 2017). For example, Hirokawa documents differences between local and federal vision or policy statements and observes that federal statements generally portray the environment as an object, while local statements portray the environment as part of the community, an aspect of "home" (Id.). Even state-level governance may be too broad to understand local concerns (Salcido, 2012). Locals may value a place differently, and these values can best be recognized and preserved or enhanced by governance at a level that gives locals a strong voice. For example, local or locally involved planners may better understand how a city relates to its surrounding ecosystem (Spyke, 2001). Ecosystem governance is context dependent, and localities have their own unique histories and politics that will drive outcomes. Thus, local governance is an experiment in political questions and political will that derive from experience with the local environment, complicating uniform approaches (Doremus, 2001). The literature suggests that local governance can better account for those complications.

Specialization

Local governance that reflects local preferences for the level of protection or kinds of environments (Adler, 2005; Bork, 2018) can allow for environmental specialization (Salcido, 2012), with some localities focusing more on protection of native biodiversity while others focus on maximizing other ecosystem benefits. Bork notes that conservationists "will be able to protect some places, to maintain desired species and iconic ecosystems, through herculean feats of management and engineering, although this may require giving up other places almost entirely" (Bork, 2021). He argues that more marginal habitats or areas resistant to change may make for poor investments of conservation resources. Exiting trading schemes suggest that a robust "ecosystem marketplace" could ensure that environmental protection resources are allocated where they can make the biggest difference, based on both ecosystem and social system characteristics (Owen and Apse, 2014).

Improving Governance Processes

Many commentators argue that local ecosystem governance can realize the strengths of democracy better than governance at other levels. The literature reflects a broad divide among those who advance this argument—many commentators, reviewed in Adler (2005), argue for local ecosystem governance based on the subsidiarity principle, sometimes termed the matching principle, which holds that problems should be addressed at the most local level of government adequate to address the problem (see Butler and Macey, 1996; Monteiro de Lima Demange, 2013), with deference from other levels of government. Another group of commentators, the polycentrists, advocate an approach where local, state, and federal governments may all be regulating the same issue, with overlapping and sometimes competing authority, in order to capture the benefits of multiple perspectives and approaches for a given issue (e.g., Engel, 2006).

The Matching Principle

Advancing the matching principle, Adler (2005) argues that "[e]nvironmental protection efforts are most likely to be optimal where those who bear the costs and reap the benefits of a given policy determine how best, and even whether, to address a given environmental concern." Based on constitutional and federalism concerns, he would allocate "responsibility for most environmental problems to state governments with the hope, if not the expectation, that state governments would leave many concerns to local or regional authorities" (Id.). This may lead to less rent seeking behavior, or at least less sophisticated or successful rent seeking (Id.). Under this view, federal regulation makes sense where there is an institutional advantage for federal control, such as where the federal government has an economy of scale advantage (some science/technology generation or establishing national standards for data types and quality, for example) (Tal and Cohen, 2007), or where state and local governments cannot or will not address environmental problems due to issues like spillover effects or other externalities, whether related to pollution or use of common pool resources (Glicksman, 2010).

Keiter discusses this view extensively in his work on public lands (Keiter, 2005), where he blends in civic republicanism to argue that "public policy should be framed through civic dialogue at the level closest to those who will be affected by it" (Id.), where local, democratic dialogue "will tend inherently to accentuate public rather than private interests, and thus result in more public-spirited and better-accepted policies" (Id.). This idea marries a reinvigoration of local democracy with greater local control, the better to "manage the pressures created by the

Anthropocene while remaining committed to the central values of the American political system" (Biber, 2017; see also Porras, 2009). The concept broadly mirrors arguments made in the field of "deliberative democracy" (Mouffe, 2000); in both cases, discussion and engagement mitigate political disagreements and conflict and increase participant buy in and acceptance of outcomes.

Building on these principles, matching-principle commentators sometimes argue that federalism concerns and the U.S. Constitution suggest a presumption for state responsibility and suggest that local environmental governance should often replace federal approaches. This justification for local control faces significant criticism from those arguing that local control leads to races to the bottom or results in suboptimal protection for other reasons (Jones, 2004). The race-to-the-bottom issue, in particular, is an important challenge for those advocating for the primacy of local environmental governance. If increased local control leads to a race to the bottom, then local environmental governance is unlikely to produce the anticipated environmental improvements. In response, many subsidiarists argue that local and state governments had already begun to address environmental issues before the explosion of federal environmental law in the 1970s, and, more importantly, that local governments would have eventually managed to improve environmental conditions; Andreen provides an empirical counterpoint, showing that states were generally failing to improve or even maintain water quality and air quality before major federal statutes drove them to do so (Andreen, 2009, 2012). For additional background on this issue, see Engel (1996), Esty (1996), and Revesz (1997).

Polycentric Governance

The polycentrists argue that overlapping local, state, and federal programs provide multiple levels of oversight, produce more of the necessary research, and can better coordinate across multiple jurisdictions (Engel and Saleska, 2005; Cosens, 2010). Multiple levels of government likely view environmental problems in different ways and at different scales, and some commentators suggest this will generate more diverse environmental policies from regulators and stakeholders (Adelman and Engel, 2008). Further, by involving multiple levels of government in trying to solve the same problem, polycentrists suggest that the problem is less likely to go unsolved if one level of government is unable or unwilling to address it, making the governing system more resilient over time (Langridge, 2002; Arnold, 2014b; Farber, 2019), especially for "massive problems" (Ruhl and Salzman, 2010). Competition between levels of government may also make desirable regulatory activity more likely (Schapiro, 2005; Engel, 2006). Finally, polycentric governance plays a central role in adaptive governance in its many forms, from dynamic federalism to adaptive federalism to democratic experimentalism (Arnold, 2014a,b; Humby, 2014; Engel, 2017). The central concept in adaptive governance is local governance, coupled with a federal framework that sets and revises goals, such that local governments have the freedom to try different approaches. The best approaches could then be adopted and adapted by other local governments. The polycentric approach is susceptible to criticisms that highlight the potential for overlapping and contradictory regulatory approaches (Camacho, 2008), high transaction costs, difficulties in achieving consensus, and loss of economies of scale (Humby, 2014).

This schism between polycentrists and subsidiarists is important for a number of reasons. For subsidiarists, local governance should supplant existing federal regulation, offering local governments more freedom to choose whether and how to regulate environmental concerns. For polycentrists, local governance should supplement independent and overlapping federal authority, giving local governments leeway to experiment in the way they govern ecosystems, provided that the outcomes meet federally or state-established minimums. This divide relates in part to the aforementioned race-to-the-bottom issue. Both groups, however, see a strong role for local governance and highlight the power of local governments to serve as laboratories of democracy (Adler, 2005), as do many other scholars outside of this dichotomy (Colburn, 2006; Bianco et al., 2020). Local governments appear suited to the experimentation that governing ecosystems in the anthropocene will require (Rosenbloom and Hirokawa, 2019).

In spite of the underlying divide, both camps also appear to agree that some measure of local control makes ecosystem management more accountable (Rodriguez, 1997; Spyke, 2001; Adler, 2005; Cosens, 2010). Local interests may be more capable of closely tracking local issues and more inclined to follow through with decision makers (Cosens, 2010). Other scholars note that Elinor Ostrom's work suggests the place-based nature of local ecosystems allow successful communal resource management, perhaps even outside of traditional democratic structures (Carpenter, 2011; Biber, 2017). For a vigorous parochialism-based critique of the idea that local governance advances democracy, see Colburn (2006).

Enabling Collaborative Governance

Much of the work on local ecosystem governance addresses governance outside traditional governance structures. Most prominent in this area are the works addressing the growth and strengths of collaborative governance (e.g. Bradshaw, 2019). This form of governance is inherently local, and those promoting collaborative governance inherently advocate for a degree of local self-determination (Rodriguez, 1997). Rodriguez, for example, explores a model of inter-local expert agencies with the hope that such entities can shoulder the demands of self-determination and accountability, while engaging in sharing of resources, authority, and ecology (Rodriguez, 1997). We discuss collaborative approaches in more detail in the section Collaborative Governance.

Local Government Powers Are Required for Ecosystem Management

Many commentators suggest that local governance is a good fit for ecosystem management because local governments have the powers to constrain or encourage actions with significant ecosystem impacts. Prof. Nolon has been perhaps the biggest driver for broad recognition of the environmental impacts of local government as currently conceived, particularly land use controls, aesthetic ordinances, and growth controls, although much of his work has been outside of law reviews and falls outside of this review (Nolon, 2003a,b, but see Nolon, 2002a,b). Urban, suburban, or municipal control of real property is extensive, and rural county lands do not escape regulation. Fischman and Hall-Rivera (2002) suggest that local governments are well-positioned to address land use change and to regulate widely dispersed small harms, both of which are core issues for ecosystem management. As Colburn (2006) notes, a local public's "right of self-direction" influences the core powers of modern local government and land use law (Biber, 2017). From exactions to zoning, local governments have governmental powers that makes legislators at other levels green with envy. Thus, "when local governments address the problems caused by industry, development, and growth, they wield tools that are uniquely situated locally and designed to assist local governments in protecting local values" (Hirokawa, 2017). This means that much of environmental law is inherently implemented as local law. For example, when commentators talk about shifting property law to accommodate the Anthropocene, they are talking about changes that may be most easily, or perhaps most constitutionally, accomplished at the local level (Biber, 2017; Sprankling, 2017; Bianco et al., 2020). Finally, enforcement of environmental law is inherently local, situated in a particular place and affecting particular people, and is already often carried out by local government entities or local or regional parts of state or federal entities (Rodriguez, 1997; Adler, 2005). Given the power advantages inherent in local governments, shifting some of the focus of ecosystem governance to those local governments may make sense.

Local governments will inevitably mediate adaption to ecosystem-associated climate risks. Local governments are responsible for providing and maintaining the public infrastructure, like roads, potable water, sewers, and open space, that allow human societies to thrive in harsh environments, so they must manage new development and ecosystem-related disruption of this infrastructure (Rolland et al., 2014). Increasingly frequent and severe floods and droughts, or changes like sea level rise, present challenges that happen everywhere, but the impacts, particularly infrastructure impacts, are local in nature, placing local governments on the front lines of adaptation (Farber, 2009; Rolland et al., 2014). Whether local governments want to act or not, they will manage many aspects of adaptation (Whitely Binder, 2009).

What Problems Are Likely to Arise in Local Ecosystem Governance?

As the literature makes clear, local ecosystem governance offers many potential advantages over traditional approaches, based in part on the powers and nature of local governance. But these same aspects of local governance also produce some potential downsides and may increase the risk of some governance missteps. The literature documents these risks, based on both case studies and on more theoretical work. We have discussed a few problems in the section The Matching Principle, above (discussing the race-to-the-bottom and challenges to polycentric governance approaches), and we review other significant risks here.

Lack of Agreement

Advocates of local ecosystem governance suggest that local governance is a better place to hammer out an agreed vision for ecosystem condition, but this assumes that such agreements are always possible. For example, Adler observes many restoration efforts falsely assume that all uses and values can be maximized at the same time, and thus no stakeholders are willing to curtail their interests (Adler, 2007). This is a well-documented problem at the federal level, particularly in areas like national forest policy, and it is unlikely to be resolved simply by shifting management to the local level. In many cases, members of the local public may have strongly held and incompatible views for what ecosystems should be. This is particularly true in the anthropocene, which is likely to be characterized by ecosystems that are increasingly driven to the breaking point by human resource demands (e.g., Holley, 2015). Ecosystems are at risk when local governance fails to generate a shared vision or shared goals for the ecosystem of interest (Bork, 2021). Finally, even well-structured participatory processes do not guarantee participation leading to agreed outcomes in ecosystem management (Wilson, 2020).

Poor Environmental Choices

In some cases, poor environmental outcomes are even more concerning than the risk of achieving no agreements at all. From overgrazing under the Taylor Grazing Act's local grazing advisory boards to population collapses under local fishery management (Houck, 1997; Keiter, 2005), many past efforts at local ecosystem management have garnered participation and even agreement, but nonetheless produced poor environmental outcomes. The grazing advisory boards, for instance, prioritized management at a local scale by the resource users who depended on good range conditions, yet they permitted massive overgrazing and resource destruction (Keiter, 2005). Absent effective regulatory guardrails, local governance models may result in overconsumption or other undesirable ecosystem conditions due to a perceived competition between short-term returns and ecosystem productivity (Hirokawa and Dickinson, 2019). Even at a local scale, short term profits available from destructive decisions may frequently exceed easily identifiable costs (Doremus, 2000).

Scalar impacts play a role here as well. When the benefits of an action are likely to be felt in the short term and at a local level, and the costs of an action are more dispersed in space or time, rational actors are incentivized to take actions that would be suboptimal when viewed more holistically. Colburn (2006) argues that this is particularly true in local governments because of their "susceptibility to parochialism and protectionist regulation." Farber (2000, 2019) likewise suggests that private local interests may often outweigh national interests in environmental protection. See the section Addressing Scale Issues for more discussion of scale issues. Of course, even when costs and benefits are both localized, some communities may choose outcomes that lead to levels of environmental destruction that others deem unacceptable. Tarlock (2002) points to the public utility duty, a perceived right to develop, deep-seated expectations about property rights, and local government competition for high tax, low service land uses as factors leading to suboptimal environmental choices. These choices are also enabled by the techno-optimism that often infects environmental decision-making at all levels (Bork, 2021).

These issues are likely to be exacerbated by the magnitude of the ecosystem management required in the anthropocene. Because many ecosystems cannot be guided back to historic baselines, ecosystem management will require coming up with new targets for ecosystem management (Kammer, 2017; Bork, 2021). This risks what one commentator calls "a pornography of possibility, in which virtually any policy aim could be packaged and marketed to activate virtually any cultural worldview" (Kysar, 2008). An environmentalism unmoored from historic norms is daunting, and many commentators are concerned that local governance will lead to outcomes guided more by the public's fancy than by sound science and planning (Camacho, 2010).

Finally, implementing environmental solutions requires a change from past practices, which can make adoption of new approaches difficult. Dowd (2015), for example, argues that local governments are unlikely to adopt a green infrastructure approach of their own accord, in spite of the benefits of green infrastructure, due to barriers associated with "community engagement, and municipal staff education and training" or a tendency to give in to local opposition to change. Similarly, Harris (2018) notes that despite significant regional pressure to recognize and adapt to climate change, stormwater management planning and related capital projects in the Chesapeake Bay watershed still generally fail to account for future climate needs. Doing nothing avoids the tasks of gathering institutional resources, completing environmental reviews, or overcoming any of the myriad other hurdles that bar action. When active ecosystem management is required for risk mitigation, but the easy default is inaction, the level of regulation is likely to be suboptimal (Bosselman, 2001; Bork, 2021).

Scale Issues

Many commentators express concerns related to the scale of local governance. Scale concerns included externalities and spillover effects as noted above (Keiter, 2005), the small size of most local actions relative to large global problems, the scale of ecosystems relative to the jurisdiction of local governments, and arguments about the need for coordination actions across ecosystems over large areas (e.g., Salcido, 2012).

Local Scale May Be Ineffective

The small scale of many actions that can be accomplished at the local scale may discourage local action at all. Exceptionally large problems may paralyze local decision makers, or decision makers may decide that action by a single local entity would impose local costs with little local benefit (Doremus, 2000; Ruhl and Salzman, 2010). Even if local governance produces positive outcomes, many ecosystems stretch far beyond the boundaries of any one local jurisdiction, and action in one area would have little effect on the broader ecosystem (Telesetsky, 2012). This can also raise fairness concerns, when some localities impose more restrictions on their citizens in order to address problems that are not entirely of local origin (Keiter, 2005). Many environmental problems—climate change, habitat loss affecting endangered species, water quality problems—are landscape level challenges that require landscape level actions (Colburn, 2006). Moreover, regulatory fragmentation can drive migration of people and land uses to less-regulated jurisdictions (Farber, 2009). As Wiener (2017) notes, state or local action remains ill-suited to addressing global conduct with global externalities. Some environmental problems do not lend themselves to resolution at a local scale (but see Engel and Orbach, 2008).

Difficulties in Intra- and Inter-ecosystem Coordination

Ecosystems of interest are often large enough that they fall under the jurisdiction of multiple local, regional, state, or even national governments, which makes governance exceptionally difficult (Bosselman, 2001; Camacho, 2008; Wilson, 2020). Ecosystem management in these settings will encounter significant bureaucratic, political, and preemption problems (Nolon, 2002a; Nicholson, 2010). Examples include overlapping and contradictory regulatory vehicles, intransigent governing entities, and a lack of the ecosystem-wide research, planning, and decision making that is required for successful ecosystem management. For example, salmon require a huge variety of intact habitats for their freshwater-ocean-freshwater life cycle, from clean, cold rivers to intact floodplains to healthy oceans. These requirements span many local jurisdictions, and successful conservation of salmon populations will require management for salmon protection in all of them (Kibel, 2017). Similar problems plague infrastructure issues: Subramanian (2016) argues that the watershed-wide demands of stormwater control demonstrate that Clean Water Act (CWA) tools like the MS4 and NPDES programs lead to fragmented, ineffective water quality control. The necessary degree of intra-ecosystem coordination may be difficult to achieve through local governance.

Extreme climate-related ecosystem changes are likely to require coordination between ecosystems as well. For example, Camacho and other commentators emphasize that shifts in climate conditions are likely to shift species home ranges over large geographic areas, and efforts to mitigate these shifts through assisted migration or habitat work will require a similarly large scope that can coordinate management of multiple ecosystems across many local jurisdictional boundaries (Camacho, 2010).

Lack of Capacity

Lack of adequate capacity will stymie efforts to increase governance of ecosystems at a local level. The capacity deficit may be institutional (non-existent or insufficient institutions, institutions lacking necessary regulatory authority, etc.), or based on insufficient expertise (scientific or otherwise) or funding levels.

Lack of Institutional Capacity

As discussed, local governments have a long history of lawmaking to manage particular aspects of local ecosystems. Nolon (2002a) offers a list of typical approaches for local environmental law: "cluster development; environmentally sensitive area protection; erosion and sediment control; grading, excavations, and fill, floodplain control; groundwater/aquifer resource protection; landscaping; ridgeline protection; scenic resource protections; soil removal; solid waste disposal; stream and watercourse protections; steep slopes; storm water management; timber harvesting; tree protection; vegetation removal; [environmental impact review] and wetlands." Notably absent? Species protections. Camacho (2017) found that, indeed, states generally have weak or nonexistent endangered species acts, relying instead on the Federal Endangered Species Act for species protection and funding. Stein and Gravuer (2008) found that only 32 states afford plant species protection, and most of those offered only weak protection. Species protection is an example of a broader problem: local governments may regulate for particular amenities of interest, but this approach ignores many issues important to ecosystem management. Regulating for particular ecosystem amenities is not the same as managing an ecosystem, and piecemeal regulations are not "genuine governance structures" (Farber, 2000; Nolon, 2002a). In many cases, local governance will require the creation of new governance structures or will require existing entities to take on new roles and responsibilities. And in cases where governments already engage in ecosystem-wide management, the management may be directed more toward serving local interests than meeting broader environmental goals (Nicholson, 2010).

In some cases, local governments may not have legal authority to engage in ecosystem management or may share that authority with other governing units, and contested or overlapping authority makes governing more difficult. Nolon (2002a), for example, advocates comprehensive management but notes that in some states, local governments have only those powers granted them by their state and require state-level enabling legislation. Kimmel (2014) describes failures of tribal governance when the tribes lacked sovereignty over their traditional territories. Tarlock (2002) noted that local governments often lack control over water rights, a key component of aquatic ecosystem protection, and suggested that local governments must have access to this power through cooperation with other government units for successful watershed governance. Even when granted power, local governments may not be willing to invest in the necessary governance structures without incentives or assistance from higher levels of government (Nolon, 2002a).

Finally, local governments that have the comprehensive authority to regulate ecosystem quality may be frustrated by state or federal preemption. Fox (2017) discussed this issue in another environmental context, highlighting the many states that have preempted local efforts to implement sustainable goals by, for instance, attempting to ban plastic straws or bags. Relatedly, other states have restricted local land use control over concerns about housing shortages (Stahl, 2020). This Achilles heel of local ecosystem governance is highlighted by other commentators as well (Colburn, 2006; Farber, 2008; Carpenter, 2011; Biber, 2017), and these concerns are addressed in sections The Matching Principle and Polycentric Governance, above. In sum, then, for a host of reasons, local governments may lack institutional capacity to govern ecosystems.

Lack of Expertise

Commentators note a lack of ecosystem expertise in local planning and building departments. One cause for this circumstance involves the occupation of the environmental regulatory space by the federal government in the 1970s. Much of the scientific focus shifted to the state and federal level, producing a growth in state and federal capacity. Nevertheless, state environmental agencies employ far more people than the federal EPA, and states perform most inspection or enforcement actions (Adler, 2005). Questions of community character (of a non-scientific nature) that are typically engaged by local planners have remained the province of local government, but local governments have not engaged scientific expertise at the same rate. Perhaps due to a lack of funding, planning departments in many local governments do not hire ecologists and biologists, and in response, local governments often must outsource environmental review in the project setting. Commentators suggest that technical assistance, performance incentives, shared and centralized expertise, and additional funding to hire experts will be required for successful local governance (e.g., Nolon, 2002a).

Lack of Funding

Many commentators express concerns about funding for local ecosystem governance. Beyond the funding for expertise identified above, ecosystem management is active management (Doremus, 2000), and it will be increasingly so in the anthropocene (Bork, 2021). Even with excellent planning for ecosystem management, implementing everything from new regulatory controls to the physical, on the ground weed pulling and other habitat manipulation requires significant funding (Id). In some cases, improved ecosystem governance may offer returns on investment in terms of improved infrastructure performance, enhanced ecosystem amenities, and improved ecosystem services, but these uncertain economic benefits may not provide sufficient incentive (Subramanian, 2016). If local governments have to foot the bill for enhanced local ecosystem governance, they are unlikely to address it of their own accord without significant and relatively certain benefits.

Perpetuation of Existing Inequalities

One final persistent and increasingly important issue highlighted by local governance scholars involves issues of equity in the distribution of natural capital and ecosystem service benefits across differently situated communities, including communities of color (Salzman et al., 2014). An equitable approach to ecosystem management requires local approaches: "Ecosystem management carries a price tag, and cities will have to address the distribution of costs and benefits" (Spyke, 2001). Despite early attention to the manner in which environmental justice challenges surface in local permitting (e.g., hazardous waste facilities, contaminated sites and prisons), the intersection of ecosystem management and equitable considerations is largely unaddressed in the literature on local governance. Yet, as Colburn (2006) notes, "[e]ven backers of local autonomy acknowledge its parochialism: virtually everyone acknowledges the role of local land use law in producing post-Brown racial and socioeconomic segregation." Hirokawa (2011b) has pointed out that suburban and affluent single-family residential properties offer more opportunities for ecosystem service benefits both under existing circumstances and as ecosystem investment opportunities. Denser, urban communities typically have less access to open space and less canopy cover from urban forests (in some cases, intentionally so; Braverman, 2008; Sullivan and Solomou, 2011). When, as anticipated in the anthropocene, even maintaining existing ecosystem services will take significant investment, it is likely that local governance will continue to perpetuate historical patterns of inequality. This is not a problem unique to local governance, and withholding local participation in environmental law may itself create environmental injustice situations (Fox, 2020). As local governments take on more of an environmental governance role, however, this issue requires continued action based on an actively anti-racist approach (Dillon and Sze, 2018).

Promising Approaches to Mitigate Anticipated Problems

Much of the environmental law literature focuses on a variety of ways to address the shortcomings of local governance. Here, we make a loose distinction between institutional approaches (including procedural approaches) vs. non-institutional ways to mitigate the negative aspects of local governance, following Wiersema (2008), and then discuss the most prominent approaches in each category. Other mitigation methods, which received less attention from legal commentators and so are not discussed in detail here, include increasing the clarity, accessibility, and transparency of decision processes; insulation of regulatory decision making from political influences; more rigorous scientific standards; and enhanced reviewability for most decisions.

Institutional Approaches

Much of the local governance scholarship has focused on institutional approaches, addressing the form and procedures scholars believe most appropriate to local ecosystem governance. Commentators ask much of these institutional approaches (Wiersema, 2008). Keiter (2005) provides a typical list of prinicples that good institutional structure should support in order to ensure fairness, accuracy, efficiency, and accountability. The principles are: transparent planning/decision processes, open to all interested participants; use of best available technical information and regular monitoring; clear and efficient planning and decision processes, with clear processes for appeals and amendments; and decisions that are both reviewable and enforceable (Id.). Beyond these fundamental principles, some commentators propose adjustments to the boundaries of existing jurisdictional units or some form of nested governance to mitigate potential local governance challenges.

Redrawing Jurisdictional Boundaries

Many scholars have suggested that aligning jurisdictional boundaries with meaningful ecosystem dimensions should be a central component of institutional reform (e.g., Adler, 1999; Doremus, 2001; Beatley and Collins, 2002; Buzbee, 2005; Nicholson, 2010; Telesetsky, 2012; Markell, 2016; and Wilson, 2020). This approach seeks to address scale problems and the lack of institutional capacity in existing governance units, while maximizing the psycho-emotional benefits of local governments.

Approaches advocating new governance institutions generally seek to better align jurisdictional boundaries with the larger scale governance needed to protect many ecosystem processes and with human environmental experiences. Nicholson (2010), for example, advocates a bioregional approach that aligns natural environmental boundaries with political units in order to better utilize a sense of place and produce self-organizing environmental governance systems. Similarly, Rosenberg (2006) suggests a regional ecosystem-based approach built around conservation of ecosystem services, with governing units defined around the intersection of ecosystem services and manageable human activities. Telesetsky (2012) advocates an "ecoscapes" approach that focuses on landscape units with "boundaries based on sustaining ecological functions and on protecting human needs for living landscapes." She calls on state governments to invest in ecoscapes-oriented restoration. Place-based science, education, recognition of local native groups, illustrations of a region as a whole ecosystem, and legal signals contribute to encouraging the regional sense of place needed for such efforts (Berry, 2014; Wilson, 2020), although much of the literature does not directly address development of the desired emotional connection to the land or otherwise operationalizing new institutional approaches. Commentators also note significant institutional roadblocks, including a lack of institutions with governing authority, "leaky" boundaries with regards to ecosystem services, and preemption issues, among other challenges. More research is needed on the types of governmental units that might govern, the source and scope of authority of these units, and how the jurisdiction of such entities can be coordinated with existing local governments.

The literature provides some examples where existing jurisdictional lines align with natural boundaries, allowing for more successful governance. McKinstry et al. (2012) examine Philadelphia's efforts to control its Combined Sewer Overflow (CSO) challenges. Philadelphia's Green City, Clean Waters program may be remarkable due to the coincidence of watershed geography and municipal authority to effectively finance green infrastructure investments (McKinstry et al., 2012). However, most local governments are not so well-situated, and McKinstry et al. (2012) note that the city-scale may offer few lessons in non-urbanized watersheds. Sonne (2014) suggests that, even within existing governance units, consolidation of authority over particular ecosystem or infrastructure attributes into a single agency could alleviate fragmentation. Other commentators suggest that simply expanding the scale of governance, rather than redrawing jurisdictional lines, could alleviate cross-jurisdictional pressures (Holloway et al., 2014; William et al., 2020).

Others provide examples of new organizations that have developed around regional ecosystems (e.g., Cosens, 2010), often motivated in part by federal environmental requirements (Guercio and Duane, 2009). Angelo and Glass (2021) explore an "Integrated Water Resources Management" (IWRM) approach to address fragmented decision-making, cross-jurisdictional inconsistencies, and inefficient and duplicative efforts, while making room for private stakeholder participation. They report on collaborative activities such as the Tampa Bay Estuary

Program, which has engaged in a robust planning process and has highlighted a significant role for local governments in achieving its mission. Many other regional governance programs are unsuccessful, as described by Adler (2007) and Camacho (2008). This approach is not a panacea, but it offers promise in many cases. The question of when existing structures provide an adequate environmental governance framework (e.g., Nolon, 2002a) and when new structures are needed remains an active area of disagreement (see details in the section Areas of Future Research).

Nested and Coordinated Governance

Throughout the literature, attention is given to benefits of both top-down (Adams-Schoen, 2018) and bottom-up regulatory structures (Spyke, 2001), and both are offered as ways to capture ecosystem complexity in a way that simultaneously protects the system and individual (Wiersema, 2008) and communicates ecosystem value to local residents while countering negative human tendencies (Doremus, 2001). From this broad base, most commentators converge around the need for some degree of nested governance, involving significant local control, coordination among governance units, and state and federal backstops to local decision making (e.g., Wiersema, 2008). Scholars refer to this approach using a variety of terms, including cooperative federalism (traditional state-federal federalism) or cooperative subfederalism (federal-state-local federalism) (Owen, 2018), dynamic federalism (Ruhl and Salzman, 2010), nested governance (e.g., Bosselman, 2001), and multi-scalar or poly-centric governance (Ruhl, 2012). Much of this work fits within the polycentric governance approaches discussed in the section Polycentric Governance. The matching principle scholars (see the section on The Matching Principle) make up a vocal opposition minority. Even among scholars advocating for larger scale local governance, often regional governance that crosses state lines, most suggest that such structures would benefit from a national mandate and oversight from a central authority (Steinzor, 2000; Baur et al., 2008; Glicksman, 2010).

Nested governance structures aim to counter the scale, capacity, and poor environmental choice problems identified above by enabling guidance and coordination of local governance through substantive regional or national policies. Keiter (2005), for example, suggests a public land management approach with "definitive federal management standards" and substantial local flexibility, in order to promote shared responsibility for public lands. Owen suggests that the benefits of traditional cooperative federalism should justify similar state-local relationships, but he notes that few states have developed systems that utilize "local implementation with continuous state administrative oversight and review" which is necessary for this approach (Owen, 2018). Tarlock (2002) reviews examples of cooperative subfederalism experiments, pointing in particular to the Virginia and Maryland structures where the states have adopted specific mandates requiring local governments to adopt land use regulations to protect the Chesapeake Bay watershed.

Although some express concern that the power and parochial tendencies of local governments are unlikely to be effectively constrained by state or federal substantive standards (e.g., Keiter, 2005; Colburn, 2006), the majority of commentators agree that a nested governance approach can usefully cabin local authority, limit spillover effects, and combine the powers of local governance with the benefits of state or national standards.

Iterative Management

Virtually all commentators agree that ecosystem governance at any scale must be iterative, generally discussing this requirement within the framework of adaptive management (e.g., Karkkainen, 2002; Susskind et al., 2010; Ruhl, 2011; Arnold, 2014b; Baker, 2015; Rosenbloom, 2018). Adaptive management champions experimental and provisional decision making: data gathered from initial decisions leads to reevaluation of those decisions in an iterative cycle of policy making, ideally improving knowledge of the social-ecological system (Karkkainen, 2003). Adaptive management produces "comprehensive learning infrastructure that promotes the systematic monitoring, assessment, and adjustment of discretionary [decisions]" (Camacho, 2010). This approach is well-structured for making necessary decisions in the face of unresolvable uncertainty, which in many ways typifies ecosystem management in the anthropocene (Benson, 2015).

Arnold has been a forceful proponent of adaptive management, both in the narrower arena of watershed governance and in local environmental law more broadly. He and his coauthors propose "four features of an adaptive legal system: (1) multiplicity of articulated goals; (2) polycentric, multimodal, and integrationist structure; (3) adaptive methods based on standards, flexibility, discretion, and regard for context; and (4) iterative legal-pluralist processes with feedback loops, learning and accountability" (Arnold, 2014a). Other authors advocate similar approaches at a multitude of scales, from adaptive management to address single ecosystems (Koliba et al., 2016) to a broad dynamic and adaptive federalism approach to governance more generally (Adelman and Engel, 2008; Engel, 2017). Potential risks of adaptive management include an overemphasis on flexibility at the risk of real, enforceable protections (Doremus, 2001) and all-to-frequent failures in the learning and iterative portions of the adaptive management cycle; entities making environmental management decisions are often loath to reopen painful decision making processes once a decision is made, even if that decision is shown to be wrong.

Non-institutional Approaches

In contrast, many commentators suggest that institutions alone, no matter how well-designed, are not likely to maximize the benefits of local governance (Wiersema, 2008). Most scholars combine recommendations for institutional reform with recommendations for other elements essential to successful local ecosystem governance, and the lines between these categories are admittedly blurry.

Collaborative Governance

This "blurriness" is particularly apparent for collaborative governance, which can take place within traditional governance structures but which may be better fostered through approaches designed for it. Collaborative governance is a hallmark of the local governance literature. The term is widely used, yet there is no single model for collaborative environmental governance; at a minimum, collaborative governance involves stakeholder participation, adaptative processes, and collaboration across political boundaries. The literature consistently touts the benefits of collaborative management: better environmental outcomes, increased public support for difficult tradeoffs, more information, trust building, and win-win solutions (Susskind et al., 2010). Collaborative governance can address local governance problems related to lack of agreement, lack of capacity, perpetuation of existing patterns of inequality, and scale problems, if collaborations extend past traditional jurisdictional boundaries (Karkkainen, 2002). Bradshaw (2019) provides a very well-researched and detailed recent analysis of collaborative governance, including in the local governance setting.

In a piece focused on collaborative local governance, based on an analysis of Audited Self-Management in New Zealand and the Delta Plan in California, Holley (2015) argues that successful collaboration might include three policy-based themes: use of incentives to garner participation, including both economic incentives and "peer pressure;" limiting avenues for legal challenges to the results of the collaborative process; and building trust. In addition, Holley stresses the importance of integrating legal and collaborative mechanisms to insure a robust process (Id). Likewise, Wiersema observes that ecosystem management demands collaboration "by multiple stakeholders to allow broad participation, facilitate learning about these human factors, and provide a forum for determining the best policy and the values that society seeks to enhance" (Wiersema, 2008; Wiersema, 1252–53).

Susskind et al. (2010) provides a revealing analysis of the failure of collaborative adaptive management of Glen Canyon Dam. The circumstances appeared appropriate: Glen Canyon Dam benefitted from a well-funded research program addressing scientific uncertainty and was subject to differing perspectives among stakeholders, circumstances that should have benefitted from a collaborative process. Susskind et al. nonetheless observe that the project suffered from poor initial design, a lack of clear guidance from Congress on the relative priorities of competing goals, and a notable lack of commitment to resolving long-running conflicts; thus, the project benefitted from neither learning nor constructive engagement. Susskind et al. offer a framework for best practices: "(1) identifying appropriate stakeholder representatives; (2) involving stakeholders in developing a collaborative process; (3) using professional neutrals and encouraging consensus building; (4) incorporating joint fact-finding to deal with scientific uncertainty; (5) producing collectively supported written agreements; and (6) committing to build long-term management capabilities" (Id). These recommendations resonate with much of the literature on collaborative decision making.

Education

Many commentators argue that effective local governance requires increased education of local decision makers and the public. Camacho (2010) calls this education the "key endeavor" and advocates a "learning infrastructure" to ground the democratic process in usable science. Adler (2007) notes this is especially true in successful adaptive management, so that decision makers can integrate the new information produced by the adaptive management process and understand how it should affect additional management decisions. Scientific and traditional knowledge can help to constrain discussion about ecosystem management by providing information about what is possible in a given location, about real costs associated with restoration efforts (Hirokawa, 2017), about risks and likelihood of success, about historic conditions, about the non-obvious ecosystem services produced by local ecosystems and which in turn support local well-being, and about myriad other ecosystem aspects (Bork, 2021). In some cases, this information may help decision makers find better environmental solutions. Ideally, new information and understanding can help process participants find solutions that align their self-interest with the common good (Wiersema, 2008). Ultimately, while many ecosystem governance decisions are ultimately value judgements, education and sound science ensure that those value judgments are realistic, weigh more of the relevant factors, and are more likely to produce target outcomes. As Hirokawa notes, a more comprehensive understanding of ecosystem services "yields results that highlight local values and priorities. This is essentially the process of self-identity: self-reflection that encompasses sense of place" (Hirokawa, 2017).

Enforceable Substantive Goals to Cabin Discretion

Some commentators express concerns that local governments will produce suboptimal levels of environmental protection, resulting in spillover effects, disparate health and environmental outcomes, poor environmental protection, or other problems. These scholars suggest limits on local authority through substantive state, regional, or national standards. Substantive standards that address ecosystem function in the regulatory process, especially if combined with a reliable system of monitoring ecosystem degradation (Steinzor, 2000), can aid in identifying locally and regionally important ecosystems and ecosystem values, as well as provide a wealth of information about ecosystem vulnerabilities and "some assurance that interests vital to long-term protection of healthy ecosystems will be adequately taken into account" (Wiersema, 2008). For instance, Hirokawa discusses Washington's Growth Management Act (GMA) and the substantive criteria adopted by local governments to curtail habitat degradation under local critical habitat regulations, including standards requiring that new development approval be based on affirmative findings that habitat "functions and values" are maintained. Other local governments regulate developments to ensure no net loss of tree canopy or function (Hirokawa, 2011a). More broadly, standards can assist in drawing connections between otherwise independent development projects, such as by coordinating cumulative impact review of separate developments.

Wiersema suggests formulation of "a set of goals that will constrain decision makers both at the lower-level scales of governance and at the higher-level scales of governance" (Wiersema, 2008; 1294–95). Wiersema notes that the specificity required in these goals goes far beyond broad statements of resilience or ecosystem integrity (Id.). Resiliency, the new governance byword, is not a sufficient goal; "promoting resilience through ecosystem heath could include managing to protect at least some portion of all ecosystem components, only foundational species, or perhaps only species deemed to be socially valuable" (Camacho, 2010). Although much work remains in identifying effective substantive standards, most scholars agree that they will be needed.

How Do We Encourage Successful Local Ecosystem Management?

Given the general optimism about local governance in the literature, we turn to questions of how local governance can be encouraged. A great deal of the literature addresses encouraging local governments to take ecosystem management seriously, given that "[t]he American local approach must … be cobbled together with support from citizens and constituents who are unabashedly parochial" (Beatley and Collins, 2002), a challenge that Long (2009) asserts can only be overcome with desire, critical institutional awareness, and an ability to imagine. Some of the literature challenges this assumption. For instance, Rosenbloom and Hirokawa (2019) and Spyke (2001) argue that productive ecosystems and appropriate management often align with local interests and point out that local governments often focus on ecosystem benefits, even if it is not done in such terms (see also Nolon, 2002a). We begin with the question of whether much additional encouragement is needed.

Current Trend Toward Increased Local Governance?

Some evidence and authors suggest that there is an ongoing trend toward increased local ecosystem governance. Existing incentives for local ecosystem management, based on federal environmental laws, climate-related disasters, and other existing pressures, may be sufficient to encourage a much more significant role for local governance. Indeed, many scholars argue that local ecosystem governance is becoming normal. Although most scholars do not differentiate between protecting amenities and more wholesale governance (see the section Lack of Institutional Capacity), a number of authors do describe trends in wholesale ecosystem governance. For example, a variety of place-based governance models, particularly for aquatic ecosystems, emerged in the late 1990s: ecosystem-based management, collaborative governance, integrated watershed management, and adaptive management (Karkkainen, 2002; Holley, 2015; Angelo and Glass, 2021; see Rodgers, 2000). This growth responded to perceived failures (or at least intransigence) in traditional top-down governance; fading concerns about the likelihood of inadequate environmental protection by local governments; and a recognition that effective land conservation must be active, non-uniform, and encompass both private and public lands, all of which is within the purview of local governments (e.g., Tarlock, 2002).

Beyond aquatic ecosystems, Keiter notes that devolving authority to increase local or state control is a consistent theme in public land policy discussions, and he describes the ongoing growth of collaborative, consensus-based public land governance (Keiter, 2005; but see Colburn, 2006). Keiter cites many examples where new federal legislation was required to enable increased local governance but suggests that it will continue to grow as a successful ecosystem management approach. Hirokawa (2012) points out that some local governments are already making extra-territorial ecosystem investments to protect drinking water sources from forest fires.

More recently, Farber and Ruhl suggest a continuing trend toward local control to adapt to climate change impacts, whether or not the local governments have adequate governance capabilities to address the new roles thrust upon them (Farber, 2009; Ruhl, 2010). Under this view, the challenge is not how to encourage local governments to work on adaptation, but rather how to change environmental law to support and facilitate the increased responsibilities local governments will inevitably face. The emergent drivers increasing the role of local governments in climate adaptation, like increased impacts to local constituents from climate-change-related extreme weather, fire, sea level rise, and other calamites (Rolland et al., 2014), may not exist in the ecosystem governance context, where losses may be less obvious and feel less urgent.

Watershed problems may provide significant incentives to encourage local governance; governments must, by necessity, address drought and other impacts to water supply, which in turn necessarily implicates state or federally species protected impacted by the water delivery systems. Together, these concerns encourage aquatic ecosystem-wide scales of governance. Getches (2001) argues that states and local governments will act when faced with tangible near-term consequences of inaction in the water setting, most often in response to a crisis (perhaps climate related), but sometimes in response to federal regulatory pressures. The local watershed governance trend identified by authors in the 1990s and early 2000s continues (Arnold, 2010; Arnold et al., 2014), and other non-water examples illustrate local experiments with ecosystem-based approaches to land use regulation and extraterritorial planning (Hirokawa, 2012). This may be a race-to-the-top among local governments, at least among those localities that are actively engaging in ecosystem governance (Rosenbloom and Hirokawa, 2019), as some local governments are expressly, persuasively, and publicly linking quality of life improvements to ecosystem investments. Finally, Colburn (2006) argues that competition between regions, and in particular cities and suburban regions, will encourage meaningful ecosystem governance without interference. Nevertheless, in spite of the signs suggesting a natural trend toward local ecosystem governance, most commentators agree that existing trends toward enhanced local governance will be insufficient to address the challenges of the anthropocene. We thus turn toward approaches designed to encourage this approach.

Ecosystem Services

Ecosystem services approaches can encourage local attention to ecosystem management, leading to local ecosystem governance. "Ecosystem services" describes the conditions or processes provided by ecosystems that sustain or benefit human life (Guswa et al., 2014). Changing environmental conditions changes the services that the ecosystem provides, and accounting for the changes in ecosystem services provides a much clearer view of the real costs and benefits of, for example, local land use decisions. Accounting for these local costs and benefits allows service-maximizing ecosystem management to be integrated into the very idea of local governance (Hirokawa, 2017). Impacts that would be unnoticed on a national scale can loom large in a local setting (Id.) Local ecosystem services governance has become increasingly common under the guise of "low-impact development" and "green infrastructure" (Holloway et al., 2014; Strifling, 2019), particularly in stormwater runoff, aquifer recharge, and urban forestry regulations. However, the literature also notes the adoption of other significant ecosystem services regulations, including support services such as geological stability, production services such as soil productivity, and cultural services such as locally special and historic places (Hirokawa, 2011a). If adopted more broadly, perhaps through a no-net-loss-in-ecosystem-services mandate, ecosystem services approaches can serve as a catalyst to operationalize local ecosystem governance (e.g., Carden et al., 2013).

State or Federal Enabling Legislation or Administrative Actions and Support

As discussed in sections Improving Governance Processes and Lack of Capacity above, local governments may lack authority to engage in ecosystem governance, or existing state or federal authorities may preempt or discourage local efforts. In the case of new governmental entities built around environmental boundaries, the entities themselves generally do not yet exist. Thus, the literature generally suggests that new state or federal legislation may be required (or at least be very helpful) for effective local governance in many instances. Bianco et al. (2020), for example, supports a change in federal preemption law to support local governance, suggesting that preemption should occur only rarely, and that Congress should expressly affirm state and local power to supplement federal standards with tighter local standards (see also Adelman and Engel, 2008; Farber, 2008). Bianco also emphasizes the need for policies promoting equitable outcomes for all, especially low income communities and disproportionately harmed people of color. Strifling (2019) provides a comprehensive history of water-related federalism issues and highlights "the need to create an enabling regulatory environment, ensure the availability of adequate resources, and build management capacity," while considering stakeholder feedback and addressing disproportionate impacts to vulnerable communities. This will likely initially increase transaction costs but may ultimately result in a more effective and efficient regulatory process (Id.). Roesler (2015) suggests federal intervention to prevent states from limiting local authority. In many cases, reforms may be administrative in nature. The Federal Endangered Species Act motivates many existing local ecosystem governance efforts in the literature, and administrative agencies could find ways to encourage these behaviors (e.g., Fischman and Hall-Rivera, 2002).

Scholars note that state or federal mandates must be accompanied by increased support to build local governance, scientific, and financial capacity. If successful local ecosystem governance will be active, adaptive, collaborative, and based on an ecosystem scale, it will require rigorous monitoring, comprehensive information gathering and dissemination, and periodic assessment and adaptation (e.g., Camacho, 2008; Farber, 2009; Angelo and Glass, 2021). This will require funds and other resources for building the information infrastructure and decision-making capacity for regional regulatory institutions (Id.), and may even require support for participation of third parties to actively engage in the policy-making process and hold decision makers and others accountable for successful outcomes (e.g., Xi et al., 2014).

AREAS OF FUTURE RESEARCH

Despite the growing body of literature on local ecosystem management, the research remains in early maturity. Much of the work has been theoretical, and the field would benefit from additional "empirical fieldwork to connect governance theory with grounded practice to identify what works, when, and how" (Holley, 2015). Although many authors have offered case studies of particular ecosystems, generalizable and broadly applicable results have been harder to extract. We also note that extensive research exists outside of the law reviews, and legal scholars should make more extensive use of that literature to deepen and enhance legal scholarship on this topic.

A few articles reviewed in this project set out specific research agendas to improve and normalize local ecosystem management. In particular, Karkkainen (2002) lays out a robust research agenda addressing collaborative governance, and virtually the entire agenda remains relevant to local ecosystem governance today. Getches (2001) suggests topics for local research must include the importance and content of leadership in communities that engage in ecosystem management, comparative analysis of consensus and majority rule decision making, the impacts of federal participation on collaborative decision making, and the significance of scientific and technical expertise for group effectiveness. Here we highlight additional areas for future research based on our review of the existing law literature.

Environmental Justice

As noted in the section Perpetuation of Existing Inequalities, the intersection of local ecosystem governance and equitable considerations is largely unaddressed in the literature. This is particularly concerning because, as this review indicates, local governance is likely to continue to grow, and it will have differential impacts on different parts of local communities. The literature also indicates that when governance of any kind fails to consider equity, explicitly, it perpetuates and deepens historical patterns of inequality. Scholars have suggested that new models of participation may be necessary to achieve equitable results (Crawford, 2009). We also note that the existing literature generally under-emphasizes tribal roles in ecosystem governance, which may provide a promising approach to addressing justice concerns in some cases. Avoiding inequitable outcomes will take additional research, self-examination, and a deep commitment to justice.

Science in Support of Local Ecosystem Governance

The literature identifies many areas in which more scientific research is needed to inform ecosystem management. The literature also addresses some of the challenges of integrating science and values in decision making (Bork, 2021), although legal scholars could draw more on work in this area from other fields.

Some of the literature expressly identifies research agendas that will assist in the regulation of ecosystem productivity and disruptions in ecosystem processes. In addition to addressing research needed to address inequalities and payments for ecosystem services (PES) programs, Salzman et al. (2014) identify research needs: challenges of scale, identifying stakeholders, comprehensive regulations, ecosystem services trade-offs, enforcement, and adaptive management. As Salzman et al. suggest, more work needs to be done to coordinate scientific research and the knowledge needs of local governments and their local ecosystems. In addition, scientific research that coordinates regulatory triggers (e.g., specific permit standards applicable to activities that might take place in wetlands, floodplains, steep slopes, and habitat) to ecosystem functionality will allow for more predictive and effective regulation that incorporates performance standards (e.g., "safe to fail" approach to riparian areas and flood potential).

Largely unaddressed in the legal literature is the time scale of ecosystem management. The literature does address cumulative and synergistic impacts to ecosystems from particular projects, typically in the context of environmental review and urban sprawl (Hudson, 2017; Hirokawa and Dickinson, 2019). However, we were unable to identify research focused on the relevance of timescale of delayed or cascading impacts within any particular region. Research about the timing of impacts would provide critical insights for land-use planners, particularly given that the time scale the land-use planners can be 20 years or more from the present. This research will allow local governments to better anticipate the challenges produced from land-use decision making today, including a better grasp on the value of vacant lands and particular land uses in the ecosystem management context.

Units of Governance

As discussed in sections Improving Governance Processes and Institutional Approaches, there is little agreement on the geographical units of ecosystem governance and their relation to other levels of government. Some scholars defend the current form of local government (Fox, 2017), some scholars report on regional compacts (Markell, 2016), and some propose overlapping structures (Buzbee, 2005), modular structures (Freeman and Farber, 2005), cooperative structures (Strifling, 2019), top-down and bottom-up approaches (Tal and Cohen, 2007), or even conditions that produce successful collaboration (Holley, 2010b). This is an area ripe for continued research.

Local Governance Fit for Particular Environmental Challenges

In many areas of environmental concern, local governments have exercised land-use authority to control social, economic and environmental risks. There is less research, and a significant need for it, on (1) how land-use authorities might be used to address storm surges, pandemics, and other incidental impacts of climatic changes; (2) how local land-use authority can be exercised to improve the adaptive capacity of communities to the physical challenges of climate change and human in ecosystem migration; and (3) how much local participation can be expected. Two areas where the literature has been particularly critical of local outcomes concern floodplain management and storm water management.

More broadly, as noted in the section Local Scale May Be Ineffective, local governance is likely to be ineffective for some environmental problems, and more work is needed to identify those areas where local governance is likely to work especially well or especially poorly.

Governance in Urban and Rural Settings

The existing local governance literature often treats all local governments very similarly, failing to distinguish between rural and urban local governments. But local governance in a large city is different from local governance in a smaller town or a suburb, and governance across a whole county with both urban and rural areas is more different still. These differences are important, given the different environments in such jurisdictions, the different legal authorities granted to such governments, and the different ecosystem risks and needs in rural and urban areas. Of course, groundwater and watershed management approaches cross these boundaries (Langridge, 2009), yet rural and urban areas are geographically, conceptually, and legally different, and ecosystem management research should more effectively distinguish among different types of local governments.

Persuading Landowners to Participate

There is also a pressing need to understand environmental compliance behaviors (Raskin, 2015). Some scholars argue that perception and narrative are critical to the process of constructing norms around local ecosystem value. Braverman (2008) suggests that constructed values, such as race, consistently play a role in how communities view natural and artificial landscapes. Spyke (2001) suggests that changes can be made to the manner in which people interact with and within their cities by focusing on citizens' awareness of local nature and improving city "charm," "defined to be tied to both nature and the betterment of the human spirit," to develop willing ecosystem managers. Hirokawa (2017) argues that laws and values are constantly mediated by influences of identity, which is inherently local. Yet the literature offers few clues into constructing this identity or using local identity to build consensus in ecosystem management.

Research into the social and psychological influences driving reluctance is likely to provide critical insights into the framing of particular activities and programs (William et al., 2020).

As Arnold (2014a) notes, we need a better understanding of how to persuade private landowners and businesses to make adaptive changes to their already-authorized practices. Why, for instance, do some farmers implement practices similar or even identical to Best Management Practices (BMPs), but nevertheless object to mandates for BMPs in their communities? Strifling (2019) suggests that unfamiliarity with green technologies and distrust drive reluctance. Similarly, Long (2009) argues that people, and their beliefs, present the main challenge to effective local ecosystem governance in the climate change context. Local ecosystem governance research should address these questions.

Ecosystem Services and PES Programs

Ruhl (2020) identifies three primary reasons that ecosystem services regulation has not figured in a more prominent fashion. First, he notes that ecosystem services "are, for all practical purposes, free," suggesting that there is little incentive to invest in ecosystem services benefits. Second, Ruhl points out that we suffer a lack of information at a granular level that would help us understand the impacts of many, if not most, biophysical changes. Third, Ruhl points out that institutional challenges might keep local governments from embracing rigorous ecosystem services policies, including the political boundaries that fragment control over ecosystem processes, which often separates actors from ecosystem service beneficiaries and can challenge political will. Hirokawa and Gottlieb (2012) observe that there may be another reason: in some ecosystems, non-use values may outweigh otherwise entrenched land use values.

Salzman et al. (2014) have identified several important research questions that could broaden understanding of how ecosystem services could fit into local governance and make ecosystem service analysis a more effective regulatory approach. First, they identify research needs relating to the distributional challenges of ecosystem service investments, such as urban forest cover, green infrastructure, and open space access. Second, they consider various elements of payment for ecosystem services (PES) programs and the difficulties in connecting public and private responsibility for making such investments, responsibilities that accrue to the beneficiaries of such investments, and the challenges inherent in accounting for and maintaining such benefits. This research need converges with non-legal research suggesting that the success of PES programs may strongly depend on design and context, where ill-formed programs may have counterproductive results. Third, Salzman et al. call for research on ecosystem governance, which they identify as "governmental, civil society and private market actors as well as the relationships between these actors and the legal and civil norms that they establish to address a particular need or interest" (Id.). In this context, questions relating to scale, participation, prioritization, and independent actors are matters for future research.

Another promising approach concerns benefit flows between jurisdictions in specific geographical areas (Ruhl, 2020). Data collection and analysis of the way ecosystem services and benefits flow from rural to urban areas could provide predictive approaches to managing the risks and benefits of upstream land development activities to other communities. Because the ecosystem services benefits at issue comprise an important component of community well-being, this research would facilitate communication and collaboration between communities—in particular, between rural communities and urban communities and their adjacent suburban neighborhoods.

CONCLUSION

Climate changes and other pressures on ecosystems require better ecosystem governance. Under future climate conditions, a wide of array of ecosystem characteristics will change, ending our passive reliance on functional ecosystems. Ecosystem shifts will be a constant, and how we govern ecosystem health will determine how well ecosystems support human life and well-being.

Ecosystem management has long been relegated to federal and state agencies, but we document the development over the last 20 years of a robust body of legal literature concerning the need for, challenges to, and form of local environmental law. In spite of the challenges we document, local ecosystem governance is a necessary component of any effort to face climate change and the accompanying challenges. Local governance offers benefits not available through other governmental structures.

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Both authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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The Role of Private Environmental Governance in Climate Adaptation

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This Article examines the role of private environmental governance (PEG) in climate change adaptation. PEG occurs when private organizations perform traditionally governmental functions such as providing public goods and reducing negative externalities. PEG initiatives that target climate change mitigation have expanded rapidly in the last decade and have been the subject of research in multiple fields, but PEG initiatives that target climate change adaptation have received less attention. As a first step, the Article develops a definition of private governance regarding climate adaption, identifies several types of PEG adaptation initiatives, and briefly identifies research gaps.

Keywords: climate change, private environmental governance, climate change adaptation, climate change mitigation, environmental social governance (ESG)

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INTRODUCTION

The private sector is increasingly undertaking private environmental governance (PEG) actions for climate change mitigation, whether through renewable power commitments, supply chain contracting requirements, investor collaborative efforts with non-governmental organizations (NGOs) to pressure companies to set carbon targets or reduce carbon emissions, or other steps. These actions are an important gap-filling effort given the limits of international, national and sub-national climate mitigation, and they can help increase climate mitigation support by moderates and conservatives in the United States who are critical to federal climate legislation (Vandenbergh and Gilligan, 2017; Gillis et al., 2021). But is the same true for adaptation? Are corporations and other private sector actors engaging in meaningful amounts of climate adaptation? If so, when should these activities be considered a form of private governance? How should these PEG adaptation activities be assessed? Should they be celebrated or discouraged?

PEG adaptation is just beginning to be a focus of academic and policy studies. Numerous studies have focused on how governmental bodies in the US and across the globe are engaging in adaptation, but these studies rarely discuss the role of the private sector (Flatt and Huang, 2012; Vogel et al., 2016). For example, the NASA website describes cities and municipalities as being on the frontline of adaptation efforts, but it makes no mention of corporations or other private sector actors (NASA, 2021). Similarly, the most recent IPCC Climate change report on "Impacts, Adaptation, and Vulnerability" also mentions only government adaptation efforts (Intergovernmental Panel on Climate Change [IPCC], 2014). Government and private reports have begun to focus on the private sector's role in adaptation, however, and have identified a substantial and growing amount of PEG adaptation activity (Caring for Climate, 2015).

This article examines the state of PEG initiatives directed at climate change adaptation. Private sector adaptation activities constitute a form of governance in some cases but often do not, and in Part II the article begins by developing a definition of PEG adaptation. Part III then identifies a variety of different PEG adaptation initiatives across multiple sectors, including retail, banking, insurance, and finance. Finally, Part IV concludes that PEG adaptation initiatives are an important and growing aspect of the response to climate change, but that substantial research gaps will need to be filled to enable these initiatives to achieve their potential.

DEFINITION

PEG occurs when non-governmental entities, such as corporations, non-profit organizations, private universities, and religious organizations, perform the traditionally governmental functions of reducing negative externalities, providing public goods, managing common pool resources, or providing a more equitable distribution of goods and services (Vandenbergh, 2013). In the last two decades, a growing literature has examined private climate mitigation initiatives (Hall and Bierstecker, 2002; Bernstein and Cashore, 2007; Abbot and Snidal, 2009; Light and Orts, 2015; Vandenbergh and Gilligan, 2015; Kousky and Light, 2019). No systematic analysis in the legal literature has examined private governance regarding climate change adaptation, though, and this article provides an initial roadmap for that effort.

Assessing which types of initiatives constitute PEG adaptation requires distinguishing private from public, mitigation from adaptation, and governance from other actions. We include initiatives within the term "private" if they are not conducted by governments and not conducted principally in response to government laws, policies or programs. We distinguish private actions from public actions not because of any preference for private actions or any naivete about the difficult distinctions on the boundary between private and public, but because private actions are often subject to different motivations and limitations from government actions. For instance, Dicks Sporting Goods bans sales of assault weapons, but many states do not, suggesting that in some cases it may be easier for a private company to engage in gun control than a state or the federal government (Vandenbergh, 2005)[1].

Focusing on private rather than public governance thus is important because a strength of bottom-up private sector initiatives is that they can bypass polarization to fill gaps in government climate laws, policies, and programs, and complement government action when it occurs (Vandenbergh, 2013). At the same time, a weakness of private sector initiatives is that they are subject to market and social pressures rather than direct electoral pressures, so they can lead to undesirable outcomes when market or social pressures do not align with the public interest. In addition, in the absence of a top-down, systematic analysis, the scope of the private governance opportunity may be overlooked by public and private policymakers and inefficient allocation of resources may occur (Vandenbergh, 2013).

We focus in this article on adaptation rather than mitigation, although we acknowledge that some actions can have elements of both. For our purposes, climate change mitigation involves reducing the causes of climate change through decreasing the release of GHG emissions into the atmosphere or increasing GHG sinks (Intergovernmental Panel on Climate Change [IPCC], 2014; Fawzy et al., 2020). Examples of PEG climate mitigation initiatives include supply chain contract provisions that require lower carbon goods and collaborative efforts to induce companies to use renewable energy, such as Walmart's Project Gigaton. Louis Leonard has argued that PEG climate mitigation initiatives constitute a loosely-coordinated private regulatory system (Leonard, 2020).

In contrast to mitigation, adaptation involves actions that reduce the harms that arise from climate change (Intergovernmental Panel on Climate Change [IPCC], 2014)[2]. The IPCC has defined climate adaptation as "the process of adjustment to the actual or expected climate and its effects," and has noted that adaptation actions seek to moderate harm or exploit beneficial opportunities, as opposed to reducing the amount of climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). Adaptation includes both imminent actions such as responses to impending climate disasters and non-imminent actions such as accounting for increased sea level when renovating or constructing infrastructure (Moser and Ekstrom, 2010). Adaptation also includes anticipatory measures taken in advance to minimize the expected negative impact of climate change, as well as reactive measures taken after negative impacts occur. Adaptation efforts may address a wide range of outcomes, including water resources, coastal resources, air quality, agriculture, and public health (Smith and Lenhart, 1996).

The principal challenge for defining PEG adaptation is to identify when private sector adaptation initiatives constitute a form of governance. Governance is not the same as government and can include the processes, mechanisms and organizations through which actors influence environmental actions and outcomes (Lemos and Agrawal, 2006; Biermann et al., 2010). If governance only refers to how society collectively sets goals and makes decisions on how to achieve them (Chaffin et al., 2016), then much of the private sector activity on adaptation is not governance. If governance also refers to situations in which the private sector performs traditionally governmental functions, however, then many adaptation actions do fall within the private governance definition.

To be considered a form of governance under our definition, an adaptation action must perform a function typically assigned to governments such as reducing negative externalities, providing

[1]An important definitional question is when an activity is simply a response by a regulated entity to government through regulation or financial incentives as opposed to a response to drivers arising from NGOs and other private sector actors. It may be possible to conduct PEG adaptation activities even when governments are captured through gerrymandering, ideology, and other limits on the responsiveness of politicians to public preferences and to pursuing public welfare. See Vandenbergh and Gilligan (2015). In short, PEG adaption efforts may be able to bypass some of the political hurdles to government action, such as world views and resistance to climate change acceptance. Eriksen et al., *Reframing adaptation: The political nature of climate change adaptation,* https://www.sciencedirect.com/science/article/pii/S0959378015300509. PEG actors are not beholden to the restraints of representative government, but whether the social license and market pressures they face yield actions that are more representative of public preferences is beyond the scope of this article.

[2]Due to the inertia in the climate system and in public climate governance, substantial amounts of adaptation will be necessary even if prompt, major mitigation efforts are undertaken in the near term. IPCC, Climate Change 2007: Mitigation of Climate Change 818 (B. Metz et al., eds., Cambridge University Press 2007).

public goods, managing common pool resources, and providing a more equitable distribution of goods and services (Vandenbergh, 2013, Light and Vandenbergh, 2016). Thus, to be within the PEG adaptation definition, an adaptation initiative should provide the type of societal benefits typically provided by government laws, policies and programs. In addition, to constitute private governance the initiative should not simply be the result of a government regulatory measure.

An example highlights the importance of our functional definition. If a company, under pressure from NGOs, employees and neighbors, includes a town within its new sea wall, it is providing a public good to the town and engaging in PEG adaptation. In contrast, many private adaptation efforts that do not qualify exclusively benefit the business, rather than providing a benefit beyond the business. If the company builds a sea wall around its plant but excludes neighboring properties, it is adapting to climate change, but it is simply protecting its assets and is not engaging in governance. Of course, on the margin these activities are difficult to distinguish—even simply making a profit serves the social goal of increasing overall prosperity, for example. But our research suggests that despite the line-drawing difficulties, many activities fall easily into the governance category, and understanding the drivers and effects of these activities can contribute important insights about ways to facilitate climate change adaptation in an era of insufficient government action on climate change.

Finally, the legal and political science literatures often refer to governance as the exercise of authority. In this view governance occurs when one party exercises control over another or when multiple parties agree to exercise control over one another (Green, 2013; Salzman and Thomson, 2019). Although we recognize that this is an intuitive and common formulation, we do not include it in our definition. To the extent authority equates to coercion in this view, a large number of activities that government engages in do not involve the use of coercion, yet these actions are not typically excluded from the definition of governance. Examples include some uses of subsidies (e.g., many oil and gas and agricultural subsidies) and the disclosure of information that enables more informed decision making [e.g., the National Environmental Policy Act environmental disclosures [National Environmental Policy Act (NEPA), 1969] and the Toxic Release Inventory toxics disclosures (Emergency Planning Community Right-To-Know Act [EPCRA], 1986)]. As a result, although we acknowledge that private governance in some cases involves the exercise of authority by one party over another, we do not view this exercise of authority as a requirement of PEG adaptation.

EXAMPLES

Although much of the policy literature on adaptation focuses on public governance, the United Nations Framework Convention on Climate Change (UNFCCC) maintains a database of private sector adaptation initiatives. In addition, recent reports by UNEP and other organizations discuss adaptation efforts by the private sector [Caring for Climate, 2015; United Nations Framework Convention on Climate Change (UNFCCC), 2021]. In Part III we discuss several examples of initiatives that meet our definition of PEG adaptation. These are not a representative sample and we have not assessed their merits, but they demonstrate the range of PEG adaptation activities underway around the world. The net effect of the adaptation activities remains to be addressed, and our selection of these examples does not represent a judgment that they are successfully achieving adaptation or are having a net positive effect. In addition, our discussion of these examples focuses on whether a private sector actor is performing an adaptation function, rather than the actor's motivation for doing so.

Retail

Coca Cola has collaborated with the World Wildlife Fund and other organizations to establish watershed restoration and community natural resource management projects in Vietnam and Thailand (UNFCCC, 2012a). Coca-Cola set the goal to return to communities an amount of water equivalent to what it uses in the production of all its products, in part through replenishing water via local restoration projects. These local adaptation initiatives have public and private benefits. They increase long term production stability by protecting and replenishing water supplies, which in turn protects the surrounding communities (who often make up the workforce) and the resources needed to make products. Coca-Cola initially selected specific watersheds based on their biodiversity and potential for conservation gains. The effort also supports local communities through water quality testing, wastewater treatment, and financing. Coke has continued to engage in similar watershed improvement projects throughout the world [World Wildlife Fund, 2015; United States Department of Agriculture (USDA), 2016], but critics have question whether these types of efforts are a sustainable model for Coke and other corporations to follow or are just greenwashing (Ward, 2014).

Mars has engaged in PEG adaptation efforts in a variety of ways, including its efforts with Basmati rice farmers in Pakistan (Caring for Climate, 2015). Recognizing that climate change effects in the region coupled with widespread farming deficiencies threaten the supply of Basmati rice, Mars worked with Rice Partners Ltd. to develop a program to decrease water usage and improve rice farming practices. The program aimed to educate roughly 500 farmers about alternative practices that use less water and require fewer inputs, and then encouraged the farmers to share lessons learned with others to drive wider adoption of efficient practices. To determine practices to promote, Mars conducted assessments of current farming practices and invested in research on less water-intensive alternatives. Mars has set both engagement rate and water reduction percentage goals, and projects these alternative practices could increase net income for farmers by 30%.

Insurance

The insurance industry is well-positioned and motivated to engage in climate change adaptation. For example, reinsurance companies Swiss Re (UNFCCC, 2012c) and Munch Re (UNFCCC, 2012b) have supported adaptation in developing countries via innovative insurance-related risk management tools.

In collaboration with the Ethiopian government, Oxfam, and other partners, Swiss Re developed the Horn of Africa Risk Transfer for Adaptation (HARITA) project to assist poor farmers, combining financing of community climate resilience projects with weather risk insurance and microcredit (UNFCCC, 2012c). The program allows cash-poor farmers to work for their insurance premiums through community-identified projects that improve irrigation and soil management, thus reducing risk and building climate resilience. The success of this project is measured by the number of people it serves and whether poorer farmers can "graduate" financially to pay in cash. This project serves as an example of public-private collaboration and stakeholder involvement, and it highlights the potential for positive spillover effects.

In the United States, the insurance industry is engaging in PEG adaptation in response to the increasing risks of sea level rise and flooding. Private insurers are increasingly wary of insuring properties that are subject to flooding and are increasing rates or denying coverage in these areas (Light, 2021). These private actors are thus pushing their insureds to adapt to climate change even though governments are often undermining market incentives, such as by subsidizing flood insurance (Klein, 2021).

Banking

Many banks are also becoming involved in PEG adaptation efforts. For instance, large mortgage lenders may account for the risks of sea level rise and increasing storm damage over a thirty-year period, and they are beginning to account for these types of climate risks, such as by requiring larger down-payments (Keenan and Bradt, 2020; Klein, 2021). These mortgage lenders are thus engaging in adaptation even as the federal government continues to both directly and indirectly encourage development in coastal areas subject to sea level rise Disincentivizing building in risky areas is a form of anticipatory climate adaptation, but whether the mortgage lenders' actions qualify as a form of governance depends on the extent to which these measures benefit the community, not just the lender.

Banks engage in some activities that more clearly qualify as PEG adaptation. For example, Banco do Brasil conducted assessments across various watersheds in Brazil to assess climate change vulnerabilities (Caring for Climate, 2015). It determined that conventional agriculture processes (such as inadequate soil management), coupled with a lack of local knowledge regarding sustainable alternatives, put many watersheds at particular risk. In response, Banco do Brasil developed the Aqua Brasil program, which it funded and developed in partnership with Brazil's National Water Agency and WWF-Brasil. The program coordinates and funds actions that foster the development and the dissemination of sustainable rural production practices to improve water levels and the quality of target watersheds. Farmers also can receive financial incentives (funded by the bank) to adopt sustainable technology. The program has helped produce 60% reduction of erosion in some watersheds.

Finance

The private sector is helping fill the need for financing climate adaptation, and the United Nations Development Project (UNDP) has prioritized increasing private sector funding of adaptation efforts (Olhoff and Bee, 2016). For instance, the market for corporate green bonds, which are bonds whose proceeds are committed specifically to finance climate-friendly projects, has grown substantially since the early 2010s. In 2018, the corporate sector, including large companies like Toyota, Apple, and Unilever, issued green bonds worth $95.7B (Flammer, 2020). Although green bonds mostly focus on mitigation, many green bonds serve a distinct governance function regarding climate adaptation. Unilever, for example, has set climate adaptation requirements for its green bonds (Unilever, 2019). Because the green bond market is not publicly regulated, private voluntary certification systems, such as Climate Bond Standards and the Climate Resilience Principles have been developed to increase transparency and mitigate concerns of greenwashing (Climate Bonds Initiative, 2018).

Energy

Energy Development Corporation (EDC) Philippines, has engaged in PEG adaptation efforts in response to recent typhoons (Tall et al., 2021). In addition to increasing the resilience of existing infrastructure with the support of a peso-denominated green bond issued by the International Finance Corporation, EDC is boosting community resilience through training on disaster response for schools, residents and local government officials. It has also established a network of first responders at project sites across the country.

CONCLUSION

We view PEG adaptation as a discrete, conceptually coherent phenomenon that is an increasingly important feature of the social response to climate change. The barriers to government climate adaptation efforts suggest that public sector adaptation efforts will be inadequate, and although some private sector climate adaptation efforts are simply risk management efforts that benefit only the company, a growing number of activities qualify as PEG adaptation. These PEG adaptation efforts range from sea wall construction to green bonds to programs targeting more efficient water management by farmers.

Research is just beginning into PEG adaptation, however, and it will be important to develop design principles that increase the likelihood that future PEG adaptation activities will fare well when evaluated based on efficacy, transparency, accountability, equity, spillover effects and other criteria. Research is also needed on the drivers of PEG adaptation. A 2012 study by Caring for Climate of 72 companies found that 86% believe that investing in adaptation creates business opportunities (Caring for Climate, 2012). Additional drivers of PEG adaptation are likely to include not only new business opportunities and risk avoidance, but also reputational concerns, retail and corporate customer pressure, investor, lender and insurer pressure, employee pressure, and manager norms (Vandenbergh and Gilligan, 2017).

Research is also needed on the extent to which PEG adaptation brings additional private sector funding to government adaptation efforts or undermines government funding, whether greater efficiencies are achieved with PEG adaptation, and whether PEG adaptation decreases or increases support for other adaptation efforts and for mitigation efforts. Initial work on adaptation and geoengineering, however, suggests a general theme: if a response is proposed as a supplement to mitigation, not as a solution, then negative spillover effects on policy support for mitigation are low (Truelove et al., 2014; Raimi et al., 2019), but much more work remains to be done on these issues.

Simply put, PEG adaptation is underway, and far too little is known about its potential drivers, challenges, benefits, and risks. The sooner these research gaps are filled, the sooner public and private policymakers will have the information necessary to know which types of PEG adaptation to pursue and which to discourage.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Inadequacy Revealed and the Transition to Adaptation as Risk Management in New Zealand

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Climate change risk is rife with uncertainty. Increased frequency and intensity of flooding and drought and progressive sea-level rise, that compound and cascade and increase risk over time, pose particular difficulties for planning. The risks require institutional and governance frameworks that are tailored to such a dynamic environment. However, most planning frameworks and their practice focus on the societal need for certainty in space and time, to enable investment decisions to be made and activities to be undertaken with some stability. This means risk is framed in a static manner using time-bound planning methods, such as lines on maps and zoning, that lock in people and assets to areas of risk that are exposed to changing risk in time and space. The consequences are being increasingly revealed globally in deltas, inland low-lying areas and at the coast, and will increase unless planning practice becomes more adaptive and anticipates the risks early enough for adjustments to be made. Current decision-making frameworks in New Zealand have been revealed as inadequate for enabling changing and uncertain risks from climate change to be addressed. We discuss how practice under the existing planning framework has exposed people and assets to greater risk, and the challenges in the transition taking place in New Zealand toward an anticipatory adaptive approach. We chart the course of this transition and suggest how current law and practice can support and embed an adaptive direction within the institutional reforms underway for more effective climate risk management.

Keywords: climate change adaptation, risk management, institutional frameworks, sea-level rise, deep uncertainty, dynamic adaptive policy pathways

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INTRODUCTION

Climate change brings with it some very different characteristics to many other hazards that risk management must address. While we are familiar with hazards such as extreme events that occur periodically, under changing climate many of the impacts are ongoing and getting worse, either by becoming more intense, more frequent, or slowly affecting people and places (IPCC, 2014). For example, temperature increases already challenge natural ecosystems, and human health and well-being tolerance levels, beyond change experienced in the past; prolonged periods without rainfall are generating decadal droughts and affecting livelihoods and contributing to migration; and rising sea levels will be ongoing for centuries. This is even if we meet the Paris target of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, and after reaching net zero emissions domestically. We also face the prospect of concurrent risks that cascade and compound within and outside national jurisdictions, and which exhibit ongoing change and uncertainties (Challinor et al., 2018; Lawrence et al., 2020a). The adaptive capacity of people is built from lived and learned experience and through customs, norms, and laws (Adger et al., 2007). However, climate change creates the specter of the risk exceeding the adaptive capacity of people and natural systems (IPCC, 2018).

Interventions to ameliorate the damage from climate change impacts are required long before damages are experienced, due to the timeframes of the decisions taken today and the lifetimes of the activities being decided (Stafford Smith et al., 2011). Such interventions, however, are perceived as costly in the short term for uncertain future benefits (Hallegatte et al., 2012). Managing changing hazards through strong risk-avoidance approaches often implies greater initial costs, through pre-emptive adaptations or opportunities foregone. Since different sections in the community differ in the values they give to near-term vs. long-term risks, such decisions are inevitably difficult and require the reconciling of conflicting views. Furthermore, socio-economic, and cultural development is likely to change those values over time. Changes in people's values and in their ability to respond to change in their economic and physical environment will affect their adaptive capacity (Smit and Wandel, 2006; Adger et al., 2007) and will also change community preferences. The value of assets at risk change over time, as will the technological and financial ability to undertake risk-management strategies. These factors compound in significance for decisions about enduring activities, for example, housing and infrastructure which remain for many decades in fixed locations. Consideration of the time horizons of decisions is critical for decision makers under changing climate conditions. However, the timeframe of current planning and political cycles often run counter to the long-term focus required for considering climate change risks.

Governments create institutions through laws and policies to limit risk of harm to society from human activities and to maintain stability for the functioning of social systems (Ruhl, 2012). However, in so doing institutional design and practice often fails to address changing risks and their inherent uncertainty. Ruhl (2010) suggested that adaptation that avoids hazards—supported by cross-policy linkages at all scales of governance—is necessary, alongside flexible regulatory instruments and conciliation processes embedded in a legal system that can respond to a dynamic world. In addition, provisions must be able to address risks that cannot be well-estimated today and must do so before evidence of significant damage is obvious.

Climate change risk is worsening, but uncertainties and ongoing change means that future states cannot be assigned probabilities. The 2019 International Standard ISO 14090 on adaptation to climate change embodies the notion of interdependent risks that have uncertainties and highlights the contribution that consideration of uncertainties has on the results of risk assessments. This means, that adaptation under changing and uncertain conditions must be robust (can operate under a range of futures) and flexible (changes can be made to decisions) (Lempert, 2019). This requires the relevant decision-making agencies to use proactive and anticipatory strategies that are underpinned by laws and policies to shift away from the reactive and protective *post hoc* behaviors of humans (Boston and Lawrence, 2018).

This paper presents a historical and forward-looking analysis of a process that has been underway in New Zealand for some decades and that reveals the inadequacies in the planning systems and risk management practices. These are now culminating in a major reform of the regulatory environment that can enable a transformation toward pre-emptive anticipatory decision making to address changing risks and build adaptive capacity. First, we take one example, sea-level rise, and show that planning frameworks and instruments have enabled static outcomes and are inadequate to address the problem of sea-level rise. The inadequacies have resulted in increased exposure of people and assets at risk, by locking in developments at the coast, making adaptation in the future extremely challenging. Second, we outline an agenda for institutional change currently being developed in New Zealand that explicitly seeks to address the dynamic and uncertain characteristics of changing climate through an anticipatory model of decision making.

Third, we provide some principles that can drive a transition to adaptation as risk management.

The analysis was undertaken by the authors (hazard, climate change experts and planners) as part of the Resilience to Nature's Challenges—Enabling Coastal Adaptation government-funded research program, and which is informing the legislative reform process. A mix of qualitative methods was used for the analysis including information from a number of sources (planning documents, published papers, direct contact with local government informants, case law under past and existing plans, and websites). Examples are presented of the most typical situations in which hazard exposure has occurred in New Zealand (**Table 1**). We have then provided examples of how some plans are trying to ensure better outcomes in the future (**Table 2**).

THE SEA-LEVEL RISE CONUNDRUM—HISTORICAL LEGACY OF TRADITIONAL PRACTICE

Sea-level rise is being observed now especially when there are perigean tides (king tides) around our estuaries and coastal locations (Stephens et al., 2018) with impacts on the function of roads, stormwater, and wastewater systems, cultural sites, human settlements, and coastal ecosystems. These impacts are also being exacerbated by more frequent intense storms when more permanent damage is sustained.

However, our institutional arrangements in law and our responses to the consequences of climate changes are based on the societal need for certainty in space and time to enable governments, businesses, and people to make investment decisions and undertake their daily lives with some stability. The

TABLE 1 | Examples of planning practice that increase vulnerability to sea-level rise.

Example	Characteristic	Occurrence and policy context
Intensification of existing urban areas close to the coast and current sea level	Zoned and serviced for conventional urban development. Where infrastructure (e.g., road, railway, or port) has underground urban services which double as/are maintained as a form of coastal protection. Pressure for densification has led to ongoing increases of unabated development	Very widespread in New Zealand, due to historic location of settlements in vulnerable areas with increasing intensification (e.g., residential, and commercial areas in Auckland, Dunedin, Tauranga, Napier, Petone and the Kapiti Coast north of Wellington and many mid-range coastal settlements) and current pressures to increase opportunities and supply of housing The NZCPS recognizes that such existing areas may require ongoing hard protection but requires local authorities to consider options to reduce risks and avoid long-term social, environmental, and economic harm from coastal hazards. There is little evidence of consideration of long-term options
Intensification or growth of small beach-side settlements	Many traditional "bach" or "crib" settlements for temporary (holiday) occupation adjacent to a beach which pre-date any planning controls. Many have been subsequently zoned for residential use to meet the growing demand for permanent and holiday homes. Many small dwellings have become large or multi-units, the land has been infilled or settlements have grown spatially, leading to a doubling or more of the number of dwellings exposed to coastal processes	Found in many parts of New Zealand. Pressures are greatest in proximity to a major urban area (e.g., Omaha Beach, north of Auckland, a recent study on tsunami risk (Paulik et al., 2019) showed 448 dwellings in 1992 had increased to 1,147 by 2012, and 15 3-storeyed buildings in 1992 had become 39 by 2012) Such intensification and expansion of urban development should have only occurred following a risk assessment. More permanent residents result in changes in community perceptions and values often resulting in greater pressure on local authorities to provide hard protection, or to enable residents undertaking their own protection resulting in problems such as "end" effects on other properties
New areas of coastal development	In rural localities where new low-density rural-residential subdivision has been permitted. The original subdivision may have included conditions on development to ensure that risks would be minimized and managed through (low) density control, coastal setbacks, and self-contained services. However, demand has resulted in further development *via* subdivision into small blocks and/or multi-unit development	In many parts of New Zealand often from the "life-style" boom of the past 30 years. Expansion of planned subdivisions during the development stages occurs (e.g., Boatshed Bay, Snells Beach, where an original 25-lot subdivision intensified to 71 lots, some containing multiple dwellings) Such "planning creep," is considered in successive applications, each of which is seen to add little additional risk. This approach is contrary to policies in the NZCPS which requires that land use change which increases the risk of harm from coastal hazards, is avoided. Councils also find it difficult to avoid developments in coastal risk areas where empty, previously consented subdivisions, exist
Intensified development behind new coastal protection	Where communities exert pressure on local authorities to allow new or refurbished hard protection structures funded by that community	Some such proposals have been rejected (e.g., Pakawau in Tasman District). However, there are many examples of councils funding protection proposals e.g., Haumoana in Hawkes Bay with a population of 1,150 where the council funded $600,000 for rock revetment protection. At nearby Clifton, population 770, the same council, and two local landowners are investing $2.8 M over 35 years to protect a road, a camping ground, and a small settlement. At Waihi Beach in the eastern Bay of Plenty, population 3000, the council evaluated options and obtained consent to build a replacement sea wall and undertake dune enhancement to protect existing properties. Funding is through a targeted rating area, where capital and maintenance is largely covered by those who benefit and 25% of the costs are funded *via* related council program (the wall has been extended, recently on the same basis to address "end effects" of the structure) The NZCPS requires that options to hard protection for existing settlements must be considered. Each of these examples has been considered through comprehensive consent processes, including an evaluation in terms of the NZCPSThe NZCPS requires that options to hard protection for existing settlements must be considered. Each of these examples has been considered through comprehensive consent processes, including an evaluation in terms of the NZCPS

(Continued)

TABLE 1 | Continued

Example	Characteristic	Occurrence and policy context
Coastal river-mouth	Development of settlements in dynamic coastal river mouths are a legacy of early settlement near navigable rivers and continued development at that site based on existing infrastructure. Significant alteration of natural systems for protection has enabled development and reinvestment behind them to continue to occur	Growth pressures have led to ongoing protection in such localities (e.g., Hokitika on New Zealand's South Island west coast is protected by seawalls and groins funded by a targeted rating area.[a,b] Regional coastal and district planning processes currently under review create opportunities for greater scrutiny of growth plans and modifications to the sea wall, including considering the feasibility of remaining in the dynamic environment affected by sea-level rise, river dynamics and the risk of seismic hazards, or of retreating)

[a] *https://www.wcrc.govt.nz/repository/libraries/id:2459ikxj617q9ser65rr/hierarchy/Documents/Services/Special%20Rating%20Districts/Hokitika%20Seawall/Asset%20Management%20Plans/Hokitika%20Seawall%20Asset%20Management%20Plan%202014%20-%202017.doc.*
[b] *https://www.stuff.co.nz/national/politics/local-democracy-reporting/121546660/plan-now-for-hokitika-retreat-from-the-sea--councillor-warns.*

TABLE 2 | Examples of proactive planning that will reduce risk over time.

Example	Description
Marlborough District Council, Regional Planning Approach	This local authority, which has a long and very complex land/sea interface, has recently comprehensively reviewed all its RMA planning documents. For the first time in New Zealand, policy has been included in the Regional Policy Statement (the highest-level policy document, which must be given effect to in all levels of RMA decision-making in the region) which has largely adopted the MfE guidance on sea-level rise allowances, undertaking to apply Dynamic Adaptive Pathways Planning (DAPP) by working with local communities to develop an action plan for sea-level rise responses. A separate Climate Change chapter identifies climate change effects as one of the major issues facing the region and identifies such future planning as the main method to address the issue
Mapua Township, Tasman District	Parts of the small seaside township of Mapua in Tasman District (current population, 5000) were identified as particularly vulnerable to coastal erosion. The council undertook a comprehensive structure planning process with the local community to determine how future growth should be provided for. As part of this process, new areas on higher hillsides, able to be accessed and serviced, were rezoned for development, while the older more vulnerable areas became "closed zones" with any further development prohibited. Strong policy in the natural resources plan supported the transitional planning toward a less vulnerable future settlement
Whakatane District	Whakatane District has 54 km of coastline, much of it vulnerable to sea-level rise and other coastal natural hazards. The district plan (operative since 2017) identifies existing erosion areas, and 2060 and 2100 hazard lines on the planning maps, along with strong policy and rules to manage development within hazard areas. Inland to the 2100 hazard line, existing buildings can be maintained, but new buildings and other structures face increasing consent difficulty, the closer to the coast that they are. Easier consenting paths are provided for new dwellings if an alternative building site for future relocation is provided. Such sites must be held available (within the same legal ownership title) for eventual building relocation. Relocation is triggered when the line of mean high-water springs is at 20 m from the closest point of the building. Draft conditions in the plan indicate what the council will require owners to do (including notations on the land title) if consent is granted. Otherwise, rules and policy make it very difficult to obtain consent for new buildings. Similarly, there are strong consenting barriers which mean that any form of coastal protection, other than methods such as dune planting, is unlikely to get consent. The processes which have led to these plan provisions are in line with DAPP, and the approach is consistent with the NZCPS

response has been to use static decision frameworks that bias responses toward retrospective, rather than anticipatory planning (Manning et al., 2015), using "protective" measures. These in turn have given people a false sense of security, leading to increased risk due to intensification of investment at the coast, driven by widespread preference to be near the coast for the apparent values it affords people (Haasnoot et al., 2021). This is a global trend. However, land use planning decisions to date have been made under a period of relatively quiescent climate, within a range of variability that humans have adjusted to—global warming is changing the range now being experienced (IPCC, 2018). Greater frequency of weather extremes across the world has led to much discussion in the literature about adaptation to changing risk and the relative effectiveness of "protect," "accommodate," "advance" or "retreat" strategies to manage the risks (Haasnoot et al., 2021). New Zealand is no exception.

The New Zealand institutional framework for addressing hazards and climate risks is based on a set of administrative traditions (Van Buuren et al., 2018) largely devolved to local government which comprises 11 regional councils, 61 territorial authorities (11 city councils and 50 district councils) and six unitary councils (territorial authorities with regional responsibilities). White and Lawrence (2020) charted the eras of institutional response to New Zealand riskscapes showing how legacies have arisen and evolved from past planning and development decisions. For example, the widespread natural forest clearance in catchments and lowland areas associated with settlement and taming a new land resulted in the loss of flood attenuation and storage capacity of the natural ecosystems, which increased flooding and soil erosion. What followed was the "protect" regime under the Soil Conservation and Rivers' Control Act 1941 which heralded the construction of some of the largest flood protection works and coastal protection structures in the country. Historically, human development took place near the means of transport—rivers and the coasts. Following a 1953 version, a Town and Country Planning Act emerged in the 1970s that had an objective that protected settlements by controlling land uses and was supported by hazards mapping. However, it was not until the 1990s that a more integrated statute emerged across land and water, which included a "reduction, avoidance, and mitigation of hazards" purpose, in the Resource Management Act 1991 (RMA). This statute, largely administered by local government, mandated national directions for coastal hazard management but did not initially include the growing recognition of the impacts of climate change. The first New Zealand Coastal Policy Statement (NZCPS) prepared under the RMA, in 1994, was underpinned by a "precautionary" approach. The NZCPS recognized the potential for climate change to affect coastal activities and required local authorities to plan for the inland migration of coastal features, and for new settlements and subdivisions to be located and designed to avoid the need for coastal protection. It was not until 2004 that "the effects of climate change" was added into the RMA as a matter which must be carefully considered in all planning decisions. The 2010 update of the NZCPS added a timeframe of "at least 100 years" when planning for climate change and directed specific planning responses for new and existing development in coastal areas subject to sea-level rise risks.

Meanwhile planning practice largely continued along a preferred "mitigation" of hazards route using "protection" and "accommodation" measures. When such mitigation measures were insufficient after weather-related disasters, limited insurance has been paid as a last resort to households from the Government's Disaster Fund.[1] This has enabled building back in the same hazard-exposed locations, rather than enabling rebuilding in areas that reduce risk (Lawrence and Saunders, 2017). Development has increased in areas of hazard risk regardless of the provision of increasingly clear national-level climate change planning guidance for assessing and managing coastal hazards (MfE, 2017). This guidance has been informed by successive IPCC reports which indicate increasingly damaging and complex climate change impacts, and the availability of new decision-making tools for pre-emptive anticipatory risk management developed in the last 10 years (Lawrence and Haasnoot, 2017; Lawrence et al., 2019b) and the value of early engagement with affected interests in low-lying coastal areas (Schneider et al., 2020).

To better understand the long-term outcomes of current planning practice in a context of ongoing sea-level rise, the authors undertook analysis of typical situations where intensification of development, or new development, has occurred in relatively hazardous coastal locations across New Zealand. Examples (**Table 1**) show how practice based on the current regulatory environment is creating a legacy of exposed inhabitants and their services that increase vulnerability over time and if sea level rises faster than current projections. This is happening through intensification and growth of existing large and small urban areas and through intensified and new developments behind protection structures and at coastal and river mouth locations (localities shown in **Figure 1**).

There are only a few examples (**Table 2**) of local authorities taking pro-active steps to set in place planning regimes that will actively reduce risk over time and that are in line with the approaches recommended in the national coastal planning guidance (dynamic adaptive planning and community engagement at its core) (MfE, 2017). These remain exceptions in a wider and unintended regime of gradually increasing exposure to coastal hazards from sea-level rise.

In summary, legacy effects of plans which include land zoned for residential development in areas which would today be regarded as unsuitable for new development because of the coastal hazards, have since accommodated a lot of intensification (e.g., parts of Christchurch, Tauranga, Petone and Kapiti Coast in the Wellington region, Auckland, Napier). This has happened because of favorable zoning and a general inability to prevent intensification of earlier low-density development.

In terms of new development, in the past two decades there are only a few proposals in coastal hazard areas which have been successfully repelled,[2] notably on the Kina Peninsula (13 lots) near Nelson and at Bay View near Napier (about 30 lots). The councils around Napier City have proactively undertaken a comprehensive coastal compartment assessment of coastal risk and have developed a Coastal Hazards Strategy using a hybrid DAPP process to assess options, develop pathways, and monitor signals of change which include triggers to identify when decisions should be made to change paths as sea level rises (Lawrence et al., 2019a).

THE INSTITUTIONAL CHANGE AGENDA

An independent review of New Zealand's RMA and its intersection with related legislation such as the Local Government Act 2002, the Land Transport Management Act 2003 and the Climate Change Response (Zero Carbon) Amendment Act 2019[3] was completed in 2020. The review was motivated by a natural environment under significant pressure, urban areas struggling to keep pace with population growth, an urgent need to reduce carbon emissions and adapt to climate change, the need for a more effective role for iwi/Māori in the resource management system that is consistent with the

[1] The Earthquake Commission Act 1993 provides insurance funding for residential property damage from natural disasters, administered by the Earthquake Commission, which is funded through a levy on private property insurance, for underwriting damages up to NZ$150,000 per claim.

[2] These two examples were challenged at the Environment Court—Carter Holt Harvey Ltd HBU v Tasman District Council Decision No. (2013) NZEnvCt 25, and Fore World Developments Limited v Napier City Council W029/2006 (2006) NZEnvC 120.

[3] Amending the Climate Change Response Act 2002.

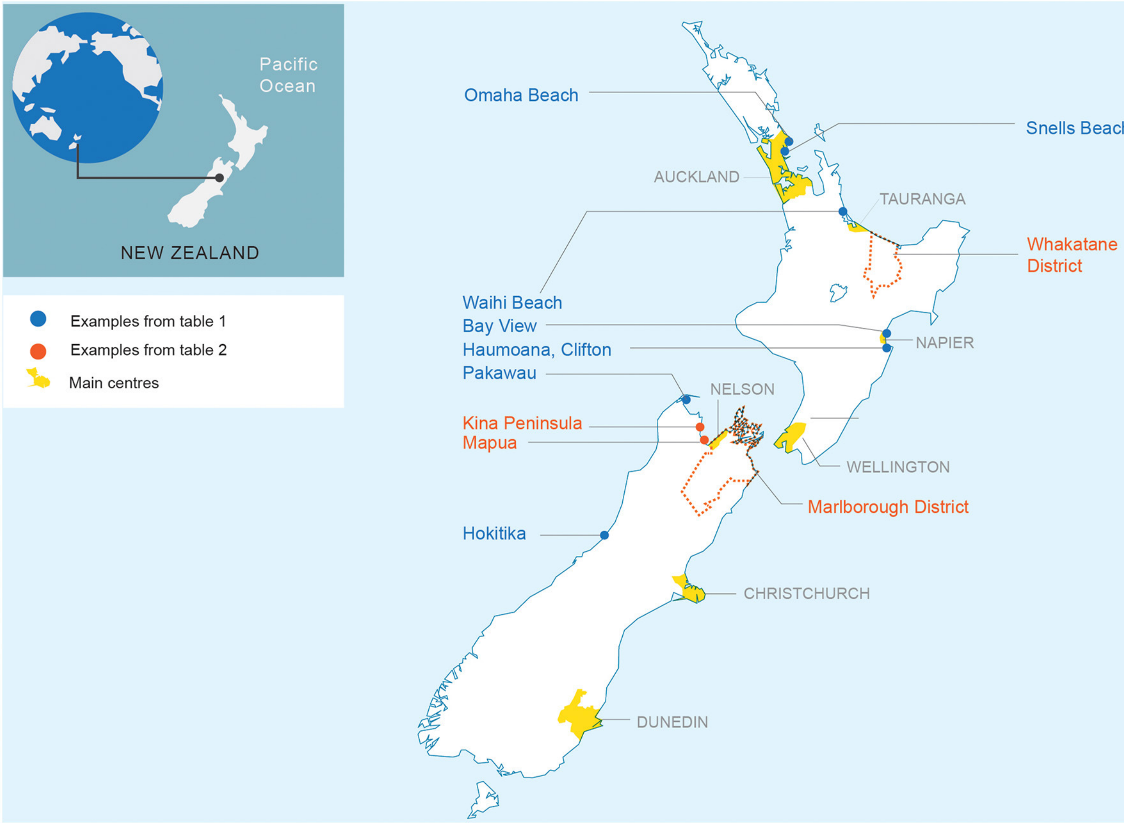

FIGURE 1 | Location of New Zealand and examples cited in **Tables 1**, **2**.

Treaty of Waitangi, and a need for greater system efficiency and effectiveness (Randerson, 2020).

The review recognized the value of a more strategic and anticipatory planning system and recommended three new statutes. First, a *Strategic Planning Act* to provide a framework for mandatory regional spatial planning for the land and marine coastal areas,[4] which emphasizes the importance of a long term view out at least 100 years, that enables areas to be excluded from development, that provides that policy and plans are subject to review every 10 years or earlier if significant issues arise, and which incorporates significant stakeholder and community involvement. Second, a *Natural and Built Environment Act* to set environmental baselines, while keeping the important synergies between the natural and human environment together, increasing national direction and instituting a national monitoring, audit, and reporting system. Third, a *Managed Retreat and Climate Change Adaptation Act* specifically to address the complexities of managing the effects of climate change, such as which level of governance manages and funds responses to climate change risks and how to address existing uses and managed retreat. Climate change mitigation and adaptation and natural hazards risk reduction would be integrated into all three statutes and would be informed by the National Risk Assessment and the National Adaptation Plan that are required under the 2002 Climate Change Response Act.

Several of the review's recommendations directly address the shortfalls of current planning legislation for addressing changing hazards. Of particular note is the linking of mitigation and adaptation in planning, requiring joint strategic plans and statutory Long Term Plans under the Local Government Act for each region, in conjunction with the territorial level of government. Under the current planning regime, the responsibility for these functions must be decided by agreement between regional and local councils, with the default being regional management. This has led to both levels of government usually trying to avoid responsibility for these functions, particularly regional councils which have little or no involvement in land-use planning. Also of note is the recommendation to introduce new planning tools that can be used for adaptive planning, such as dynamic adaptive policy pathways planning (Haasnoot et al., 2013) which is recommended in the national coastal hazards and climate change guidance for addressing uncertainties and changing risk (MfE, 2017; Lawrence et al., 2018). Stronger national direction is envisaged from the Government in response to the National Adaptation Plan under the Climate Change Response Act. Legacy effects (lock-in) are envisaged as being addressed in the Climate Change Adaptation Act through

[4]Based on 14 regions rather than the current 100+ regional and district plans.

changes to "existing use rights" and provision of compensatory funding mechanisms.

In summary, the reforms now currently underway will put the focus on planning at a strategic level that can address key hazard and climate change risks, with stronger national direction and more joined up statutory processes and outcomes. To address the changing risks in an anticipatory manner, response pathways are envisaged as being embedded in plans as they are developed, rather than requiring multiple subsequent plan change processes. An inbuilt monitoring of change process through signals and triggers for shifting pathways ahead of the consequences of climate change is envisaged.

Statutory alignment and new statutes can clarify mandates, but they cannot assure successful implementation. The success of institutional reform for addressing changing hazard risk relies upon an enabling implementation environment, including organizational leadership, effective processes for genuine community engagement, practice capability and capacity, and monitoring of the changing risk through institutional arrangements and evolving science.

Our over-view of current practice demonstrates how statutory change, like the RMA in 1991, takes time to reset past practice. The changes, especially to the NZCPS in 2010, created an opportunity to reduce coastal hazard risk, but this was not taken up widely in practice because development pressures and absence of central government support for local authorities dealing with those pressures, dominated decision making. Indeed, over time the situation has enabled increasing exposure and vulnerability and a legacy impact that has become entrenched and is very hard to unbundle and with potentially large associated costs. Unlocking greater flexibility on the ground to remove risk through a managed staged retreat of settlements and their services over time, holds promise as a cost-effective alternative to the costs of temporary "protection" and "accommodation" measures in low-lying coastal areas, which continue to lock in expectations of ongoing protection and a sense of safety. This "levee effect" in Tobin (1995) entrenches risk and reduces the ability to adjust to changing conditions, transferring the risk to future generations in more costly forms that cannot keep up with the pace of climate change impacts. A further aspect which the reforms will need to address is the transfer of submerged areas back into the coastal marine area, where New Zealand law makes it subject to the Marine and Coastal Area (Takutai Moana) Act 2011, a complex statute which provides for both public and customary interests, and in some circumstances, ownership based on traditional rights. The issue of hard coastal protection, which has been generally discouraged in current policy, but which is commonly favored by communities under threat, is also likely to become subject to national direction through this statute.

New Zealand has the opportunity to mandate adaptive planning, tools and monitoring provisions as signaled by the RMA reform agenda, in a way not hitherto undertaken in statute or practice to date anywhere. The promise held out in terms of a single new coastal hazard planning statute which will over-ride other planning instruments, and address land ownership and land uses in at-risk areas together, providing the means for compensation for current owners, is novel and potentially ground-breaking. The development of the policy and principles on which the new statute will rest, while at an early stage, is being watched with close interest by the many stakeholders within and outside of New Zealand also grappling with the effects of sea-level rise.

DRIVING A TRANSITION TO ADAPTATION AS RISK MANAGEMENT

Reflecting on the history, current practice and outcomes, and the planning system reforms currently underway, we now distill a set of principles that might drive us toward adaptation that can anticipate outcomes and develop flexible pathways to navigate the changing future.

To date our experience in New Zealand has followed a path where communities, planning practitioners and decision makers are learning by doing, seeing their peers and other communities experiment and fail, or succeed in achieving their objectives. Changes to the riskscapes and the responses to them (White and Lawrence, 2020) motivate new opportunities for advisors and communities to take up new approaches often enabled by science investment and which has practical value for decision makers (Kench et al., 2018; Kool et al., 2020; Lawrence et al., 2020b; Ryan et al., 2021) witnessed by the recognition of new approaches in the reform process in New Zealand (Randerson, 2020).

International colleagues and networks have collaborated on the development of new approaches and tools and highlighting them in the scholarly literature to be diffused through the IPCC assessments, thus giving them legitimacy (Lawrence and Haasnoot, 2017). They then have been embedded in national guidance (MfE, 2017) and proposed in law. However, this process is incremental and slow, not least because there are missing parts to enable implementation, but also in the understanding of the very nature of climate change as a policy problem that could inform more robust decision making by shifting practice toward adaptive planning processes. This understanding is in direct contrast to the established principle of "existing use rights" within current law, and landowner expectations of the provision for "reasonable use" of land also provided for within the RMA. Both concepts, make the implementation of adaptive planning complex in relation to land use, with no certainty of success.

Understanding the Value of a Precautionary Approach

The principles underlying adaptive planning are fundamentally driven by the precautionary principle, which in the climate change context guides its application. The precautionary principle arises from the notion of anticipating large and negative consequences or irreversibility and has evolved to mean that uncertainty should not be used as a defense for inaction in such circumstances, i.e., that avoidance or protective action should be taken ahead of full scientific proof of harm. The principle became codified in law and guiding frameworks as a "do no harm" principle [e.g., Principle 15 of the Rio Declaration 1992; Article 3.3 of the UN Framework Convention on Climate

Change 1992]. These instruments use terms such as "anticipate, prevent or minimize," making the distinction between responses that occur *after* a climate "event" that causes damage and a precautionary one that suggests responses *before* a climate event. The precautionary principle is thus characterized as an anticipatory principle because it recognizes that climate change has the potential for widespread and large consequences for societal functioning which can be avoided, or at least minimized, and guiding implementation to avoid unnecessary costs that could be regretted. The precautionary principle has been embedded in the design of statutory instruments in New Zealand since at least 1994 (e.g., the first New Zealand Coastal Policy Statement under the RM Act), and in adaptive practice applied in other dynamic and changing systems, such as for consents in the marine area for aquaculture, and for the allocation of groundwater.[5]

Its utility relies upon how actual response measures within a quasi-legal context can accommodate uncertainty and dynamic change effects. When uncertainty and high consequences exist together, as they do for coastal hazards over the long term, using information as if it were certain is problematic (Fisher and Harding, 2006) potentially resulting in unintended consequences when the future turns out to be different. This is precisely why static instruments of planning are inappropriate for circumstances with changing risks. Focusing on uncertainty where there is a risk of "serious" and "irreversible damage" therefore can be a strength of the precautionary principle because the consequences could overwhelm the coping ability of the institutions in the future, thus compounding negative impacts on society.

Understanding Deep Uncertainty to Match the Problem With the Planning Instrument Design

Climate change presents to decision makers a type of problem that requires new approaches and tools that can anticipate risk, to avoid harm because of uncertainties about the future. These have been developed from the "deep uncertainty" tradition (Marchau et al., 2019) where "deep uncertainty" is defined as domains of decision making where the experts do not know or the parties to a decision cannot agree on the external context of the decision, how the system works and its boundaries, and/or the outcomes of interest from the system and/or their relative importance (Lempert et al., 2003). Deep uncertainty also arises from actions taken over time in response to unpredictable evolving situations (Haasnoot et al., 2013). These characteristics are all present in decision making on adaptation to climate change and in particular to ongoing sea-level rise.

Experience to date in New Zealand has been with adaptive planning outside of the regulatory processes. Dynamic Adaptive Policy Pathways (DAPP) planning has been used in coastal and flooding situations, for the assessment of coastal compartment risk, and for the development of preferred pathways that can be used to start the decision process for particular design parameters in structures and design flows for river management (Lawrence et al., 2019a,b). Signals and triggers along several pathways have been developed as management tools for giving warning and identifying the conditions under which current adaptations will no longer meet the objectives (Stephens et al., 2017, 2018). However, there is only one example in New Zealand where DAPP as a process has been enshrined in a statutory document (**Table 2**) based on the NZCPS as national direction. In that case, DAPP has been identified as the method which is to be used for future planning processes and decision-making in areas of identified coastal hazard risk, through a regional policy, but has not yet been given effect in the planning rules where land use activities and subdivisions are consented.

The planning law reforms that are under way have flagged the value of an anticipatory approach to adaptation. The review highlighted DAPP planning as an example that can be used to address changing climate risk and uncertainty, and indeed for any domain that has elements of dynamic change and uncertainty in the future around the pace and magnitude of change, such as in urban areas and ecosystems. The problem that DAPP can assist with under a planning regime where greater certainty is desired, yet certainty cannot be assured, is its ability to help identify adaptation options that do not lock in path dependency that increases climate change risk. By not prescribing a single pre-determined solution, DAPP planning helps develop agreed suites of responses as options and pathways that can be implemented when pre-determined signals warn of an impending threshold, thus giving time to implement a more lasting option or pathway. Such signals and triggers for decision making can be defined through physical climate change, geomorphic change, social tolerance, cultural or economic values, as indicators of frequency (time) or damage (impact), for example.

Participatory Governance

Fundamental to democratic governance is the social contract with the governed. The governed comprise individuals, communities, different groups, sector interests, policy, and service delivery agents. Their interests are diverse, with each having different power and influence over decision makers. The closer governing agencies are to the people, the more difficult it is to deliver within an electoral cycle. The further away the governing agents are, the greater is the risk that decisions will be inappropriate or irrelevant. What gives decision making traction is credibility, salience, and legitimacy (Cash et al., 2003) of processes that are built on trust. Trust is built through working together in long term collaborative relationships, co-creating knowledge and confidence amongst the actors in "safe spaces," with an eye on the long term and an enabling environment that develops negotiating skills and breaks down power dominance in any one person or group (Vij et al., 2021). Where people's values and in particular their sense of place is threatened by ongoing sea-level rise and the response to it, participatory governance is critical for implementation of adaptive planning decisions (Schneider et al., 2020). This takes time but can be driven more

[5]Staged consents with conditions on duration, area, scale, intensity, and nature of the activity, with monitoring and reporting under the Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012; for aquaculture through regional coastal plans developed under the RMA; and for adaptive water allocations for groundwater consents.

effectively if mandates and roles are clear and decision-making processes are defined and mandated by statutory direction and oversight.

In New Zealand, such participatory roles are mandated under the Local Government Act where arguably the pressures from interests on elected officials have often led to perverse outcomes for coastal adaptation, through delay or adopting business as usual protection adaptations, or through the threat of or actual legal challenge to policy responses.[6] These have had a chilling effect on proactive planning for known hazard risks (Lawrence et al., 2013). There is also evidence that high level national governance direction that is single purpose and short-term, may deliver perverse outcomes for adaptation (e.g., under the National Policy Statement for Urban Development 2020, which requires councils to identify growth areas to meet theoretical standard growth requirements). A more participatory governance model that relies upon a partnership approach using adaptive approaches could better bridge the respective mandates and roles and has been recommended in New Zealand and embedded in national guidance (MfE, 2017; CCATWG, 2018).

Assessments of the use of pathways approaches internationally have revealed the need for mechanisms that put values assumptions central in adaptive decision making and address social inequities (Gorddard et al., 2016). Understanding past change as a motivator for new and transformative futures (Fazey et al., 2016) has been emphasized, along with the important role of stakeholder participation in pathway development (Lin et al., 2017) as a way of addressing "power sensitive" design principles for climate change policies and their implementation (Vij et al., 2021).

CONCLUSIONS

The challenge going forward for reforming the planning process in New Zealand is how to turn a static planning process, with high expectations that land ownership conveys development rights, into a dynamic one that gives certainty of outcome sufficient to change society's "hard-wired" desire to be "protected," while at the same time governing from a participatory planning standpoint with a long view.

We proffer our perspective on the missing elements in the planning system that have been consistently identified as barriers to effective coastal adaptation (MfE Hawke's Bay Regional Council, 2020) and that if addressed could enable an anticipatory and adaptive planning system and practice to evolve more quickly.

1) Improved institutional frameworks and governance. Clarity of mandate and roles that reduce ambiguity and build capacity at the level of governance best suited to the decision-making domain and which are well coordinated across inter-dependent parts of a system, are arguably a foundation for reducing climate change risks as they change and worsen over time. Too many small local government agencies with the same responsibilities across two levels of local government has often created capacity and coordination difficulties for integration and resulted in perverse outcomes that are hard to shift in a world where the risks are changing quickly when decisions inertia is embedding legacy risks. Where regional and territorial local government functions exist in unitary councils,[7] or where several councils co-join under a regional council, greater traction of proactive coastal planning has been observed, due to scale across a wider area and mean high water springs, consistent administration across regional and district responsibilities, resource efficiency and greater expertise.
2) Better community engagement about the coastal hazard risks that affect the direction of development, enables the values of current and future generations to be reflected in coastal risk assessments and opens up opportunities for innovative leadership and adaptation through well designed processes. Such processes can address and manage power interests which often have led to perverse outcomes increasing exposure to coastal hazards.
3) Equitable access to authoritative information, along with information on changing risk profiles.
4) Clearly stated statutorily binding objectives for vulnerable localities which set in place future pathways for change, and which avoid lock-in of increased risk, for example by anticipating change, that enabling building back better or somewhere else for sea-level rise, designing urban areas for more frequent flooding and through greater alignment across relevant statutes.
5) Using decision tools that are "fit for purpose" in a changing worsening situation, that can anticipate risk and uncertainty and enable flexible choices to be made by enabling a change in decision ahead of the risk being realized.
6) Effective monitoring systems that can track signals and triggers in a timely way, that are well embedded in risk management and decision-making processes of the responsible agencies, and that can be administered effectively as change occurs (in the physical environment and within organizations).
7) Legal changes to property rights, as they currently create perverse incentives for decision making on climate change risks and lead to ongoing increase in assets and number of people at risk.
8) Funding mechanisms targeted at anticipatory planning to avoid future risks and to address land use change where existing uses and assets are at risk.

While these suggestions are by no means the only missing parts to an effective statutory framework for climate change adaptation as risk management, they are the critical elements that can help embed an adaptive direction for planning practice and from which it will be difficult to resile. Like all reforms, the acid test is whether such changes can be implemented as

[6] *Weir v Kapiti Coast District Council* (2013) NZHC 3522, 19 December 2013; *Awatarariki Residents Incorporated vs. Bay of Plenty Regional Council and Whakatane District Council* (2020) NZEnvC 215.

[7] Tasman Resource Management Plan, Marlborough Environment Plan, Clifton to Tangoio Coastal Hazards Strategy 2120.

best practice or whether decisions continue to be made that lock in developments to ongoing risk by focusing on short-term benefits of protection at the expense of future generations. Our paper has shown the nascent practice that could build the capability and capacity to anticipate climate risks and the reform mechanisms that could incorporate the concepts behind adaptation as risk management and thus leverage a transition to more adaptive coastal planning practice where sea-level rise is the dominant hazard.

AUTHOR CONTRIBUTIONS

JL conceived the paper and wrote the first draft. SA and LC contributed to the planning examples and with JL identified gaps in the planning system. All authors contributed to the article and approved the submitted version.

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POLICY BRIEF
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Regulatory Fragmentation: An Unexamined Barrier to Species Conservation Under Climate Change

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Requirements for the protection or restriction of species are based on regulatory classifications such as "native" or "invasive," which become anachronistic when climate change drives species outside of their historical geographic range. Furthermore, such regulatory classifications are inconsistent across the patchwork of land ownership that species must traverse as they move between jurisdictions or when transported by humans, which obstructs effective regional management. We surveyed the U.S. laws and regulations relevant to species movement and found that the immigration of species to new jurisdictions makes paradoxical existing regulatory language that sets the categories of species deserving protection or removal. Climate change is universal and progressing rapidly, which provides a shrinking window to reconcile regulatory language originally developed for a static environment.

Keywords: regulatory fragmentation, climate change, conservation, natural resources law, Anthropocene, endangered species, invasive species, public lands

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INTRODUCTION

Species migrations of hundreds to thousands of kilometers were a common response to past periods of rapid climate change (Davis and Shaw, 2001), and, because movement was not coherent across species, the species composition of ecological communities changed substantially with these climate disruptions (Blois et al., 2013). Contemporary climate change is already driving species shifts and community realignment (Blois et al., 2013; Moritz and Aguda, 2013). Since the rates and magnitude of contemporary climate change are projected to be as high or higher than those past analogs (Raftery et al., 2017), it is virtually certain that species range shifts will grow larger and more ubiquitous this century.

Species displaced long distances by climate change will thus increasingly have to traverse a patchwork of jurisdictional boundaries to survive. However, the regulatory status of species that disperse beyond their historical ranges varies from jurisdiction to jurisdiction and often hinges on whether they are considered "native," an ambiguous designation for species undergoing range shifts. Like habitat fragmentation, which can impede the capacity of migrating species to keep up with shifting climates (Warren et al., 2001), such "regulatory fragmentation" can compromise management strategies under climate change (Craig, 2008). Although regulatory programs are emerging at local, state, and national scales that attempt to address some of the impacts of climate change on species conservation (National Academies of Sciences, 2016), there has been no systematic effort to address the mismatch between a body of regulatory language designed for a static environment and a future context of extensive and ubiquitous species movement (Scheffers and Pecl, 2019).

The management and conservation of species is presently built on regulatory classification schemes that focus on the historical and/or existing ranges of species (e.g., "native" or "non-native"), consideration of the extent of past human instigation ("invasive," "introduced"), and the prevalence of the current population opaquely combined with cultural determinations of a species' significance (e.g., "invasive," "endangered"), (Executive Office of the President, 1999). Such retrospectively oriented classifications may become anachronistic when species ranges shift. Making matters worse, these regulations differ between jurisdictions, and jurisdictional boundaries matter because natural resources law is generally grounded in treating different types of lands as distinct from and largely unconnected to others. As a result, in many areas throughout the U.S., federal, state, local, and private entities own parcels of land arranged in checkerboard or more chaotic patterns, with concomitant differences in regulations (Camacho, 2011).

This "regulatory fragmentation" poses unprecedented challenges to coherent management across geographical regions and governmental scales. because, under a changing climate, the ranges of many species will shift far beyond where they are currently considered "native" or "protected," potentially across many administrative, state, and international borders (Dawson et al., 2011). Other species will move slowly or not at all, creating a landscape where ecological communities contain mixtures of "old native" species, "old invasive" species, and new species recently arrived via self-propelled, ostensibly "natural" dispersal or via direct (intentional or unintentional) human introduction. Experience from past natural and anthropogenic species introductions suggests that the ecological impact of new combinations of species is difficult to predict. Immigrant species that are rare in their current habitat might become common as they expand into new regions under novel future climates, or vice versa (Ricciardi and Simberloff, 2009). Newly arrived species might outcompete, prey upon, or otherwise harm "old native" species, or vice versa.

Here, we use illustrative scenarios to show how current regulatory language can become problematic, even paradoxical, when climate drives species out of their historical ranges. Our goal is to make regulatory fragmentation as visible to conservation biologists and strategists as habitat fragmentation, which is routinely used in the assessment and planning of species conservation (Dickson et al., 2017). Our approach is to use simple "climate envelope" projections of species range shifts, developed by us and others, not as predictions but as plausible scenarios, illustrating how far, and by which route, species might move under climate change this century. We then collate and interpret the set of laws and regulations that apply to species movement in the jurisdictions that the species crossed in our "migration" scenarios. This approach allows us to identify a set of likely unforeseen consequences of the current regulatory landscape. We believe that the types of regulatory paradoxes illustrated by our scenarios are likely to pose general problems in the near future, but we emphasize, for clarity, that the specific migratory pathways we delineate in this paper are only realistic scenarios. Actual migratory pathways will depend on the realized trajectory of greenhouse gas emissions, the actual climate response to those emissions, and many details missing from our model, like species interactions, dispersal barriers, etc., (Moritz and Aguda, 2013). Our analyses focus on the United States, but the broad issues of regulatory fragmentation under climate change apply in the regulatory context of most other countries and in trans-global governance as well (Trouwborst et al., 2015; Scheffers and Pecl, 2019; Somsen and Trouwborst, 2020).

POLICY IMPLICATIONS OF REGULATORY FRAGMENTATION

Regulatory Fragmentation Might Endanger Beneficial Taxa

Some current management rules might inhibit the movement of species considered by policymakers to be "beneficial," such as rare or vulnerable taxa. Harwood's woolly star (*Eriastrum harwoodii*), for instance, is a rare plant endemic to 31 populations in the Mojave Desert of California. Harwood's woolly star is protected on both state land and by federal agencies, such as the US Bureau of Land Management (BLM) in its historical range, thanks to its classification (rank 1B) by the California Native Plant Society (see **Supplementary Table 1** for details). The future geographic range of Harwood's woolly star will depend on the trajectory of regional climate; the details of the woolly star's physiology, demography, dispersal, etc.; and its interaction with other species, each of which is largely unknown. To illustrate the regulatory challenges faced by migrating species, however, we applied a simple but plausible range shift model to Harwood's woolly star under a moderate climate change scenario as a heuristic example (**Supplementary Document 1**). Under this scenario, the most likely 21st century migration route takes the species 240 km southeast into southern Arizona, where local habitat is projected to be similar that of its current range (**Figure 1**). Southward migrations under climate change can occur when the combination of local climate factors favoring species habitat outweigh the general tendency of warming to move habitat polewards (Rapacciuolo et al., 2014). The biological challenges of this range displacement will be augmented by the uneven standards of protection that result from regulatory fragmentation. Our estimation of its most likely migration route crosses 41 legal boundaries involving over a dozen state and federal entities (**Supplementary Table 1**), including a daunting shift into Arizona, which does not provide protections for rare species not listed under the US Endangered Species Act (ESA). Once it crosses state lines, this species has no protected status, even if it were to again settle on BLM land in Arizona (Bureau of Land Management, 2008; **Supplementary Table 1**).

While our modeled migration pathway is unlikely to be the exact route Harwood's woolly star takes this century, the fragmented landscape crossed by the woolly star in this example is typical of the piecemeal mixture of rules alternately protecting or obstructing newly arriving species that derives from varying definitions of terms like "native" across jurisdictions. In another example, the USFWS actively promotes reintroductions of native

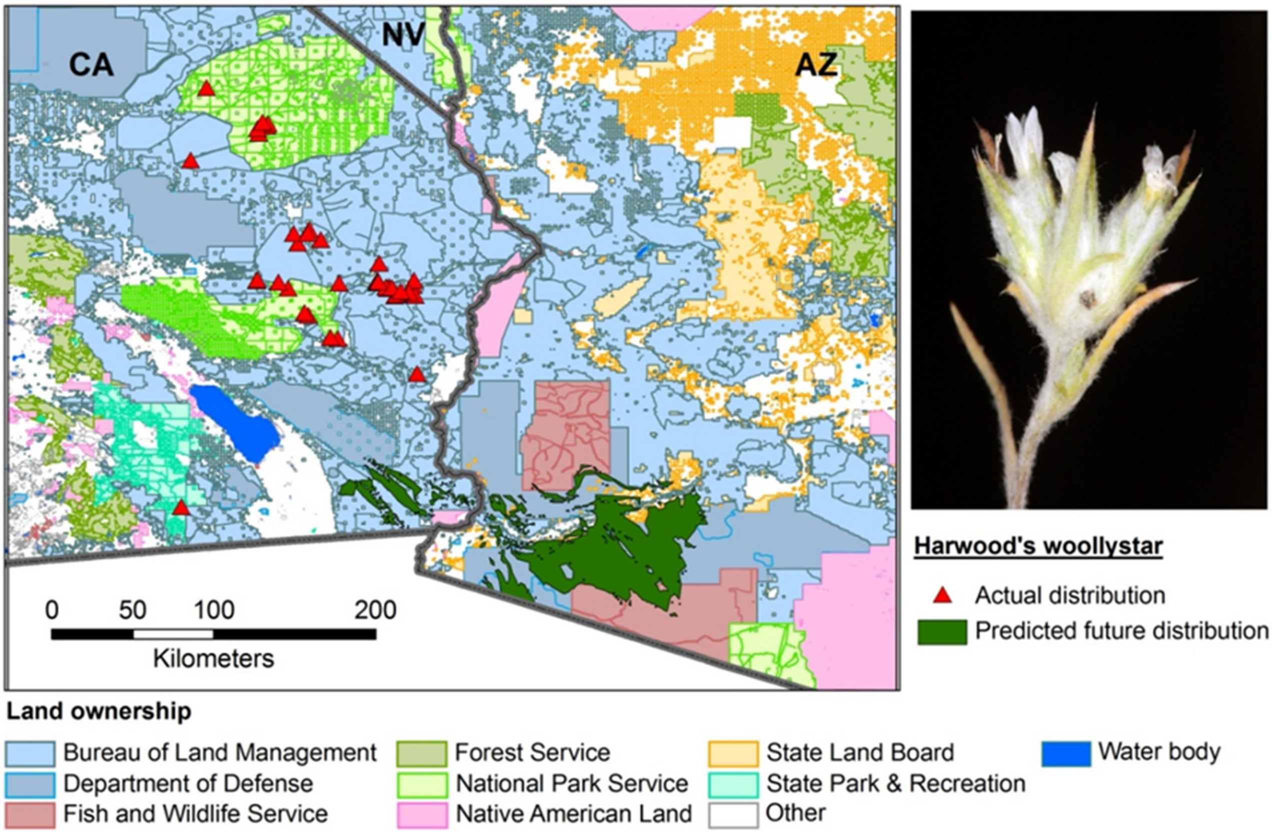

FIGURE 1 | Harwood's woolly star is currently endemic to California and protected on state and federal land. Under a moderate warming scenario, suitable habitat for this plant might shift to the southeast, forcing it to traverse a fragmented regulatory landscape. Populations arriving in Arizona might lose state and federal protection (see text).

species in US National Wildlife Refuges as long as they were not "naturally" extirpated, but it discourages such introductions for vulnerable non-native species unless essential and prescribed in an endangered species recovery plan (USFWS, 2021). This makes the status of "new natives," particularly those that are not listed as endangered, problematic. Even species listed under the ESA, often considered the highest level of protection in the US, face changing levels of protection as they traverse the fragmented regulatory landscape. For example, some protections against damage to a federally listed plant established on federal land disappear if the plant disperses to non-federal land (United States, 1983), making non-federal land a greater barrier to climate change-induced species movement. Finally, though wide-scale shifts in climatic conditions are likely to impose significant stress across taxonomic groups, such regulatory barriers do not apply equally across taxa: The legal barriers to movement under the Endangered Species Act for federally listed endangered plants on non-federal land, for example, are less than for federally-listed endangered animals (United States, 1983). It is possible of course, that such regulatory inconsistencies could be addressed by discretionary enforcement of contradictory rules, though that leads to additional complications, which we explore later.

Because active adaptation strategies, such as managed relocation, are already being discussed and used as a component of species conservation under climate change (Richardson et al., 2009), it is also important to consider the impact of direct human assistance on the regulatory status of spreading species. In most jurisdictions, if the governing authority determines that species moved by humans to minimize or mitigate the impact of climate change are "introduced," such species receive less regulatory protection and more regulatory resistance than if their arrival was not facilitated by direct human intervention. The National Parks Service, for example, defines and manages "exotic species" as "those species that occupy or could occupy park lands directly or indirectly as the result of deliberate or accidental human activities," while native species include "all species that have occurred, now occur, or may occur as a result of natural processes on lands designated as units of the national park system," (U.S. National Park Service, 2006). Thus, active management intended to preserve a species might paradoxically lead to lowered protective status for that species. Laws favoring purportedly "natural" migration over conservation-oriented human introduction are increasingly untenable in the context of a rapidly changing patchwork landscape that subjects wildlife to substantial physical and regulatory dispersal barriers.

Short of deliberately relocating taxa, some conservation biologists have advocated expanding the potential habitat for protective species to include either environments believed to have supported these species in the past, or environments deemed potentially suitable for species based on other inferences (Hiers et al., 2012). The regulatory complications identified above for managed relocation might also apply to efforts to expand conservation decision space by including habitats not currently occupied by the target species.

Regulatory Fragmentation Might Protect Harmful Taxa

Climate change also complicates regulations meant to inhibit harmful species movement. In many U.S. jurisdictions, only non-native species can be deemed "invasive" [e.g., Executive Office of the President (1999)], meaning that the ambiguous and inconsistent process of determining native status described above could result either in a policy of control or eradication of newly arrived climate refugees, or at the other extreme: in active protection. The existing paradigm for invasive species management focuses on prohibiting only certain blacklisted species. In the novel ecological communities created when "new natives" mix with "old natives," the difficulty of establishing such lists will be compounded by ambiguity about the status of "new natives" combined with the difficulty of assessing the acceptable impact of "new natives" in the context of novel ecological communities. These problematic aspects of determining "invasive" status in a dynamic biological setting thus raise the risk both of inhibiting the movement of species deemed beneficial and of facilitating the movement of species that may cause considerable harm. Making matters more troublesome for big-picture conservation and resource management policy, these contrary treatments could occur simultaneously in different jurisdictions depending on the laws, policies, and interpretations of different agencies or landowners.

Black locust (*Robinia pseudoacacia*), a native tree in the Ozarks and southern Appalachians, is identified as an ecological threat in the Upper Midwest, due primarily to its habit of establishing dense groves that exclude native vegetation (Hoffman and Kearns, 1997). Eight states in the eastern US consequently have laws or regulations limiting the movement of black locust, or encouraging its eradication (see **Supplementary Document 1**). In Wisconsin, black locust is listed as a "restricted" invasive species, mandating a statewide plan for controlling the species, including prohibitions on the transport, possession, transfer, or introduction of the species (**Supplementary Document 1**).

Ironically, in projections of the habitat range of black locust under a high greenhouse gas emissions scenario, black locust is projected to become rare or extinct in the western range of its native habitat by 2,100, shifting its primary habitat to Northeastern and Midwestern states, including states where it is currently considered invasive (**Figure 2**; Peters et al., 2020). Given this possibility, and the logic of the Harwood's woolly star example in the previous section, it might be reasonable to ask whether such states might wish to have a mechanism for reclassifying former invasive as "new" native species.

Alternatively, a tempting argument for continuing efforts to curtail migration of black locust in the Northeast and Midwest, even should a scenario like that depicted in **Figure 2** unfold, might be that it has a proven record of negative impact on "old native" species. Such an argument, handily distinguishing a "good" new native like Harwood's woolly star, from a "bad" new native like black locust, ignores the fact that climate change of the magnitude predicted for this century has historically disrupted "old native" communities and shifted biomes (Williams et al., 2004). Might a policy of continued black locust eradication in Wisconsin look as non-sensual to future generations as it would for us to consider black spruce to be "invasive" in formerly glaciated Canada, and "native" in the Southeastern US, where it thrived in glacial times (Williams et al., 2004)? And what if black locust were to become in danger of extinction in parts of its historical range, as it does in the southern Ozarks in the scenario depicted in **Figure 2**? In fact, USFWS might be required to list black locust if it were likely to become at risk of extinction in the foreseeable future in any significant portion of its range. Fundamentally, the regulatory context for species shifting geographically under climate change should play a larger role in discussions about the conservation challenges posed by the Anthropocene (Corlett, 2015).

"Soft" Language Allows Flexibility, With the Potential for Mixed Consequences

We looked closely at the suite of regulations relevant to the projected movement of Harwood's woolly star and determined that management action is often contingent on soft language potentially allowing management flexibility (**Supplementary Table 1**). For example, the Department of Defense monitors and controls invasive species "whenever feasible" (Department of Defense, 2011), and the United States Forest Service strives to prevent, control, and/or manage invasive species in National Forests "as appropriate" (USDA, 2004). In our projected displacement of Harwood's woolly star, the most protective interpretation of existing regulations would mean that the species would remain under either proactive or, at least, passive protection by land managers for 55% of its route, leaving over 100 km of its journey transiting across land where it is neither protected or actively discouraged (**Figure 3**). Under the least protective interpretation of regulatory language, where state or federal agencies determine that Harwood's woolly star is non-native and is determined to cause harm to existing taxa, managers could decide to actively control or eradicate species like Harwood's woolly star along half of its projected migration route.

Such soft language *could* work to the benefit of regional management. In some cases, such discretion might allow

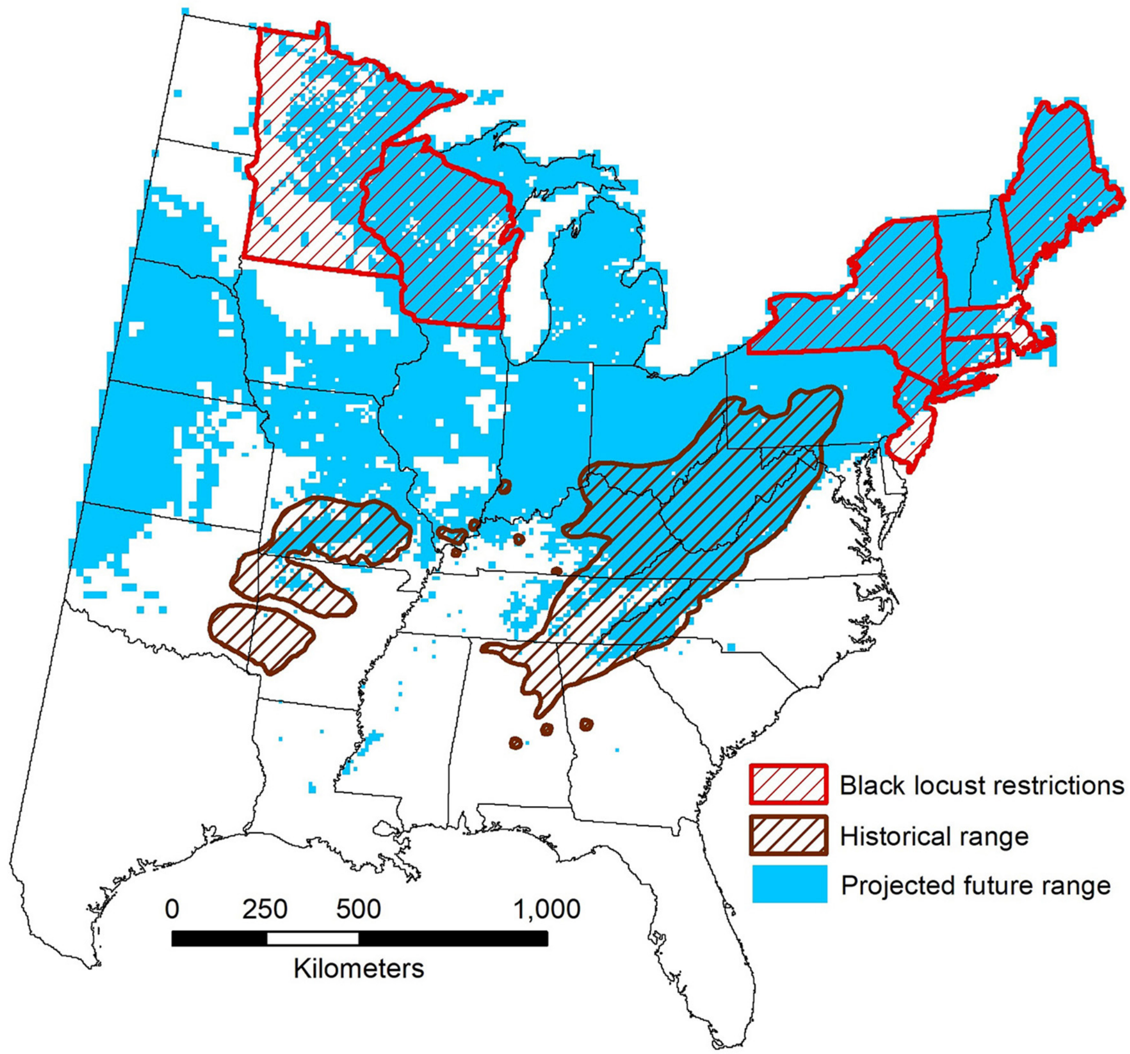

FIGURE 2 | Historical native range (brown polygon) of black locust and its projected future range under a high greenhouse gas emission scenario (blue polygons, Peters et al., 2020). Each state highlighted in red has laws or regulations that require active eradication measures or otherwise restrict the movement of the species (see **Supplementary Document 1**).

administrators to avoid inconsistencies and paradoxes associated with a strict interpretation of laws regulating species movement. For instance, this soft language allows breathing room for new efforts fostering greater collaboration between jurisdictions, such as the Landscape Conservation Cooperatives and large-scale multi-species Habitat Conservation Plans (Wilhere, 2002; National Academies of Sciences, 2016). However, reliance on vague regulatory language—originally developed largely to arrest movement rather than to facilitate it—will only provide temporary reprieve. Concrete legislative or regulatory guidance rooted in the dynamic nature of species conservation would ultimately create greater consistency and long-term viability of conservation under changing climate. While providing land managers discretion may allow for the adjustment of management to account for changing conditions and new information in localized contexts, placing the burden of controversial normative decision making on local managers who are often under-resourced, constrained by strict performance targets, and subject to local pressures is unwise.

ACTIONABLE RECOMMENDATIONS AND CONCLUSIONS

Existing regulatory language, processes, and structures meant to protect beneficial species and deter harmful species will become increasingly problematic as climate changes this century. A new regulatory infrastructure is required to promote long-term ecological function and biodiversity in the face of wide-scale pressure from climate change. Not only the substantive

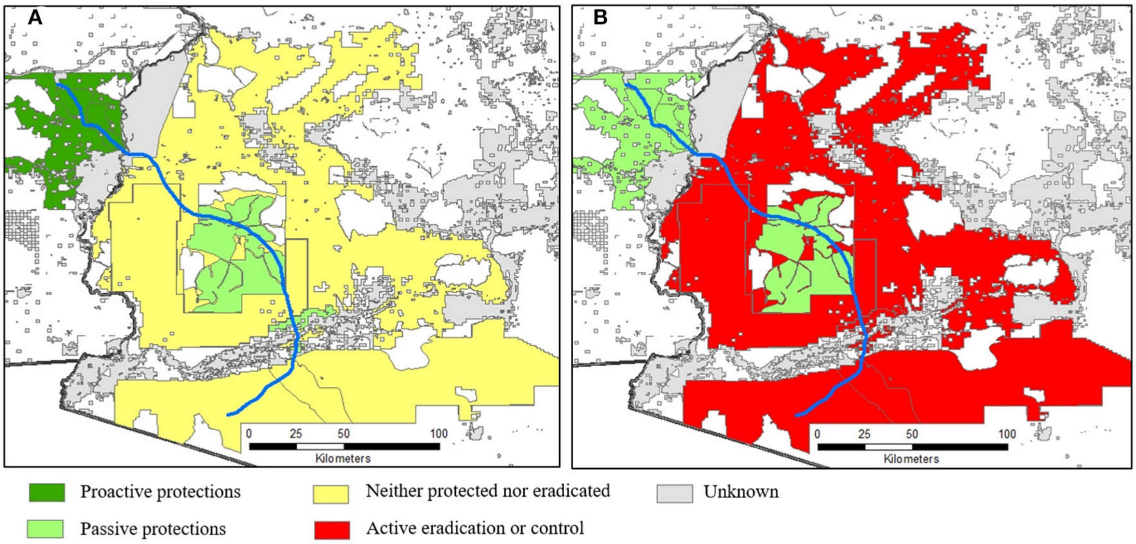

FIGURE 3 | Regulatory status of Harwood's woolly star in jurisdictions along a plausible climate-driven migration route (blue line): **(A)** Under the most protective interpretation of relevant regulatory language; **(B)** Under the most restrictive interpretation of relevant regulatory language (see **Supplementary Table 1**).

strategies, but also the processes and institutional structure of ecosystem governance, must be reshaped—recognizing that such changes will undoubtedly pose fundamental ethical questions for conservation governance.

First, the *substantive* standards governing species movement need to be reframed away from categorical dualisms like native/non-native and introduced/natural that dominate the law and policy. Classifications like "native" and "invasive" have long provided simple, though occasionally controversial (Somsen and Trouwborst, 2020), guidelines for normative decisions about which species are and should be locally promoted or impeded. The current regulatory paradigm emphasizes the preservation of historical conditions and the minimization of human intervention, but these goals are becoming increasingly at odds with each other. Moreover, these standards will be increasingly untenable as species make essentially permanent range shifts accompanying climate change.

Accordingly, it is important to immediately begin the difficult task of establishing new standards. Rather than a myopic focus on promoting native species and minimizing active management, laws and policies should be reoriented to promote beneficial and discourage harmful movement. This necessarily means increased emphasis on ecological health over historical and wildness preservation objectives in conventional conservation strategies like ecosystem-based and landscape-level conservation planning, species recovery planning, or even private land management incentives to increase or decrease permeability (Kostyack et al., 2011). Yet advancing ecological health in the face of landscape-level climatic change will likely require employment of active interventions such as assisted migration, biotechnological strategies (Camacho, 2020), and reconsideration of invasive management strategies.

For instance, the President might update Executive Order 13,112 and 13,751 to define "invasive species" to remove the requirements of being both non-native and introduced. Static regulatory designations of species as native or non-native will primarily be useful as rebuttable presumptions in cautious risk assessment of species movement in increasingly non-static natural environments (Camacho, 2015). In other words, active translocation strategies like assisted migration under laws like section 10(j) the ESA as well as in Federal land agency regulatory guidance might rely on risk assessments that include rebuttable presumptions that (1) the movement of an ecological unit is appropriate in locations where it already exists or existed, and (2) immigration or intentional translocations to areas outside a species' historical or current range is not appropriate. In some contexts, policymakers might instead remove distinctions between, for example, "introduced" and "natural" movement completely when such a distinction provides little guidance for when species movement might be beneficial or harmful.

We unequivocally acknowledge, however, that determinations of what are beneficial or harmful movements are value laden and contextual. Science and management expertise alone cannot solve the problem. To be sure, policymakers will need to work closely with scientists and local managers to develop and implement measurable criteria that balance the increasingly competing goals of preservation and biodiversity in the broader framework of promoting ecological function at broad scales. Ongoing efforts by biologists, climate scientists, and social scientists to improve forecasts of the species composition of future ecological communities will, of course, be vital (Blois et al., 2013; Bonebrake et al., 2018) as will continued scientific progress defining and analyzing the ecological targets of conservation, like "biodiversity" and "ecosystem health," which remain contestable and elusive. General principles of invasion biology, like the set of biological traits linked to "weediness" will be worth considering in establishing rules and priorities for managing novel communities. Conservation scientists and managers must increasingly direct their efforts toward characterizing the value of ecological phenomena and the metrics of operationalizing values of ecological constituents, processes, and systems in the context of the tradeoffs raised by resisting, allowing, or assisting species movement (Camacho, 2020).

Yet even a vast reduction in scientific uncertainty will not clarify the difficult ethical and ultimately political questions raised by climate change's effects on biodiversity. Under the scenario posed in **Figure 2**, for instance, current regulations would prioritize "old native" species over "new natives" in an increasingly untenable way. Improved scientific understanding (of climate trajectories, of the demography and ecology of "new natives," etc.) cannot by itself resolve this problem. Laws must address if and how species that move into new jurisdictions under climate change will be encouraged or controlled, and they must address the likely scenario that "native" communities will be different in the future. If legislators determine that humans should take an active hand in protecting species from the ravages of climate change by introducing them to new habitats, it will no longer make sense to deem such "introduced" species less worthy of protection in their new homes. Such decisions are fundamental value choices that raise tradeoffs that not only require the input of the resource management and scientific communities. More importantly, they necessitate thoughtful and inclusive public deliberation through the democratic process.

Accordingly, ensuring robust conservation governance *processes* is at least as important an endeavor for conservation law in the Anthropocene. Federal and state legislatures in the U.S. must reevaluate not only the ends but also the means of species management policy under climate change. New dynamic and adaptive processes and institutional authority are needed for managing species as they move across jurisdictional boundaries (Camacho, 2020). This includes integration of adaptive species movement management in, for example, ESA recovery planning and habitat conservation planning for listed species, federal land management planning, and state wildlife action plans for other vulnerable species.

Climate change also raises deep *structural* and institutional concerns about the continued efficacy of fragmented species management institutions in the United States. But it also provides an opportunity to reimagine species conservation in ways that recognize and mediate linkages between artificially disparate jurisdictions through tailored reallocations or coordination of authority (Ruhl and Salzman, 2009; Craig, 2010; Camacho and Glicksman, 2019). Coordinating institutions particularly over information dissemination and generation, planning, and implementation may help reconcile disparate regulations among the many local, state, and federal jurisdictions. Yet an increased federal presence over funding and standard setting over wildlife movement may increasingly be necessary to minimize transboundary harms, promote harmonization, and leverage economies of scale while maintaining the expertise, diversity, and experimentation advantages of still primarily decentralized authority (Camacho, 2020). More fundamentally, a meaningful democratic dialogue about the goals, procedures, and structures of species management in a changing world is needed to foster regulatory species management policies that are as complex and dynamic as the threats to ecological function and diversity presented by a rapidly changing climate.

AUTHOR CONTRIBUTIONS

AC and JM contributed equally to the conceptualization and writing of the manuscript. JM designed the geographic analyses. AC led the collation and analysis of the laws and regulations. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.735608/full#supplementary-material

Supplementary Table 1 | Regulatory classification for Harwood's woolly star under climate-driven migration scenario.

Supplementary Document 1 | Details of climate shift scenarios and regulations restricting black locust in U.S. eastern states.

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This Is the Way the World Ends, Not With a Bang but Bonds and Bullets

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This article explores instinctive frames of human decision-making in environmental and resource economics. Higher-moment asset pricing combines rational, mathematically informed economic reasoning with psychological and biological insights. Leptokurtic blindness and skewness preference combine in particularly challenging ways for carbon mitigation. At their worst, human heuristics may generate perverse decisions. Information uncertainty and the innate preference for bonds-and-bullets portfolios may impair responses to catastrophic climate change.

Keywords: skewness, kurtosis, information uncertainty, irreversibility, environmental economics, asset pricing, portfolio theory, behavioral economics

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1. INTRODUCTION

Climate change confronts humanity with the prospect of catastrophic harm. Indeed, the threat is sufficiently grave that it should be regarded as existential. Homo sapiens numbers among the species that the sixth great extinction of the Phanerozoic Eon may erase (Wake and Vredenburg, 2008; Ceballos et al., 2017).

Catastrophic climate change stems from human activity. The anthropogenic contribution to this calamitous state of affairs, however, also includes innately human frames for evaluating risk and making decisions under uncertainty. This article seeks to examine human decision-making and its impact on humanity's prospects for averting a climate catastrophe of its own device.

Environmental economics highlights the impact of emotion and cognitive bias on risk assessment and management. Like mathematical finance, environmental policymaking is a species of risk management. The treatment of physical uncertainty and behavioral heuristics in environmental economics differs from comparable factors in traditional finance more in degree than in kind. This article therefore evaluates the greatest challenge in environmental economics according to the tools that traditional finance applies to valuation problems.

Specifically, this article applies higher-moment asset pricing and related financial principles to problems in environmental and resource economics.

Part 2 of this article describes a higher-moment capital asset pricing model, or CAPM+. The Taylor series expansion of expected financial returns enables a generalization of conventional asset pricing models from its reliance on mean and variance to higher statistical moments. By extending financial analysis to skewness and kurtosis, higher-moment asset pricing harmonizes financial economics with prospect theory, a popular model of behavioral economics.

Avoiding catastrophic climate change can and should be evaluated as a valuation problem. Although environmental economics routinely requires the valuation of natural resources, including ecosystem services, explicit reliance on the CAPM and mathematically related models is less familiar. To bridge this gap, part 3 contextualizes CAPM+ and related aspects of environmental economics, particularly the spread between willingness to pay and willingness to accept.

After defining the difference between probabilistic risk and aleatory uncertainty, part 4 describes how uncertainty generates tension within foundational works in environmental economics. In earlier work with Robert Lind, Kenneth Arrow originally argued that the government's unique ability to absorb and finance risk permitted a purely risk-neutral approach to environmental decision-making. In later work with Anthony Fisher, however, Arrow acknowledged that irreversible commitments of resources might warranted a more circumspect approach. Evaluations of risk and uncertainty in environmental economics must account for this contradiction.

Part 5 describes an evidently universal set of financial preferences in the face of uncertainty. Psychologically informed models based on the work of Abraham Maslow predict that humans will respond differently to risk as they ascend a perceived hierarchy of needs and aspirations. In practical terms, higher-moment asset pricing of ecosystem services leads to an innate pairing of subsistence measures with highly speculative responses to threats perceived as remote.

The resulting "bonds-and-bullets" approach, this article concludes, bodes ill for effective responses to climate change and other challenges of the Anthropocene. Human psychology predisposes this species against preemptive, preventive mitigation measures, in the hope that miraculous feats of geoengineering may eventually prevail.

2. HIGHER-MOMENT ASSET PRICING

2.1. The Taylor Series Expansion of Expected Logarithmic Returns

The conventional capital asset pricing model (CAPM) seeks to describe the cost of capital for firms and asset allocation choices by investors. In its canonical formulation, the CAPM relies principally upon the optimization of mean return relative to the variance of the market-wide portfolio (Fama and French, 2004). Among its many flaws, however, the CAPM fails to reflect human behavior (Shefrin and Statman, 1994).

A higher-moment capital asset pricing model may be derived from the Taylor series expansion of the logarithm of expected returns. Higher-moment CAPM (or CAPM+), once paired leading behavioral accounts of economics, explains seemingly "irrational" phenomena such as skewness preference and the bonds-and-bullets structure of financial decision-making.

A four-moment variant of CAPM+ is expressed in terms of mean, variance, skewness, and kurtosis (Jurczenko and Maillet, 2012). It can be derived from the Taylor series expansion of logarithmic returns from a continuously compounded financial series (Harvey and Siddique, 2000, p. 1269; Jondeau and Rockinger, 2006, p. 33; Harvey et al., 2010, pp. 469–470):

1. Let us express continuously compounded financial returns in logarithmic form:

$$r_t(k) = \ln\left[1 + R_t(k)\right] = r_t + r_{t-1} + \ldots + r_{t-k+1}$$

2. The Taylor series expansion approximates $f(x)$ at $x = a$:

$$f(x) \approx f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \ldots$$

3. The expansion of $f(x) = \ln(1 + x)$ at $x = \mu$ expresses that function in terms of mean, variance, skewness, and kurtosis:

$$f(x) \approx \ln(1+\mu) + \frac{x-\mu}{1+\mu} - \frac{(x-\mu)^2}{2(1+\mu)^2} + \frac{(x-\mu)^3}{3(1+\mu)^3} - \frac{(x-\mu)^4}{4(1+\mu)^4} + o[(x-\mu)^5]$$

where $o[(x-\mu)^5]$ represents the fifth order and other remaining terms.

The formulation in ¶ 3 exhibits an alternating pattern of positive and negative signs. Modest assumptions such as positive marginal utility and decreasing risk aversion support this summary of CAPM+: Humans prefer high values for odd-numbered moments (mean and skewness), but low values for even-numbered moments (variance and kurtosis) (de Athayde and Flôres, 2004, p. 1336; Estrada, 2004, p. 241; Jondeau and Rockinger, 2006; Brunnermeier et al., 2007; Bali et al., 2011, p. 33). This trait enables higher-moment asset pricing models to provide effective guidance in advanced portfolio design and hedged trading applications (Brooks et al., 2012; Knif et al., 2020).

Exploring moments beyond variance explains many of the *descriptive* failures of conventional financial theory. The welfare implications of higher-moment asset pricing stem from disparate investor reactions to odd- and even-numbered moments. *Behavioral* departures from strict rationality begin with skewness, the first odd-numbered moment beyond variance. Kurtosis is properly associated with epistemic failures, with the inability to predict (let alone adapt to) previously unobserved phenomena. Consequently, skewness and kurtosis heavily influence environmental and resource economics.

Skewness preference arises when investors privilege skewness (the third moment) over expected return (the first). This departure from conventional rationality may represent the most obvious application of CAPM+. A wide range of behaviors of interest to various bodies of financial regulation reflects skewness preference: lotteries, prize-linked savings, private equity, crowdfunding, and initial public offerings. A preference for skewed outcomes, especially when the expected return is zero or negative, underlies many economic conditions thought to warrant regulatory intervention.

2.2. Flagging Prospect Theory

Especially in the cumulative formulation that acknowledges first- and second-order stochastic dominance, prospect theory gives behavioral meaning to skewness preference and its fourth-moment counterpart, leptokurtic blindness or insensitivity (Kahneman and Tversky, 1984; Tversky and Kahneman, 1992). Although Daniel Kahneman and Amos Tversky relied on a two-piece utility function to define prospective theory's value

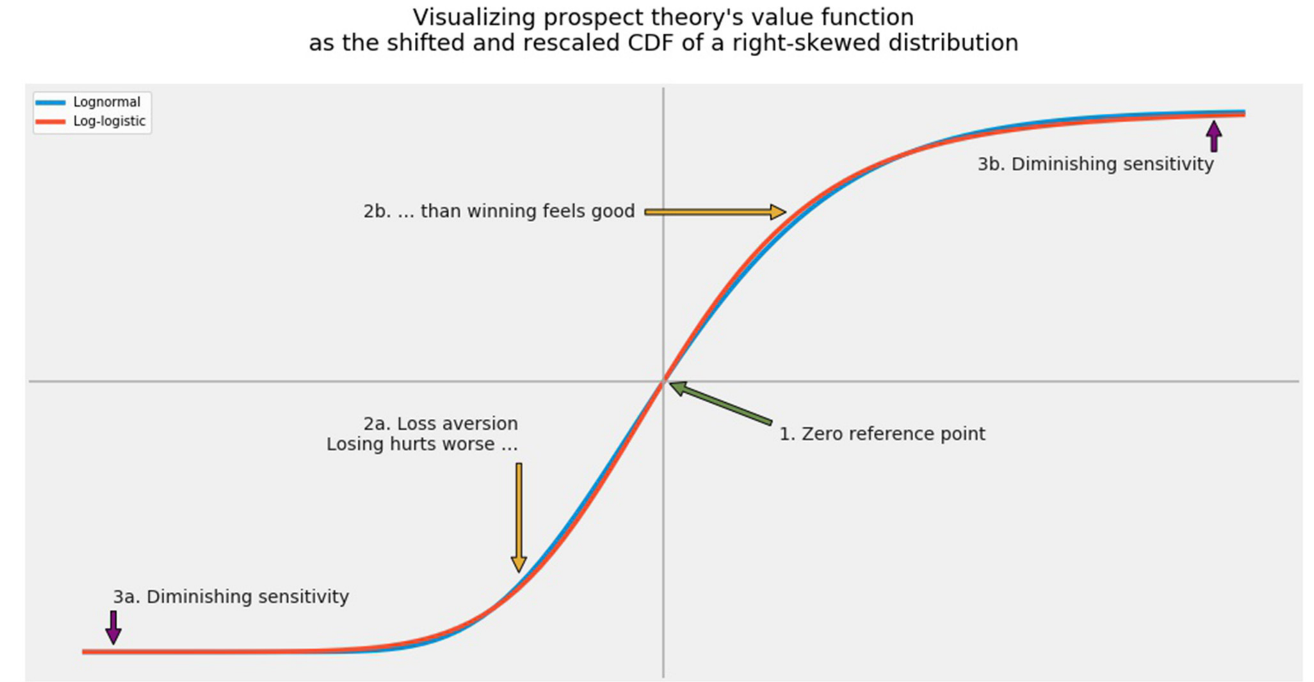

FIGURE 1 | Visualizing prospect theory as the cumulative distribution function of a right-skewed probability distribution.

function, the cumulative distribution function of a right-skewed distribution such as the lognormal or the log-logistic illustrates all of that function's important properties.

Figure 1 displays three important properties of human decision-making under uncertainty. First, humans evaluate all decisions according to a fixed reference point. Second, humans are averse toward losses. All else being equal, losing hurts worse than winning feels good. Third, humans over time become less sensitive to changes in utility, no matter whether such changes are gains or losses. "If prospect theory had a flag," the banner in **Figure 1** would depict those three principles (Kahneman, 2011, p. 282).

Although volatility figures prominently in nearly every model in mathematical finance, even-numbered moments are harder to interpret. Starting with variance, however, finite higher moments cannot be assumed. If, as has been hypothesized for nearly six decades, financial returns follow a stable Paretian distribution (Fama, 1963, 1965; Ortobelli and Rachev, 2001), even variance (and, *a fortiori*, higher moments) may be infinite. This analytically debilitating mathematical property stems from the definition of a generalized Pareto distribution (Castillo and Hadi, 1997; Gençay and Selçuk, 2004, p. 291–292).

Leptokurtosis may be the most tractable statistical representation of tail risk and epistemic blindness. It provides a statistical basis for the longstanding distinction between probabilistic risk and aleatory uncertainty. Leptokurtosis likewise describes prospect theory's phenomenon of diminishing sensitivity at each extreme. These treatments of the fourth moment provide a mathematical bridge between rational and behavioral accounts of economic decision-making. This unity arises because human perception becomes duller precisely where information, as an empirical matter, becomes less attainable.

Combining these insights with behavioral finance explains the prevalence of "bonds and bullets" wealth allocations in numerous economic circumstances. Bifurcating even-numbered moments reveals the mathematical congruence between two seemingly divergent economic instincts. When forced to confront the loss of basic means of survival, humans do focus on downside risk. But once hope meets fear, even risk averse individuals will entertain upside gambles. Merging these insights expands the mathematical toolkit of finance and environmental economics.

3. HIGHER-MOMENT ASSET PRICING IN AN ENVIRONMENTAL CONTEXT

3.1. Matters of Housekeeping

Part 2 suggests how higher-moment asset pricing might affect environmental and resource economics. The Taylor series expansion of logarithmic returns counsels against simplistic reliance on the naked magnitude of expected gain or loss. Higher-moment pricing and valuation models reveal the opposite effects of odd- and even-numbered moments. But another boundary looms between mean and variance, on one hand, and the paucal moments of skewness and kurtosis. The most potentially treacherous decisions under uncertainty respond to internal asymmetry and extremity within the distribution of returns.

Ernst Haeckel is credited with introducing the term *ecology* from *OiKOÇ*, the ancient Greek word for house (Gould, 1977, p. 76 n.*). *Economics* and *economy* share the same root. By uniting human *economy* with natural *ecology*, environmental economics defines housekeeping in both social and biological terms (Caradonna, 2014, pp. 112–113).

Law and policy give voice to the idea of ecology as housekeeping through sustainability and the precautionary principle (Cameron and Abouchar, 1991; McIntyre and Mosedale, 1997; Sand, 2000). The definition of sustainability, at least, is contestable. The narrowest definition of environmental sustainability stems from strict notions of the human ecological footprint, which in turn dictate a definition of sustainability according to physical flows of energy and matter (Heal, 2012).

By contrast, the Hartwick principle holds that renewable environmental resources, non-renewable resources, and capital investments are subject to exchange (Hartwick, 1977). Because the Hartwick principle directly compares physical energy flows with financial returns, it is the starting point for any application of financial economics to environmental topics (Gowdy and McDaniel, 1999).

3.2. Contingent Valuation of Biodiversity and Ecosystem Services

Contingent valuation of ecosystem services is central to policy regarding climate change mitigation and related questions of natural resource economics (Carson et al., 2001; Champ and Bishop, 2001; Poe et al., 2002). Skewness preference and pricing premiums associated with uncertainty and kurtosis beset ecological valuation.

Perhaps the most striking application of higher-moment asset pricing to the valuation of ecosystem services involves biodiversity conservation, including the politically salient and controversial subfield of bioprospecting (Chen, 2014). A more outlandish instance of skewness preference in natural resource economics can scarcely be imagined. If the logic of bioprospecting is stretched to its absurd extreme, Costa Rica's biodiversity is worth saving only to the extent that endemic organisms with pharmaceutical potential can be profitably exploited.

Disputes over bioprospecting and its rhetorically rude cousin, "biopiracy" illustrate an extension of the rank effect from behavioral finance to resource economics. According to the "rank effect," investors are likelier to sell their extreme winning and losing positions, even without considering the economic fundamentals of any firm in the portfolio (Hartzmark, 2015). Focusing exclusively on the best and worst positions, wholly without regard to the actual level of returns effectively ignores the rest of the portfolio (*ibid.*). Biodiversity, to say the least, vastly exceeds the genomic profitability of species of greatest commercial interest to humans.

3.3. Willingness to Pay vs. Willingness to Accept

Disaster law as a specialized branch of environmental law emphasizes downside risk and uncertainty (Chen, 2011). This emphasis highlights an anomaly in environmental economics. Stated preference studies often strive to quantify *either* respondents' willingness to pay (WTP) for environmental enhancements *or* their willingness to accept (WTA) compensation for environmental degradation.

Neoclassical economic theory presumes that WTP and WTA quantities should be equivalent. Experimental outcomes suggest otherwise. There is a considerable premium for willingness-to-accept compensation in cases of degradation, relative to willingness-to- pay bids in cases of enhancement (Hanemann, 1991; Shogren et al., 1994; Sayman and Öncüler, 2005). In addition, both WTA and WTP distributions are quite wide, in the sense their standard distributions are quite often multiples of the mean amount. This appears to be an artifact of numerous 0 responses in WTA surveys (Amigues et al., 2002, p. 25) and high bids in WTP surveys (Sillano and de Dios Ortúzar, 2005, p. 540).

The obvious behavioral explanation for the WTA/WTP premium lies in the endowment effect (Kahneman et al., 1990) and the closely related notion of myopic loss aversion (Benartzi and Thaler, 1995). Because losing hurts worse than winning feels good, willingness to accept on the downside should be expected to exceed willingness to pay on the upside. Behavioral accounts of finance, however, should never be detached from economic fundamentals (Zhang, 2005, p. 69). That admonition suggests that the WTA/WTP premium reveals more nuanced human judgment. That judgment is consistent with higher-moment asset pricing and related ideas of liquidity preference and comovement among asset classes.

Static, unconditional models of finance assume that agents live no longer than a single period (Merton, 1973). As a descriptive matter, this assumption is demonstrably false. Worse, the single-period assumption is normatively deficient, even morally repellent. One need not embrace notion of "deep ecology" to reach this prescriptive conclusion (Naess, 1988). Even Hartwick's rule of weak sustainability demands a commitment to compensate future generations for immediate consumption of exhaustible resources.

The WTA/WTP premium is most pronounced in two settings. First, there is a significant premium for public and non-marketable goods relative to "ordinary" goods readily available in private markets (Horowitz and McConnell, 2002). Second, consumers demand a high premium for goods whose future, contingent value is currently uncertain (Zhao and King, 2004).

In concert, the presence of a large premium in these contexts reveals an awareness (or at least an intuition) that assets have value only relative to the broader state of the economy. These principles suggest that instruments of exchange and storehouses of value within the *human economy* have worth only relative to the biological and abiotic condition of *global ecology*.

Under conditions of relative abundance and stability, Hartwick's assumptions regarding exchangeability and frictionless intergenerational bargaining may hold. In a manner of speaking, Merton (1973) meets Coase (1960). But finite carrying capacity and the potential disruption of physical flows within ecosystem services serve stern notice that the ecological basis of human economy cannot be treated as static and permanent. The premium for willingness to accept over willingness to pay thus represents the environmental equivalent of the liquidity and equity risk premiums in behavioral finance.

3.4. From Information Uncertainty to the Psychology of Bonds and Bullets

The balance of this article will address two additional aspects of higher-moment thinking in environmental economics. At this pivotal stage, a brief preview of parts 4 and 5 is warranted.

First, innate reactions to dispersion, ambiguity, and uncertainty are the domain of even-moment effects within CAPM+. In environmental economics, these effects explain the progression from the Arrow-Lind theorem of risk-neutral public investment to Kenneth Arrow's own partial repudiation of his own work in later work with Anthony Fisher. The tension in these treatments of information uncertainty leads naturally to the dismal theorem, which arises from the work of William Nordhaus, Martin Weitzman, and other economists evaluating the costs of anthropogenic climate change.

Second and perhaps even more pressingly, the ultimate question is how humans will handle ecosystem services and the terrestrial life support systems under attack in the Anthropocene. Highly risk-seeking behavior has been observed in settings such as subsistence farming and diamond mining. Wealthy actors are engaging in similar "shots-at-greatness" behavior with respect to fossil fuel and climate change policy. Because these preferences reflect expectations of high levels of kurtosis, higher-moment asset pricing helps explain why "bonds-and-bullets" portfolios have such universal appeal. Less optimistically, CAPM+ suggests that this heuristic approach to managing risk may disserve humanity in a moment of existential exigency.

4. UNCERTAINTY AND LEPTOKURTIC BLINDNESS

4.1. Probabilistic Risk vs. Aleatory Uncertainty

Purchases and sales within an exchange economy constitute a "central nervous system" (Supreme Court of the United States, 1940, p. 225, n. 59). Finance analyzes the market for capital to support speculative undertakings (Supreme Court of the United States, 1935, p. 689 [Stone, J., dissenting]). Prices as tools for transmitting economic knowledge within a collective "wisdom of prices" (Hayek, 1937, 1945; Grossman and Stiglitz, 1980).

An efficient capital market's very *raison d'être* is to reward investors who assume the risk of entrepreneurial failure (Ross, 1976). Indeed, the "first law of finance" dictates that excess return over a risk-free asset should correspond to volatility (Anderson et al., 2009, p. 233). Legal authorities recognize that abnormal returns are associated with elevated risk (Supreme Court of the United States, 1909, p. 49).

In environmental settings as elsewhere, the basic problem of finance becomes difficult, perhaps even intractable, when the investment horizon stretches into an indefinite future. Even without regard to temporal scales, risk management becomes virtually impossible where risks are poorly perceived and probabilities cannot be accurately estimated (Farber, 2011, p. 906).

A useful point of departure is "the impact of uncertainty on the behavior of investors and, ultimately, on market prices" (Campbell et al., 1997, p. 3). Knight (1921, pp. 19–20) and Keynes (1937, pp. 213–214) first recognized the theoretical difference between quantifiable, statistical risk and unknowable uncertainty. Situations where statistical probabilities can influence decision-making stand apart from truly aleatory circumstances where information is so vague that it eludes quantification (Epstein and Wang, 1994, p. 283; Runde, 1998, p. 539).

Uncertainty affects all economic activity (Bloom, 2009; Bachman et al., 2013; Baker et al., 2016), from household savings (Giavazzi and McMahon, 2012) and government borrowing (Pástor and Veronesi, 2012, 2013) to investment across the real economy (Born and Pfeifer, 2014; Fernández-Villaverde et al., 2015). When uncertainty clouds the economic outlook, risk averse consumers are the likeliest to realize option value from publicly supplied goods and services (Weisbrod, 1964; Cichetti and Freeman, 1971).

Ambiguity surrounding information affecting firm valuation has a powerful tendency to cast capital markets into uncertainty (Zhang, 2006, p. 105). Uncertainty exacts a far steeper toll on the downside, and not merely because the prospect of loss ground terrifies human decisionmakers. Coercion, after all, arises from "[t]hreat of loss" and not from "hope of gain" (Supreme Court of the United States, 1936, p. 82 [Stone, J., dissenting]). Economic retreat, whether attributable to an economy-wide recession or to bad news affecting an isolated sector or even a single firm, necessarily throttles the flow of information among buyers and sellers (Bloom, 2014, p. 162).

4.2. A Formal Model of Information Uncertainty

In all settings, economic agents prefer "known rather than unknown or vague probabilities" (Epstein and Wang, 1994, p. 284). Difficulty in judging the quality of information leads agents to "treat signals as *ambiguous*" (Epstein and Schneider, 2008, p. 197). All risk premiums rise alongside information uncertainty as investors ponder the probability of default, the amount at stake in potential business failures, transaction costs associated with bankruptcy, and even the size of the default premium itself (Christiano et al., 2014).

A specification of information uncertainty proceeds in two steps. First, an observed financial signal, or s, can be defined simply as $s = v + e$, where v indicates fundamental value implied by future cash flows or dividends, and e represents error or noise (Zhang, 2006, p. 105 n.2).

The second step consists of measuring the variance of the observed signal. Combining the variance of the firm's underlying volatility, or $\text{var}(v)$, with $\text{var}(e)$, the variance of the error term as an indicator of informational quality, enables information uncertainty to be expressed formally: $\text{var}(s) = \text{var}(v) + \text{var}(e)$ (*ibid.*). This second formula recognizes the possibility that variance in cash flow or a series of returns may reflect not only fundamental economic variance, but also an additional premium based on information uncertainty.

The human reaction to uncertainty profoundly affects valuation and pricing. When agents face information uncertainty on top of risk, "they demand a higher premium" (Anderson et al., 2009, p. 234). This expression formalizes the relationship between risk and uncertainty (*ibid.*, pp. 234–235):

$$\mathrm{E}_t\, r_{e,\,t+1} = \gamma V_t + \theta M_t$$

where E designates the expectation operator, r_e indicates excess return over the risk-free baseline, V indicates market-wide conditional volatility, and M measures uncertainty throughout the economy. The temporal indexing variable t governs all of these variables as well as the expectation operator.

γ and θ, the coefficients in the foregoing formula, indicate aversion, respectively, to risk and uncertainty. Positive values for γ as well as θ imply that a positive premium for both risk and uncertainty (*ibid.*, p. 234). In other words, investors will demand compensation bearing unknowable uncertainty as well as predictable risk. The expression, $E_t\ r_{e,\,t+1} = \gamma V_t + \theta M_t$, should therefore be understood as a special instance of the more general formula, $\mathrm{var}(s) = \mathrm{var}(v) + \mathrm{var}(e)$.

In all events, it is crucial to distinguish between a fundamental economic signal ($s = v + e$) and information uncertainty as the sum of variance in informational quality and variance in the signal itself [$\mathrm{var}(s) = \mathrm{var}(v) + \mathrm{var}(e)$]. The variability in many signals may stem from different sources of information, some less quantifiable than others. Uncertainty along economic, legal, scientific, and technological dimensions raises the cost of investing, by private actors as well as the government, in low- or zero-carbon generation and other responses to climate change.

4.3. Uncertainty's Arrow: From Risk-Neutrality to Irreversible Commitments

4.3.1. Risk-Neutrality

The economics of climate change demonstrates how uncertainty affects sunk costs and asset-specificity. Mitigation and adaptation efforts straddle Kenneth Arrow's divergent approaches to managing risk in public investments. Public ownership provides a neutral legal and economic baseline by which to gauge risk and uncertainty. A fifth of the United States' trillion-dollar electrical power industry remains publicly owned and continues to provide a viable alternative to private ownership (Bradley, 2003).

The spreading of risk among taxpayers reduces the costs of risk-bearing associated with public ownership to negligible levels (Arrow and Lind, 1970, pp. 374–375). In some circumstances, risk-adjusted return on a publicly owned investment might exceed that of a comparable private firm (Hirshleifer, 1965, 1966). Kenneth Arrow accordingly urged governments to "ignore uncertainty in evaluating public investments" (Arrow and Lind, 1970, p. 376).

According to the formula, $\mathrm{var}(s) = \mathrm{var}(v) + \mathrm{var}(e)$, the government's ability to eliminate the cost of risk-bearing collapses the definition of uncertainty into nothing more than variability in the underlying economic signal. Variability in fundamental value expresses the variability formula in its entirety. Critically, expected return on public investment serves as the exclusive yardstick of value (*ibid.*, p. 374). In formal terms, $\mathrm{var}(s) = \mathrm{var}(v)$ and $s = v$.

4.3.2. Irreversible Commitments

Befitting the contemporaneous emergence of intertemporal asset pricing (Merton, 1973) and the sustainability principle (Solow, 1974; Hartwick, 1977), Kenneth Arrow eventually took account of intergenerational differences (Arrow and Kurz, 1970, p. 12). Four years after devising his risk-neutral formula, Arrow reevaluated the role of public investment and ownership (Arrow and Fisher, 1974, p. 313). The rule of risk-neutrality yields in favor of a new cost-benefit analysis if public policy "involves some irreversible transformation of the environment" and permanent loss demands reevaluation of future "expected values" (*ibid.*, pp. 313–314).

Arrow's later contribution to environmental and resource economics presciently anticipated many different types of irreversible events. In addition to biological extinction and the destruction of geological formations and phenomena, Arrow foresaw "increasing concentration[s] of carbon dioxide" and "attendant climatic changes" (*ibid.*, p. 319). The legal *Zeitgeist* of the early 1970s likewise demanded environmental impact statements and interagency consultation before "any irreversible and irretrievable commitment of resources," including endangered plant and animal species [National Environmental Policy Act of 1970, 42 U.S.C. § 4332(C)(v); Endangered Species Act of 1970, 16 U.S.C. § 1536(d)].

In stark contrast to his original hypothesis of risk-neutrality, Arrow's later approach to irreversibility effectively maximizes uncertainty. In the formula, $\mathrm{var}(s) = \mathrm{var}(v) + \mathrm{var}(e)$, presuming or detecting irreversibility is tantamount to assuming that $\mathrm{var}(e) \gg 0$. Accordingly, fundamental volatility in cash flow or dividends, conditioned on subjective aversion varying over time, serves as an adequate proxy for uncertainty (Bekaert et al., 2009).

5. ANTHROPOCENE RISK MANAGEMENT

5.1. The Dismal Theorem

On the other hand, severe uncertainty can drive variability, either in valuable flows of ecological services or in the quality information regarding those flows, effectively toward infinity. In other words, either $\mathrm{var}(s) \to \infty$ or $\mathrm{var}(e) \to \infty$. Alternatively, the value of those flows may implode within a foreseeable timeframe, such that $v, s \to 0$. These are apocalyptic circumstances. A comparably cataclysmic approach to economic analysis is warranted.

The enormity of the Anthropocene catastrophe invites even more extreme approaches to uncertainty. When climate change inflicts an infinite amount of expected loss, the dismal theorem disables "standard economic analysis" altogether (Nordhaus, 2011, p. 240). More formally, since no amount of learning can prepare humanity for unlimited exposure to a fat-tailed risk, ordinary actuarial details such as risk assessment, social discounting, and the calibration of premiums to permit the smoothing of consumption all fall by the wayside (Weitzman, 2009, pp. 10–12, 18).

Risks contributing to the fat, leptokurtic tails associated with the dismal theorem bear many names. Whether it is described as variance risk (Carr and Wu, 2009; Bali and Zhou, 2016), tail risk (Bollerslev and Todorov, 2011; Kelly and Jiang, 2014), jump risk (Todorov, 2010; Dreschler and Yaron, 2011), or rare disaster risk (Gabaix, 2012), this risk resides at extremes where human epistemology exceeds its limits and outcomes observe no finite limits.

5.2. Rethinking Maslow's Hierarchy of Needs

5.2.1. The Original Hierarchy

No matter how dismal its prospects, humanity must choose. Even opting to take no action represents a choice. Human responses to risk and uncertainty are almost assuredly irrational in the rigid sense of *Homo economicus* (Faber et al., 1997; McMahon, 2015). But a closer look reveals that human decisions assume "orderly" rather than "chaotic and intractable" form (Tversky and Kahneman, 1992, p. 317).

Abraham Maslow's hierarchy of needs (Maslow, 1943) has proved to be a durable if crude psychological model. The Maslowian hierarchy is often depicted as a pyramid with sequential layers of survival, safety, love and social standing, esteem, and self-realization (at the apex). **Figure 2**'s alternative depiction, showing the hierarchy as overlapping and persisting waves, may be more accurate and persuasive (Krech et al., 1962, p. 77).

Maslow's enduring popularity intuitive appeal of his hierarchy of needs: It portrays human nature in a way that most people intuitively recognize and appreciate (Abulof, 2017, p. 508). In a study of innate frames of mind and decision-making heuristics, Maslow's hierarchy of needs—appropriately enough—stands atop the pyramid of ideas.

5.2.2. A Transcendent Adjustment

With a modest adjustment, Maslowian psychology continues to serve as a viable model of decision-making amid risk and uncertainty. By placing self-actualization atop his hierarchy, Maslow decoupled "the desire to fulfill one's own unique potential" from human biology (Kenrick et al., 2010; p. 297). As a matter of sociology, self-actualization can be affirmatively maladaptive to the extent it is decoupled from respect by and for other members of a community (*ibid.*, p. 298; Kurzban and Aktipis, 2007).

At its most perverse, self-actualization might be nothing but overconfidence or even naked narcissism. Since it arises from the failure or refusal to look for evidence that might contradict one's own beliefs (Shefrin and Statman, 1994, p. 331, n. 21; Gervais and Odean, 2001), overconfidence is confirmation bias on stilts. Recognizing that an overemphasis on the individual violates the "functional logic of human evolutionary biology," some psychologists have excised self-actualization from Maslow's hierarchy (Kenrick et al., 2010, p. 298). In later elaborations of his own work, Maslow himself revised the apex of his pyramid to include spirituality, altruism, and grander aspirations beyond the self (Maslow, 1969, 1996).

In place of self-actualization, Maslow ultimately inserted *transcendence*. He defined transcendence as "the very highest and most inclusive or holistic levels of human consciousness, behaving and relating… to human beings in general, to other species, to nature, and to the cosmos" (Maslow, 1971, p. 269). Even as the world collapses during the Anthropocene, individuals still strive for the transcendent. Everyone wants a shot at greatness. Environmental economics provides a channel by which humans may reassert their own ambition and expressive desires within the calculus of existential risk-taking.

5.3. Up From Subsistence

5.3.1. Bonds and Bullets in Bangladesh

As one of the earliest departures from the stiff formalism of classical mathematical finance, Roy's safety-first criterion counseled investors to minimize the probability of falling below their lowest acceptable level of returns (Roy, 1952). Safety-first portfolios depart in important ways from the methods of mean-variance optimization prescribed by the canonical capital asset pricing model. Human investors relying on intuitive risk management combine large, relatively safe positions, often consisting of cash and bonds, with a few speculative instruments with far greater upside potential. This approach to combining safe and speculative investments pairs the extremes in Maslow's hierarchy, from the strictly physiological to the transcendent.

The resulting "bonds-and-bullets" investment strategy transcends economic and cultural boundaries. It might even be a human universal. Agricultural and resource economists were among the first economists to embrace safety-first (Shahabuddin and Butterfield, 1986). Because their survival is at the mercy of pests, storms, floods, or even "invading armies," subsistence farmers provide a prime illustration of the compatibility of survival-oriented and aspirational instruments (Lopes, 1987, p. 287).

A subsistence farmer seeking to optimize her or his prospects must allocate extremely scarce resources between two wildly different assets. On one hand, food crops guarantee survival, with as stable a level of variance as can be expected in agriculture. Such security comes at a price: It demands acceptance of ongoing, abject poverty. By contrast, less reliable, more volatile cash crops promise higher returns. Planting rice while pursuing one's dreams appears to be humanity's innate and perhaps universal plan for surviving while retaining a kernel of hope (*ibid.*).

At this point, however, formal financial economics and the psychology of subsistence part company—at least as a matter of framing. Behavioral economists simplify the narrative of subsistence agriculture as a "gamble on cash crops" in an aspirational, even desperate, bid "to escape poverty" (Shefrin and Statman, 2000, p. 137).

Subsistence farmers disagree. They do not regard the decision to plant a combination of rice and opium poppies as gambling (Kunreuther and Wright, 1979; Ortiz, 1979; Lopes, 1987, p. 287). Subsistence farmers' allocations between food and cash crops satisfy the same emotional mixture motivating rich as well as poor agents: fear, hope, and aspiration. Indeed, if conditions can be so dire that a higher allocation of acreage to cash crops may be

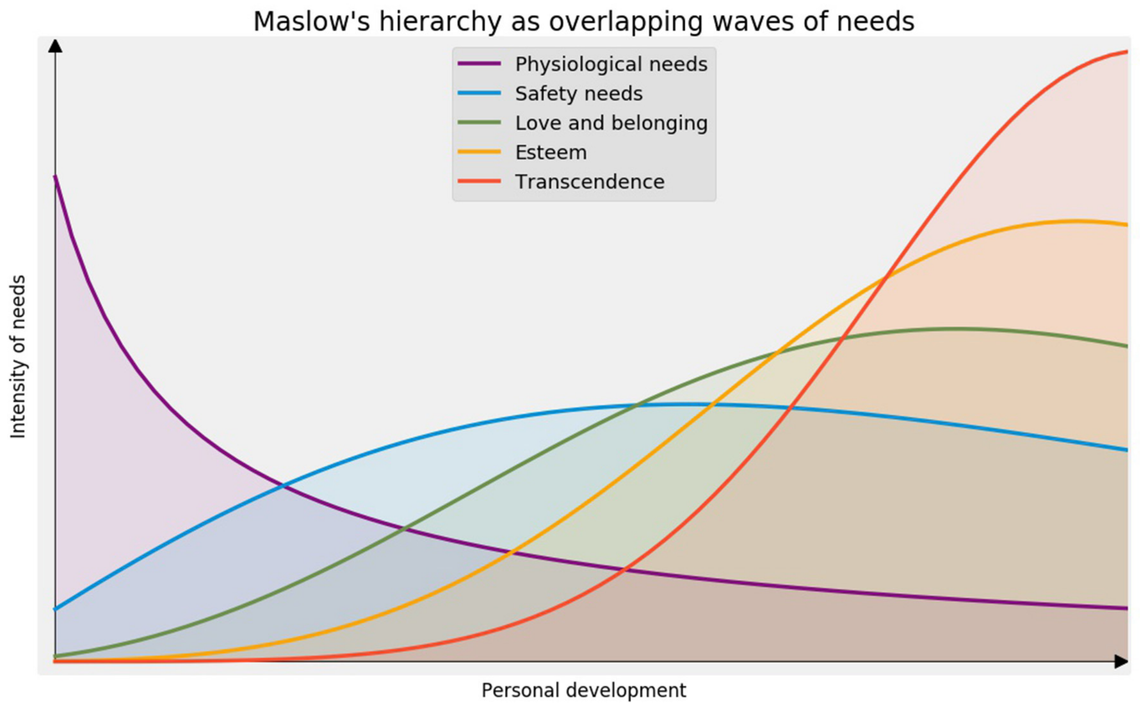

FIGURE 2 | A dynamic depiction of Maslow's hierarchy as overlapping waves of needs.

an affirmatively rational bid "to maximize … chances of survival" (Shahabuddin, 1982, p. 95).

5.3.2. Digging for Diamonds

Diamond miners in Sierra Leone face a similar subsistence-driven dilemma (Davies, 2000, 2008). Miners throughout Africa work under arrangements similar to sharecropping: They borrow heavily from mine owners in exchange for a share of any mining profits. Should a mine fail, however, the owner never refunds loans net of laborers' earnings. All-or-nothing wagers on diamond mining has plunged Sierra Leone into economic and political turmoil for decades (Maconachie and Binns, 2007; Le Billon, 2008; Davies, 2010; Wilson, 2013).

Sierra Leone is hardly alone among developing countries that suffer the "resource curse" (Ross, 1999, 2015; Mehlum et al., 2006; Robinson et al., 2006). Lopsided bets on natural resource extraction stunt economic growth in countries whose mineral wealth should be a blessing.

As with subsistence farming in Bangladesh, however, diamond mining in Sierra Leone must not be relegated to a mythical category of risk management that is confined unique extremely poor countries. In affluent countries, firms on the verge of default routinely wager on their own resurrection by taking risks that might be condemned as excessive under ordinary conditions (White, 1989; Akerlof and Romer, 1993). Neither the managers of these firms nor their investors face a credible threat of starvation. Nevertheless, they combine the lowest and highest levels of Maslowian thinking in ways that are identical to the psychology of subsistence agriculture and mining on credit. In their own way, wealthy entrepreneurs and their backers in affluent countries are also digging for diamonds.

5.4. Shaping Bets for the End of the World

Translating bonds-and-bullets portfolio construction into the language of higher-moment asset pricing produces a convenient shorthand for this sort of risk-taking: Kurtosis preference. Affluent investors build layered portfolios according to opposite ends of Maslow's pyramid. While the bottom layer preserves capital as a bulwark against penury, the top layer takes "a shot at riches" (Shefrin and Statman, 2000, p. 141). This split portfolio assumes that the tails at either extreme will be fatter than the rest of the distribution of returns (*ibid.*, p. 145). The combination of caution and optimism underlying this approach reflects the rank effect in behavioral finance (Hartzmark, 2015). It overestimates probabilities associated with the worst outcomes—and with the best (Shefrin and Statman, 2000, p. 141).

Kurtosis preference and bonds-and-bullets risk-taking appear to be innate frames for making decisions under conditions of extreme preference. But the innate optimism of the odd-numbered moments, especially skewness, lurks as a treacherous pitfall. Another existential threat to humanity illustrates the problem.

The Covid-19 pandemic, the greatest public health crisis in living memory, has killed millions around the world. Covid arguably poses a more immediate threat than climate change. At the very least, Covid-19 infection happens at the personal level and can reveal itself in hours rather than decades. Yet large swaths of the population perceive *neither* risk as urgent (Ruiu et al., 2020; Botzen et al., 2021). Indeed, at least in the United States, denying the threat has arguably become a badge of political allegiance. The same logic that urges Covid deniers to await deliverance through hydroxychloroquine, ivermectin, or some other miraculous therapeutic motivates a political preference to defer climate action. Justice delayed, as it were, is simply waiting for the *deus ex machina* of solar radiation management or geoengineering on the cheap.

In the opening passage to *Their Eyes Were Watching God*, Hurston (2006) distinguished those fortunate few whose ships "come in with the tide" from perpetual dreamers whose ships of dreams "sail forever on the horizon, never out of sight" (p. 1). Less wistfully, Nick the Greek lauded thrill-seeking gamblers who await the single "streak of luck" that might make up "for all the bad times" (Thackrey, 1968, p. 67).

Once the prospect of infinite loss has entered the casino, though, the dismal theorem counsels complete reconsideration of all approaches to risk management. That same principle also offers no guidance of its own. Humanity is consequently left to rely on its own instincts.

Those instincts may be quite destructive. In the context of Covid and other pandemic diseases, such instincts may defeat cooperative public health measures, as humans defer and avoid perceived risks associated with vaccination in favor of last-second therapeutic measures. To like effect, behaviorally influenced environmental decision-making often disfavors measures for mitigating climate change. The urgency of immediate sacrifices diminishes in the shadow of miraculous deliverance through future responses such as solar radiation management and other grandiose feats of geoengineering.

6. CONCLUSION

The dismal theorem forces humanity to confront an existential threat of its own creation: catastrophic climate change stemming from human activity. Because functioning, reliable flows of natural resources that sustain human life are the most vital of ecosystem services, the problem can and should be framed as one of resource valuation and risk assessment.

This article has approached what is arguably the greatest problem of environmental and resource economics according to tools normally applied to the valuation of financial assets. The existence of a premium for willingness-to-accept (WTA) valuations relative to their theoretical willingness-to-pay (WTP) equivalents suggests that resource valuation is as susceptible as financial risk management to innate heuristics and cognitive bias.

The resulting exercise bodes ill for humanity's prospects. The erasure of functional ecosystems and the contribution of climate change to mass extinctions represent the irreversible commitment of resources. Innate responses to skewed outcomes, especially under conditions of epistemic blindness associated with highly leptokurtic distributions, induce humans to assemble bonds-and-bullets portfolios laden with low-probability, high-payout instruments. Financial decisions ranging from corporate management in wealthy countries to subsistence farming and artisanal diamond mining in poor countries portend a similar approach to climate change mitigation and adaptation. The allure of last-minute rescue through heroic feats of geoengineering cripples efforts at cooperative and preemptive climate mitigation.

Long ago and in a seemingly distant setting, Oliver Wendell Holmes gave legal voice to decision-making in the face of uncertainty: "Every year, if not every day, we have to wager our salvation upon some prophecy based upon imperfect knowledge" (Supreme Court of the United States, 1919, p. 630 [Holmes, J., dissenting]). At its darkest hour, instinctive decision-making heuristics may serve humanity poorly. "This is the way the world ends/This is the way the world ends/This is the way the world ends"—not with a bang but bonds and bullets (Eliot, 1971, p. 59).

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Climate Adaption for Energy Utilities: Lessons Learned From California's Pioneering Regulatory Actions

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This Policy Brief provides lessons learned from regulation of climate adaptation by energy utilities. The regulatory bodies responsible for oversight of investor-owned energy utilities are ill-equipped to regulate climate adaptation in the energy sector; but they may be the only institutions with authority to do so. In 2018, the California Public Utilities Commission initiated the first quasi-legislative procedure to regulate investor owned energy utilities' climate adaptation activities. The Commission's new rules for climate adaptation offer some general guidance on climate adaptation, and require investor owned utilities to conduct and submit climate vulnerability studies. Structural limitations, including conflicting interest, capacity of staff, and scope of the problem hampered the success of adaptation regulation, which failed to address fundamental questions about what constitutes adaptive measures.

Keywords: climate adaptation, energy, private utilities, regulation, California

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INTRODUCTION

The regulatory bodies responsible for oversight of investor-owned energy utilities are ill-equipped to regulate climate adaptation in the energy sector, but may be the only institutions best suited, and with authority, to do so. The California Public Utilities Commission (Commission) issued the first climate adaptation regulations for regulated energy utilities in 2020—recommending scientific tools, standards, and decision-making process; and requiring the three largest private utilities in California to undertake climate vulnerability assessments with a vulnerable community engagement component. The Commission convened a multi-stakeholder working group to advise on its initial approach to adaptation regulation. While there were notable successes to the Commission's approach, significant structural limitations hampered the Commission's process and the outcome of the regulatory proceeding. This policy commentary presents an overview of this first attempt in the United States to formally regulate climate adaptation processes for private energy utilities, from the perspective of two of the working group participants, and presents recommendations for future regulation of climate adaptation by private energy utilities[1].

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CLIMATE CHANGE IMPACTS ON THE ENERGY SECTOR

Climate change affects all aspects of the energy sector: energy production, consumption, transmission, and distribution. Researchers at the California Energy Commission estimate that the demand for electricity to cool homes could increase around 5% compared to historical levels by 2030 (Franco and Sanstad, 2008). More extreme heat events mean that electric demand for cooling on especially hot days would increase even more as shown in **Figure 1** (Auffhammer et al., 2017). This effect will be magnified in areas that already have very hot summers, like Los Angeles and Sacramento. And it is in these areas where almost half of California's disadvantaged communities[2], many of which cannot afford to meet their basic energy needs, are located. These communities will be challenged to meet increased energy needs because lower income households tend to be poorly insulated and often don't have efficient cooling equipment. Meeting these increased energy needs means increased utility bills for these communities.

In late August 2020, a heat wave settled across the Western United States. It brought power shortages with it. As overheated homes and businesses turned up their ACs, demand for electricity exceeded available supply. Under normal conditions, energy hungry states could temporarily import electricity from their neighbors to avert power shortages. In this case, states like California could not import electricity, because its neighbors faced the same conditions. Extreme heat days have already increased[3] in the region and heat waves are expected to get longer, more frequent, and more severe[4].

Climate change also impacts the amount of electricity renewables produce and when they produce electricity. For example, extreme heat reduces the efficiency of solar panels and changing precipitation patterns affect how much hydroelectric power is available at any given time. These changes in electricity production patterns and demand, both caused by the climate crisis, can compound to make it harder to serve California's clean energy needs.

California makes use of excess hydropower from the Northwest to meet its clean energy needs. Seattle City Light's power planners recently found climate change is causing electricity demand in their service territory to increase in the summer; at the same time, decreased snowpack and changing precipitation patterns are decreasing available hydroelectric generation capacity.[5] The Pacific Northwest already depends on hydropower for around half of its energy needs. Seattle City Light must now plan to meet this increased without relying on fossil generation to avoid further contributing to climate change and to comply with the state of Washington's carbon reduction goals[6].

Finally, climate change also impacts utility infrastructure. Recent wildfires in California, some of which were ignited when high voltage transmission lines interacted with dry vegetation[7], are a prominent example. Increasingly hotter and drier summers, again due to climate change, mean conditions conducive to deadly wildfires which also have immense financial implications that include a $21 billion wildfire safety fund that will be developed from the utility's electricity customers[8]. This alone is expected to increase electric rates by at least ∼19 cents/kWh or around 75% in Pacific Gas and Electric service territory (Chhabra and Hay, 2020).

Higher temperatures also impact the performance of electric transformers and substations (Burillo et al., 2019); electricity losses from transmission and distribution cables increase as it gets hotter; sea level rise threatens substations near the coast[9]; and climate change is expected to cause disruptions to and the need for repair of fossil gas infrastructure.

HOW CAN THE ENERGY SECTOR ADAPT TO THESE IMPACTS?

Ameliorating climate impacts to the energy sector, requires funding and expertise go beyond "business as usual" planning. Utilities need climate-relevant expertise to identify infrastructure and system upgrades, operational changes, and develop adaptation solutions; regulators need this expertise to understand whether investor-owned utility (IOU) proposed upgrades are prudent. IOU shareholders make profits on infrastructure investments (such as constructing new substations and transmission lines), not on operational spending (better maintenance of existing infrastructure). Regulators need to understand what investments are most cost-effective to mitigate climate threat while delivering clean and reliable power to be able to assess IOU upgrade proposals and to proactively guide climate adaptation efforts by IOUs.

Adaptation measures require investment. Some, such as "hardening" of transmission infrastructure to reduce wildfires, require billions of dollars of investment. Under the current rate-making structure, each investment results in increased rates. Even though some of these investments are necessary to prevent much greater costs that come with climate damage, this poses a unique challenge for regulators, especially those with a duty to ensure electricity is affordable.

Finally, keeping electricity affordable is essential to mitigating climate change. A key component of climate change mitigation is displacement of fossil fuels by clean electricity (e.g., switching to electric cars and all electric buildings from fossil fuel powered ones), this requires that electricity remain an affordable

[2]Disadvantaged communities are an official designation of California's Environmental Protection Agency for identifying vulnerable communities based on demographic and environmental factors. California Office of Environmental Health Hazard Assessment (2017).

[3]California Office of Environmental Health Hazard Assessment (2019).

[4]Cal-Adapt. *Extreme Heat Days & Warm Nights*. Available online at: https://cal-adapt.org/tools/extreme-heat/ (accessed May 21, 2021).

[5]Seattle City Light (2015).

[6]Department of Ecology, State of Washington. *Reducing Greenhouse Gases*. Available online at: https://ecology.wa.gov/Air-Climate/Climate-change/Greenhouse-gases/Reducing-greenhouse-gases (accessed May 21, 2021).

[7]National Public Radio (2019).

[8]Natural Resources Defense Council (2019).

[9]Pacific Gas Electric Company (2016).

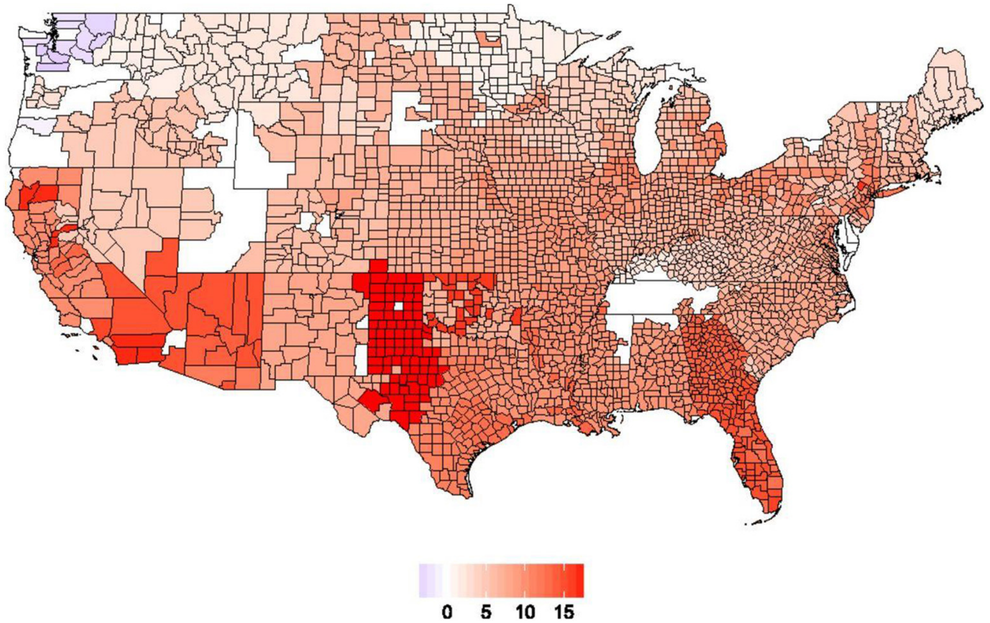

FIGURE 1 | Changes in Peak Load Under RCP8.5 Scenario Across the United States. Peak Load Varies Geographically, with the Largest Increases in the South and West. Coloring Reflects the Percentage Increases in Peak Load due to Temperature Rise by the End of the Century (Auffhammer et al., 2017).

alternative to other fuels. Currently electric prices are already comparable with gasoline and natural gas prices in California. If electricity prices increase at a faster rate than polluting alternatives, then electricity won't remain a viable alternative.

For a regulator to oversee climate adaptation by utilities in a way that allows for investment while keeping energy affordable, commissions first need to establish standards for determining what constitutes adaptive measures. Without such standards, financing for climate adaptation is *ad hoc*—leaving open the possibilities of being over inclusive (every project is adaptive, so rates go up) or too restrictive (no project is adaptive, so no adaptation investment). It also leaves open critical questions about who should fund what. For example, should wildfire insurance be funded through electricity rates or through an outside source? And how should that be determined?

OVERVIEW OF THE COMMISSION'S CLIMATE ADAPTATION REGULATION AND PROCESS

The Commission issued a final decision on August 27, 2020. Much of the decision offers general guidance for the utilities about how to plan for climate change[10]. It also requires some key specific action on the part of utilities. Fist, private energy utilities in California must complete and file climate vulnerability assessments every 4 years. The vulnerability assessments at minimum must consider climate impacts to infrastructure, potential ways to manage climate risk, and include a discussion of how climate change impacts marginalized and vulnerable communities[11]. within their service territories. The decision requires utilities to focus on the next 20–30 year time frame for impacts, while including an intermediate 10–20 year time frame and a long-term 30–50 year time frame. Strikingly, the decision requires personnel changes within the utilities; they must each create cross departmental "climate change teams" that report independently to the senior vice president level or above. Board members likewise are instructed to take responsibility for climate adaptation planning for infrastructure, operations, and services. The decision left open the possibility of allowing the energy utilities to recoup costs for vulnerability assessments and climate adaptation measures through General Rate Cases. The decision, however, does not establish standards or guidance on how to evaluate whether measures proposed by utilities are adaptive, maladaptive, or irrelevant to climate adaptation.

Because the Commission categorized the climate adaptation proceeding as quasi-legislative, as opposed to quasi-judicial, there was significant flexibility in how the Commission could develop the record in this proceeding. Behind the Commission's decision was a multi-year engaged stakeholder process, with in-person facilitated workshops, reports, and opportunities for written comments. These meetings were broken down in to a handful of topics: (1) what should the definition of climate change adaptation be in the context of private energy utilities[12], (2) what

[10] Public Utilities Commission (2020).

[11] The Decision refers to these communities as "Disadvantaged Vulnerable Communities" or "DVCs." The Decision uses a state environmental justice screening tool, CalEnviroScreen, to determine which communities constitute DVCs; specifically they are those communities with 25% highest scoring census tracts; all tribal lands; census tracts with median household incomes less than 60% of state median income; and census tracts that score in the highest 5% of Pollution Burden within CalEnviroScreen.

[12] Southern California Edison (2019).

data sources, models, and tools the utilities could or should use to plan for climate adaptation[13], (3) how to include consideration of vulnerable and disadvantaged communities[14], and (4) what the decision making, or risk consideration, framework should be for climate adaptation[15].

The timing of these meetings is notable. The first workings group meeting to discuss regulating climate adaptation and energy utilities was held in San Francisco on January 25, 2019. Four days later, and one block to the north, Pacific Gas and Electric Co. would file for bankruptcy after the most destructive wildfire in the State's history to date. The wildfires and the bankruptcy were taboo topics at the meetings, with specific instructions from the Commission staff to not address either.

Meetings were run by Commission Staff, who usually began the sessions with a specific proposal and then asked the participating parties to comment. Many of the workshops also made use of outside facilitators, usually from other state agencies which had more experience in climate adaptation policy. Expertise among participants varies. The three largest utilities sent teams of engineers, risk managers, government relations staff, and occasionally DEI staff. A variety of environmental organizations participated, though could not spare as much staff or time to the proceeding–each sending usually one person—with the exception of the California Environmental Justice Alliance, which makes good use of law students to staff agency participation. And the Commission's independent consumer advocates branch sent between one and three people, depending on other staff constraints (for a complete list of participants, see Reports 1–4).

Utility representation dominated the working groups, not only because of their greater numbers. To develop the record, the Commission needed written reports from the working group sessions. But assigned the job of notetaking and report writing to the utilities[16]. It should be noted that the utilities themselves along with other participants protested this assignment. Although there was an opportunity to correct accidental misrepresentations, the reports were put together under difficult circumstances by non-expert note takers, representing businesses that had a financial stake in the outcome of the proceeding. However, as part of the process leading up to the decision, each report was formally adopted by the Commission, with an opportunity for written comments.

STRUCTURAL LIMITATIONS OF THE COMMISSION'S PROCESS

As the first Public Utilities Commission to regulate climate adaptation by private energy utilities, the Commission should be lauded. But, the Commission's failure to establish guidance or standards by which to evaluate climate adaptation means that the attempt to regulate didn't address the most important question. While the Commission is best positioned to regulate climate adaptation in the private energy sector, it is ill equipped to do so. As other regulators look to tackle climate adaptation, there are some structural limitations that we should be sober and direct about, which repeatedly hampered the Commission's process, making it perhaps too challenging to address critical fundamental questions about climate adaptation for regulated utilities. We discuss what we found to be the most significant and pernicious limitations here: competing interests, capacity, and scope of the problem.

Competing Interests

Public oversight of private industry is premised on the idea that there would be competing interests. The firm is designed to maximize profits, the regulator is supposed to protect the public from the excesses of the firm's attempts to maximize. There are institutional incentives for organizations' representatives to act to further these goals. Hence, utilities regularly supported guidance that would limit oversight and increase ways to collect money from rates. For example, as discussed below, Pacific Gas and Electric Company was eager to have a flexible definition of climate adaptation and all three of the large utilities sought to limit climate adaptation to hard infrastructure—for which they can collect a return on investment—and not for "soft infrastructure," like changing maintenance schedules or considering staffing changes—for which utilities cannot collect a return on investment.

Bounded rationality among individual participants was also tied to more personal competing interests. It is not surprising that a hypothetical electrical engineer specializing in transmission line capacity would not be enthusiastic about a requirement for community engagement, and instead hope to focus the conversation on topics within their area of expertise. Given that there was limited time and resources to conduct and learn from adaptation workshops, the initial bounded rationality of participants dictated the content of the workshop outcomes.

In other words, the stated common goal of climate adaptation was not overarching in reality. Where adaptation would conflict with core institutional and individual interests, those non-adaptation interests controlled. What is concerning about this otherwise mundane fight over interests is that climate change is an existential threat—but we can't help ourselves, on an individual and organizational level, to keep fighting the same old fights.

Capacity

The Commission has a large staff, roughly 1,000 people, who deal with a wide variety of issues—from determining wildfire liability for electric utilities to regulating energy efficiency programs. Multiple staff work on the same proceeding through the proceeding's duration. Staff are frequently shuffled from one proceeding to another as they get promoted, are re-assigned, or due to turnover. As a result, relatively new staff—with limited access to institutional memory—sometimes end up being tasked with managing complex proceedings like climate adaptation.

[13] Pacific Gas Electric (2019b).
[14] Pacific Gas Electric (2019a).
[15] This last working group also included elements of a cancelled working group (formerly group 3) on the question of how to coordinate climate adaptation across multiple proceedings within the Commission. Southern California Gas Company (2019).
[16] California Public Utilities Commission (2020).

Although staff turnover impacts most aspects of the Commission's work, the Commission has built up institutional knowledge for most of its work areas. Unfortunately, climate adaptation is a new and complex work area. There was little to no in-house expertise. Staff therefore ended up relying on the most active stakeholders in the proceeding—e.g., the IOUs, which have institutional capacity and a financial interest in the outcome of the proceeding.

Scope

The size of the problem may be too big. There are two attributes of climate impacts that would regularly stall out dialogue during the working group process. First, climate impacts are cross-cutting. Climate impacts tend to not confine themselves to one economic sector or another. Extreme heat and sea level rise do not "target" utility infrastructure to the exclusion of other industry, communities, or ecosystems. This allowed an opening for parties to suggest that the issue was beyond their jurisdiction. Second, climate impacts—especially those in a +3C or +4C world—are scary. When faced with a question about how a utility should plan for or respond to a massive exodus of its ratepayers over time—e.g., people moving out of California because houses and businesses are literally underwater, or wildfires become intolerable[17], or it simply becomes too hot—the response from parties was that those scenarios were such existential threats that it was not worth thinking about. This made it difficult, if not impossible, to discuss and plan for worst case scenarios.

ACTIONABLE RECOMMENDATIONS

- Regulatory Commissions should regulate climate adaptation by private utilities. The commissions are best positioned to guide and oversee adaptation in the private energy sector, because they have experience in and authority to review utility decisions in light of public interest. The IOUs are best positioned to make investments and act to mitigate climate risks. They also have a vested interest to spend as much as they can on hard infrastructure. But, from an energy equity and climate mitigation perspective, there is a need to keep energy costs down. Regulatory Commissions are meant to do exactly that.
- To overcome some of the structural limitations discussed above, regulatory commissions need to invest in expertise and staff capacity to have the authority and know-how to regulate and oversee private energy sector adaptation, and push back on IOU emphasis on hard infrastructure

[17]USA Today (2019).

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- Regulatory commissions and IOUs need additional funding from outside the electric sector to (1) build up expertise on this subject and (2) to fund upgrades to energy infrastructure for the purpose of adaptation. Two possible avenues for this funding are:
  - A new federal grant-making process to fund climate adaptation action for energy utilities
  - State legislative action to identify an appropriate source of money for a climate adaptation fund. For example increased carbon fees on polluters[18].
- Commissions undertaking a climate adaptation regulation should develop a framework to:
- Establish guidelines and standards by which to evaluate whether a measure should be considered adaptation, and if so
- determine whether and how such measures should be funded by ratepayers as opposed to from outside the electric sector.

CONCLUSION

To enable regulatory commissions to successfully oversee climate adaptation of the energy sector in California, advancements in policy, regulatory structures, and analytical expertise are needed. New analytical expertise is required to identify climate risks and determine cost-effective investments in utility procurement, operations, and infrastructure to adapt the energy sector to climate change while continuing to reduce the energy sector's carbon impact. Regulatory advancements are necessary to determine how commissions should oversee and guide IOU spending on climate adaptation to minimize climate risk cost-effectively. Policy advancements are necessary to identify new sources of funding for these investments so that all costs of mitigation and adaptation aren't loaded on to the price of electricity, which must remain affordable to meet our climate goals; and to empower commissions to take on this new responsibility.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

[18]California already has a precedent for this: California Climate Investments spend revenue collected from the state's cap-and-trade system on environmental and public health initiatives in the state's disadvantaged communities. California Climate Investments. *Cap-and-Trade Dollars at Work*. Available online at: http://www.caclimateinvestments.ca.gov/ (accessed May 21, 2021).

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Building a Climate-Resilient Power Grid: Lessons From Texas-Size Storms and the Queensland Floods

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When a city is lashed by storm or swamped by epic rains, there's at least one predictable moment in the chaos: the lights go out. In this article, we focus on the challenge of protecting assets from storms and floods in the era of climate breakdown. This often involves physical fortification or smarter placement. To understand the policies and decisions involved, we examine recovery efforts following storm- or flood-based outages that occurred this century in the state of Texas in the United States and the state of Queensland in Australia. We first describe the outages, their consequences, and the policy recommendations and responses that followed. We then evaluate the recovery processes, focusing on the challenge of protecting assets like substations and transmission structures. We find that each jurisdiction could do more to incorporate forward-looking climate data, to match the level of government authority to better fit the desired function, and to capably fund the work to be done.

Keywords: Australia, climate change adaptation, climate change disaster, electricity, infrastructure, United States

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INTRODUCTION

When a city is lashed by storm or swamped by epic rains, there's at least one predictable moment in the chaos: the lights go out. The widespread loss of electricity—essentially a disaster within a disaster—can force a whole region to its knees. From rancid food to emergency-room nightmares, communities take a punch when the lights go out. Aging power grids leave us more susceptible to risks like these. And the growing intensity of floods and storms on account of climate change make things even worse. In earlier work, we have examined the most important elements in making a power grid more resilient to climate breakdown: protecting assets, smartening network distribution, and greening the inputs (Lyster and Verchick, 2018).

In this article, we focus on threats posed to the power grid by storms and floods—two prevalent hazards now amplified by the climate crisis. Our goal, as in our earlier work, is to identify strategies to strengthen "climate resilience," defined by the United Nations' Intergovernmental Panel on Climate Change as "the ability to cope with a climate disturbance and recover in a way that preserves one's essential character, while at the same time exercising the capacity for adaptation, learning, and growth" (Intergovernmental Panel on Climate Change IPCC, 2018, 557). "Adaptation," in this sense, describes the ability "to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (Intergovernmental Panel on Climate Change IPCC, 2018, 542). To understand the policies and decisions involved, we examine recovery efforts following storm- or flood-based outages that occurred this century in the state of Texas in the United States and the state of Queensland in Australia. While these states differ in various ways, they share certain characteristics that are enlightening. Namely, both are states in wealthy, industrialized countries; both exist within federal systems known to favor local land-use controls; both contain sprawling landscapes prone to coastal and riverine flooding; and both operate in electricity markets that are loosely regulated and that rely strongly on market incentives.

We first describe the outages, their consequences, and the policy recommendations and responses that followed. We then evaluate the recovery processes, focusing on the challenge of protecting assets like substations and transmission structures. We find that each jurisdiction could do more to incorporate forward-looking climate data, to match the level of government authority to better fit the desired function, and to capably fund the work to be done.

TEXAS-SIZE STORMS

This century, Texas has been struck by intense storms, causing epic flooding in the summer and freak cold snaps in the winter. The damage has called the efficacy of the power grid into question. In 2008, Hurricane Ike hit southeastern Texas, knocking out power for more than 2 million residents in the Houston metropolitan area for up to 2.5 weeks. The main cause: tree limbs blown into power lines (Fehling, 2013). After Ike, Houston's main utility, CenterPoint Energy, significantly enhanced vegetation management along its rights of ways and installed smart meters capable of detecting and reporting on local outages (St. John, 2015).

In August 2015, Hurricane Harvey charged the Texas coast, bringing 130 mile-per-hour winds and an enormous amount of rain. In just a few days 25 trillion gallons of water fell on the south-eastern part of the state. Experts attribute 82 deaths to the storm and property damage amounting to US$125 billion (TLBO, 2017). The storm tore through hundreds of electricity lines and flooded dozens of facilities. More than 10,000 MW of electricity capacity went offline; 300,000 customers lost power (St. John, 2015; Lott, 2017; Amadeo, 2020). CenterPoint Energy's multi-million-dollar smart grid project was no match for a storm this big, and its automated communications features proved of little use (TLBO, 2017). The storm interfered not only with electricity generation and distribution, but also with fuel production, crippling one third of U.S. oil refineries (EOS, 2018, 122).

To assess the damages from Hurricane Harvey and develop better policy, Texas governor Greg Abbott appointed a commission charged with developing a framework for reducing the risk of future disasters. The many recommendations of this comprehensive report can be reduced to two main prescriptions: (1) assess and prepare for future risks and (2) coordinate local decision making (EOS, 2018, 105). But there was a big hole: while almost every weather extremity in Texas is backlit by global warming, the 157-page report mentioned "[a] changing climate" only once (EOS, 2018, 114). Instead, the Report spoke continually of "future-proofing" the state—a concept not precisely defined but which involves "anticipating future storm events" and "minimizing their effects on lives and property" (EOS, 2018, 154). The Report never defines what data would be necessary to anticipate future storms, nor does it mention the relationship between climate change and future conditions.

To take some examples relevant to the electricity grid, the Report urges local governments to avoid siting important facilities in areas designated by the U.S. Federal Emergency Management Agency (FEMA) as "100-year flood" zones (that is, having an "annual exceedance probability," or AEP, of 1% or higher), (EOS, 2018, 108). If a local government (city or county) chooses to allow development in such areas, the Report recommends the government require a level of protection designed to protect against such inundation along with an added margin of safety, or "freeboard." To protect, "critical facilities," including those related to electricity generation and distribution, the Report acknowledges that levees or seawalls may prove an effective option (EOS, 2018, 113). It also encourages further examination of a multi-billion-dollar coastal barrier system that some have proposed as a way of protecting the greater Houston area from storm surge (EOS, 2018, 114). The Report urges facilities to voluntarily adopt hazard mitigation plans, citing the Houston Medical Center's efforts (EOS, 2018, 116).

The Report assigns many decisions to local governments, including those related to levees, construction standards, and warning systems (EOS, 2018, 112). To avoid "a patchwork of flood mitigation strategies" within the same watershed, the Report urges local governments to collaborate with one another where needed. The Report emphasizes that interventions made upstream "should *never* hurt downstream neighbors" (EOS, 2018, 122, emphasis in original). For resilience projects on the coast, the Report recommends "a formal process by which the state and local jurisdictions can work together to identify and prioritize projects that will contribute to the overall goal of future-proofing the state" (EOS, 2018, 124).

More recently, in February 2021, a major cold snap—known as Winter Storm Uri—paralyzed the state, leaving as many as four million people without electricity or heating fuel in icy temperatures. Water pipelines burst, and water treatment plants failed. All told, more than a hundred people died (Sandoval et al., 2021). The main culprit was a failure in power generation related to natural gas, which supports two-thirds of the state's electricity needs. When natural gas wells and pipelines froze, normal production fell by 45%, leaving many gas-fired power plants without fuel (Gimon, 2021, 4-5). Some gas-fired power plants, with their own pumps and pipes to deal with, were also immobilized (Roberts, 2021). Without evidence, some state officials and conservative news outlets blamed the mess on "ugly wind generators" (Douglas and Ramsey, 2021; quoting Sid Miller, Commissioner of Texas Department of Agriculture). In fact, wind—which makes up only 7% of the planned winter capacity—performed as well or better than expected (Aronoff, 2021). At any rate, almost none of the power-producing infrastructure—from derricks to pipelines to wind turbines to power plants—had been equipped with adequate insulation, heating elements, or other forms of weatherization (Cooper, 2021; Hernandez et al., 2021).

In addition to lax mandates on weatherization, Uri also focused attention on other features of Texas's power network. First, electricity in most of the state is run by a single network operator; thus, Texas effectively has its own grid that is isolated from the western and eastern grids that cover the nation's other contiguous states. This isolation frees the state's electricity market from federal oversight, something that state leaders see as an advantage. Unfortunately, an islanded grid also prevents the easy importation of electricity in times of emergency. Second, the state's electricity market works on a rather extreme model of "retail choice." This allows customers to choose between long-term contracts with steady rates or contracts "that pass along fluctuating wholesale prices for a nominal fee" (Aronoff, 2021). What is extreme is that even in emergency situations, retail rates can be allowed to climb as high as US$9,000 per MWh. As a result, some customers received bills as high as US$10,000 for the month during that time (Burke, 2021).

It may be too early to know what policy changes, if any, result from Uri. At the time of writing, there seems to be little appetite for mandating weatherization for power generators or further connecting the Texas grid to transmission networks outside the state. As for the altitudinous power bills, the state's attorney general has pledged that US$29 million of the retail charges would be forgiven as part of a bankruptcy settlement with the power company involved (Burke, 2021). There does not seem to be wide interest among legislators for changing the law to prevent such a spike from happening again. Winter Storm Uri, it should be noted, was not without precedent. In 2011, a similar February cold snap froze Texas's power generators, triggering rolling blackouts for millions of customers (Hernandez et al., 2021). In 2014, a January freeze did the same (Schwartz et al., 2021).

THE QUEENSLAND FLOODS

Like Texas, the Australian state of Queensland has become known for its dramatic floods. The state's own website declares living with floods "a natural part of life" (Queensland Government, undated). Even by that standard, the torrents of 2010–11 were remarkable. Beginning in November 2010, a series of heavy rainstorms began rolling across the state over the course of several months. In the floods that ensued, thousands of residents were forced to flee their homes. Whole towns were submerged. Ultimately, the inundations—which also affected New South Wales and Victoria, though to a lesser degree—claimed 33 lives and destroyed billions of dollars of property (AIDR, undated).

The floods ruptured much of Queensland's electricity network, killing power even in areas with no physical damage (QFCI, 2012). Three hundred thousand customers lost power in two major towns, Ipswich and Brisbane. In the Lockyer Valley, one of the most seriously affected rural areas in Queensland, 5,000 people lost power (QFCI, 2012). In addition, the floods submerged open-pit coal mines and railway links, leading to global shortages of both coking coal (used in steel making) and thermal coal (used for power production), (Blas, 2011).

To assess and learn from these floods, the Australian government established the Queensland Floods Commission of Inquiry which released its report QFCI, 2012. The Report called for better mapping, updated flood-risk assessments, and more precise building codes. It also urged the state government to draft "model flood planning controls" for local councils to use in developing new planning schemes (QFCI, 2012, 12–3, 15–6, 21–2). Among other things, such controls would require that electrical substations be built so as to remain operational during floods of a particular magnitude based on a risk assessment that considered local needs and resources (QFCI, 2012, 246). While the Commission acknowledged the need to better understand climate change impacts like heavier rain and rising seas, it stopped short of recommending that such impacts be factored into future planning.

To support flood-management programs, the Australian government launched an authoritative national flood information and metadata database called the "Australian Flood Risk Information Portal (AFRIP)." The portal provides localized flood studies, hazard mapping, and management plans, including those relevant to grid resilience (Geoscience Australia, Web Portal, undated). There are currently 1,571 flood studies available on the portal, dating from 1909 to 2018, including 300 from Queensland. However, as of 2018, the portal contained "few studies … that include climate change scenarios" (Coast Adapt, 2018).

In addition, Queensland's new State Planning Policy (SPP) addresses risk and resilience against natural hazards as one of several "state interests" that must be considered and applied in the development and amendment of local government planning instruments. Notably, the SPP counts the "projected impacts of climate change" among the risks associated with natural hazards (Operations Support, 2017; Queensland Government, 2017, 8, 51).

Queensland does not require electric utilities to have flood plans, though the state's two main power companies—Energex and Ergon Energy Network—recently adopted a risk management plan that specifically addresses floods. The plan aims to "ensure the safety of the community in the event of damage or impact, manage and minimize the risk to network assets, improve response and maintain customer supply" (Ergon Energex Energy, 2019). Impressive in both detail and scope, the plan inventories existing assets, incorporates quantitative date from previous storms and floods, and is designed to integrate new observations. Still, it does not appear to directly factor in future climate impacts.

OPPORTUNITIES FOR IMPROVING CLIMATE RESILIENCE

In other writings, we have examined several important features of climate-resilience planning (Lyster and Verchick, 2018; Verchick, 2018). Here we focus on three features that should be better emphasized in the planning processes coming out of Texas and Queensland. That is, effective resilience measures should be (1) *forward-looking*, (2) *"fit to function,"* and (3) capably *financed*.

Forward-Looking

Forward-looking measures are ones that do not rely entirely on *past* impacts to inform *future* resilience standards. They instead incorporate science-based projections of future climate impacts like hotter temperatures, more precipitation, and rising seas.

The Texas Commission recommends using flood-plain designations provided by FEMA; but those designations do not incorporate climate projections. To its credit the Texas Commission urged local governments to add a margin of safety, or "freeboard," to projects within flood zones as a way to "future proof" them (EOS, 2018, 107). Yet there is no specification of how much freeboard is appropriate or what data should be used in making the determination.

The Queensland Commission recommended that the state or local government identify "flood plains" and suggested that facilities, including substations, be fortified for flooding or avoid the areas. However, it made no call for integrating future climate impacts into the maps. In response, Queensland adopted new mandatory construction standards for buildings, including those associated with electrical utilities. The law establishes a minimum freeboard standard of 300 millimeters (1 foot). Local councils may increase that amount if they want. There is no indication that climate data were used in selecting this standard.

For its part, Ergon Energy has since revised its flood level standard for the establishment of new bulk supply and zone substations. Its new standard requires zone substations to be built at or above the 0.5% AEP flood level (a so-called "200-year event"). That is more protective than a 1% standard. But like the freeboard standards adopted in Queensland and some jurisdictions in Texas, the 0.5% AEP flood level does not appear to follow from climate projections.

Including climate data can make a big difference. In the wake of Hurricane Sandy (2012), Con Edison, the electric utility serving New York City, was required by state regulators to add 3 feet (1 meter) to its plans to fortify several *existing* substations to account for expected sea level rise and a margin of safety. After 2 years of more deliberate study (which included consultations with climate scientists as well as robust public hearings), the utility concluded that the design standards of those fortified substations could be exceeded in <20 years. It has since raised the standard for all *new* construction in floodplains. Accordingly, the existing fortified substations are likely to be again retrofitted in the coming decades or abandoned (Con Edison, 2021).

In the United States and Australia, few electric utilities take future climate impacts into account in any programmatic way. According to researchers at Columbia University's Sabin Center on Climate Change Law, those in the U.S. electricity sector frequently cite "limited data availability as a hindrance to climate resilience planning" (Webb et al., 2020, 10, Box 5). Power companies do need better information, which continues to improve. They also need better decision-making tools—ones that are adaptive, rather than static, and that can accommodate deep certainty. Traditionally, electric utilities have based their investment decisions on cost-benefit analysis—a poor fit for disaster planning of many kinds (Verchick, 2010, 195–222). Cost-benefit models rely on quantified values for cost, harms avoided, and probabilities of loss. Where disasters are concerned—particularly those amplified by climate change—the degree of harm and probability of event are deeply uncertain. Cost of fortification may be the only value capable of plausible quantification, putting one in the cynic's position of knowing "the price of everything and the value of nothing" (Wilde, 1892/1995, 403).

More promising, we think, is a new wave of decision-making models based on flexible "policy pathways." Under this approach, utilities deploy no-or low-regrets resilience measures immediately and then set thresholds, or "trigger points," for taking actions that have greater trade-offs or that require more study. The trigger points "are based on pre-determined risk levels that, if left unaddressed, would result in severe impacts and potentially irreversible consequences." (Webb et al., 2020, 7–8). A trigger point, for instance, might be a calendar date indicating an era of statistically heightened storm risk or a finding that sea has risen 20% higher than had been predicted by that time. The goal is to put off long-lasting or irreversible decisions as long as possible in order to allow policy makers to learn as much as they can about the dimensions of the problem (Haasnoot et al., 2012; Kwakkel et al., 2016).

Another method, which relies on vast computational experiments, is called "robust decision making." Under this approach, pioneered by the RAND Corporation, researchers use powerful computers to subject policy options to a wide range of plausible, future scenarios in order to determine which option or set of options performs best over a range of varying circumstances (Lempert et al., 2013). The computational cost is high. In a hypothetical exercise involving a flood-prone river in the Netherlands, the evaluation of 14 policies over a range of scenarios required 70,000 computational experiments (Kwakkel et al., 2016, 179). Choosing the best decision-making approach obviously depends on the complexity of the task and the resources available.

It is a commonplace in climate change policy that the past is no longer a reliable measure for the future. Yet neither Texas nor Queensland has internalized this message in resilience planning. This situation is not only allowed, but arguably enabled by government decisions made at the federal level. While uncertainty in climate forecasts is sometimes cited as a reason for not considering future change, there are decision-making methods that can help policy makers protect people and property from future climate impacts even in the context of uncertainty. Such methods should be explored in Texas and Queensland.

Fit to Function

"Fit to function" is a phrase we use to describe the *level of governance* that is the best fit for the function that policy makers envision. The Texas and Queensland recovery prescriptions emphasize decision making and implementation at the local level. This tendency is sensible where climate resilience is concerned. Future climate impacts will be variable and contextual. Because of the urgency of the challenge and the lack of proven methods, experimentation—much of it occurring at the local level—will be key. Decentralization can also leverage local knowledge and take better account of community preferences (Camacho and Glicksman, 2019, 199).

There are some functions, however, that demand more centralized efforts. The development and distribution of scientific and economic research, for instance, would appear to benefit from economies of scale and the avoidance of redundancy. Financing expensive, protective infrastructure (whether machine-made or dependent on restored landscapes) is also an appropriate and necessary function of a federal or national government. The high cost of robust decision making, which demands high levels of computer power and expertise, also justifies a federal role. Because the design of infrastructure in one locality can significantly affect the welfare of citizens in other localities, there will often be a need for uniform standards, sometimes best implemented by a central authority (Camacho and Glicksman, 2019, 200–01). When the federal government is the primary funder, uniform standards also assure taxpayers that their money is being used prudently. Such assurances can help build public confidence in resilience efforts.

One example of such a standard is the U.S. Federal Flood Risk Management Standard, requiring federally funded infrastructure to be built with a higher margin of safety to account for future climate impacts like extreme floods and sea level rise (White House, 2021a). The standard, which was first issued by President Obama in 2015, was rescinded by President Trump in 2017 (before it could take full effect) and later *reinstated* by President Biden on his first day in office. Unfortunately, many federally funded infrastructure projects related to Hurricane Harvey had already been completed by the time the standard was reinstated.

While local autonomy is an important value (particularly where risk tolerance is involved), there is a fine line between delegating authority and abandoning responsibility. The Texas Report frequently reminds municipalities that their authority to select options will depend in part on their ability to pay. In summing up the section on city, rural, and industrial assets, for instance, the Texas report advises: "Each community must decide on its optimal portfolio of flood mitigation strategies, based on specific local characteristics and their ability to pursue them" (EOS, 2018, 122). The problem is that if the "local characteristics" include poverty or social marginalization, the prospect for meaningful choice is pretty narrow.

Under Australia's constitutional arrangements, the states and territories bear primary responsibility for flood risk management (Wenger, 2013, 65). A problem with assigning flood planning to local government is that local councils differ vastly in size and wealth. Thus, most of Australia's 537 local councils cannot afford to hire specialized flood management staff (Geneva Association, 2020, 29). The federal government has released a variety of tools, including the National Partnership Agreement for Natural Disaster Resilience, the National Climate Resilience and Adaptation Strategy; the National Disaster Risk Reduction Framework; and the National Land Use Planning Guidelines for Disaster Resilient Communities (Australian Government, 2015; Planning Institute Australia, 2015; Australian Government, 2018). They all refer to the need to build resilience to climate change but provide only high-level guidance to state, territory, and local governments—National informational tools include the AFRIP and the yet-to-be-completed Electricity Sector Climate Information Project to develop high-quality climate data and simulations to support power system resilience (CSIRO).

Over the last 10 years, these and other efforts have led to a significant improvement in "the coverage, consistency and quality of flood risk mapping across Australia." (Geneva Association, 2020, 32). Even so, the "limited availability of funding has led to a patchy approach to assessment and understanding of flood risk across Australia" (Geneva Association, 2020, 32). In Queensland many at-risk communities still lack flood mapping (Geneva Association, 2020, 32).

Scaling government action to fit the desired function is a perpetual challenge. While there are good reasons to prefer decentralized approaches in preparing for climate change, centralized action should be strongly considered in situations demanding large resources or in situations prone to spill-over effects from one community to another. In the cases of Texas and Queensland, policymakers are right to emphasize local decision-making and community engagement. But the U.S. and Australian governments have an obligation to ensure that the states and local governments have the requisite scientific information (including flood maps informed by climate data), scientifically informed guidelines for setting protective standards, and broad access to technical assistance. In regions, like watersheds where the actions of one community can affect the welfare of other communities, federal authorities have a duty to make sure a minimum standard, informed by climate data, is in place to protect everyone. Further, federal and state authorities should ensure that a community's lack of resources or technical expertise does not unduly restrain it in making choices to protect the welfare and property of its residents. These considerations should be integrated into future resilience plans in Texas and Queensland.

It is important to remember that discussions about jurisdictional scale also take place in a context of constitutionally delegated powers. While not identical, the federal frameworks of the United States and Australia are similar in prominent ways. Both nations show a cultural and constitutional preference toward state-based land-use planning, while the federal governments exercise broad authority to tax and spend. The concept of "co-operative federalism," broadly defined as an arrangement in which the state and federal levels of government share regulatory powers, is also a mainstay of energy and environmental policy in both countries (Wiseman, 2018, 235–37; Kallies, 2021, 212). Of course, what is legally or politically possible in the United States or Australia may be off-limits in nations with more centralized or de-centralized governance structures. Such difference must be taken into account in applying the lessons learned in our case studies.

Capably Financed

As the previous discussion suggests, where broad-scale resilience is concerned, affordability is a major issue. Electricity infrastructure requires large up-front capital investments. The U.S. and Australian governments have each contributed many billions of dollars in recovering from these storms and floods, but serious funding gaps remain. The emphasis in both countries on "back end" recovery efforts over "front end" risk-reduction efforts complicates the problem (Geneva Association, 2020, 45). After all, smart investments in disaster prevention can repay themselves many times over (Bratspies et al., 2018, v).

In Texas, Houston has recently announced that a US$1.4 billion shortfall could delay completion of its post-Harvey recovery efforts. The city had been hoping for a 2021 federal disaster grant which instead went to other parts of the country (Lazano, 2021; Oberg and Hatfield, 2021). According to the *Associated Press,* "[t]he projects in need of the most funding are in some of the area's poorest neighborhoods that have repeatedly flooded in recent decades" (Lazano, 2021). The state of Texas is charged with allocating US$4 billion in federal funds to local communities, an insufficient amount that has led to much interregional squabbling, including allegations that Governor Abbot has inappropriately taken control of federal funds that were originally intended for Houston (Oberg and Hatfield, 2021). President Biden has promised to invest boldly in climate resilient infrastructure and a modernized grid (White House, 2021b; Worland, 2021). At the time of this writing, it remains to be seen if federal lawmakers will follow his lead.

In Australia, those calling for strong investment in grid modernization were disappointed by the release of the nation's 2021–22 budget (Hancock, 2021). Although the budget promises investment of more than AU$15 billion investment in road, rail, and freight upgrades, investments in upgrading the grid were <AU$50 million (Commonwealth of Australia, 2012, 47).

The electricity markets in Texas and in Australia are light on regulation and heavy on consumer choice. Such market-friendly approaches, in theory, maximize capital investment by allowing utilities to recover capital expenditures through higher rates. This was the idea behind "retail choice": if a utility knew it could charge a high price during an ice storm, it would have an incentive to make sure its equipment could operate in such conditions. While some argue that price spikes during winter storms were theoretically sufficient to encourage generators "to invest in protecting their equipment or building backup resources," this clearly did not happen (Gimon, 2021, 10). It seems that not even the utilities understood the probabilities well-enough to see that resilience investments would have paid off handsomely (Gimon, 2021, 11). Or maybe they correctly predicted that customer backlash would deprive them of such profiteering.

The Australian Energy Market Operator (AEMO), which regulates the nation's electricity market, also uses a "retail choice" model, but with a safety valve. AEMO caps the maximum spot price for retail electricity at AU$15,000/MWh (about US$11,126/MWh) with an automatic emergency cap of AU$3,000/MWh (or $US2,225/MWh) that is triggered during sustained periods of high prices. (AER, 2019; AEMO, 2020, 15) Texas caps the spot price for electricity at US$9,000 per MWh but without an emergency cap (Blumsack, 2021). But like the Texas model, Australia's market-friendly system is not enough on its own to attract the capital needed to build a sustainable grid. Generally speaking, Australia's "return on investment" formulas for establishing rates are more oriented toward efficiency and resilience than similar models in the United States. However, some argue there is still a gap between what universal resilience demands in up-front investment and what Australia's electric utilities are able to recover from customers (ENA, 2015, 7–8).

Investing in climate resilience makes good economic sense, but the up-front costs are high. Modernizing the electricity grid in the United States or in Australia will require tens of billions of dollars. The longer that governments defer these investments, the costlier these projects will be (and the more damage they will incur in the meantime). Current levels of government funding are insufficient to drive the change that is needed. Further, formulas used in regulating electricity rates may not adequately encourage utilities to invest in resilience measures or smart-grid technologies on the scale that is required. This is particularly true in the United States (Aas and O'Boyle, 2016). The U.S. and Australian governments should robustly fund grid resilience and modernization. Governments at the federal or state levels should revisit pricing formulas to encourage investments in resilience. These governments should also consider mandating use of certain resilience technologies as a way of driving modernization in the electricity sector.

CONCLUSION

Protecting the power grid from climate disaster is not a job that will be completed quickly or easily in any country. Strictly speaking, it will never be completed at all. Because climate change is a dynamic process and because our knowledge and technology will continually evolve, the pursuit of climate resilience is an ongoing task. What won't change, we believe, is the need for policies that are *forward-looking*, "*fit to function*," and capably *financed*. In protecting electricity infrastructure against the ravages of climate breakdown, Texas and Queensland are on the right track. Still, they can do more in each of those areas.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Shifting Baselines May Undermine Shoreline Management Efforts in the United States

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Rising sea levels, extreme weather events, and unsustainable coastal zone development pose serious threats to growing coastal communities. Human actions, such as shoreline development and hardening in at-risk areas, can damage nearshore ecosystems and exacerbate existing risks to coastal populations. A comprehensive understanding of shoreline changes in response to development, storm events, and sea-level rise is needed to effectively mitigate coastal hazards and promote adaptive and resilient coastlines. To determine whether human modification of shorelines can be accurately quantified and assessed over time, we evaluated past and present shoreline mapping and classification efforts in the United States. We coupled a review of available US shoreline data with a survey of coastal planners and managers involved with US state shoreline mapping programs. Using these data, we estimated the current extent of shoreline modification along the Atlantic, Pacific, and Gulf US coasts. However, we found that quantifying shoreline modifications over time nationally—or even within a single state—is currently infeasible due to changes in shoreline resolution associated with advances in shoreline mapping methodologies and a lack of regularly updated shoreline maps. State-level analysis from surveys revealed that 20 US coastal states have undertaken shoreline mapping projects, with sixteen tracking shoreline type and/or condition. However, of the 36 shoreline maps and databases identified, only half (18) were updated regularly or had planned updates. Lacking shoreline change data, coastal communities risk accepting increasingly degraded coastal zones and making poor management decisions based on shifted baselines. Thus, we recommend increasing the scale and funding for several ongoing innovative shoreline mapping efforts. These efforts are particularly focused on improving and standardizing shoreline mapping techniques, as well as establishing accurate baselines for shoreline conditions in the United States. Without accurate baselines and regular, consistent updates to shoreline data, managers cannot manage shorelines in a way that effectively mitigates coastal hazards while also promoting socio-ecological resilience in a changing climate.

Keywords: coastal protection, shoreline hardening, coastal management, hazard adaptation, shoreline mapping

INTRODUCTION

Global coastal zones are home to dense and increasing populations. Although the world's coast represents only 20% of the global land area, it hosts 41% of the world's population (Martínez et al., 2007). Twenty-one of the world's 33 megacities, each containing more than 8 million people, lie within 100 km of the coast (Martínez et al., 2007). In the United States (US), 14 of the 20 largest cities are situated on the coast, with the rate of land consumption in these areas often greatly outpacing the growth rate of the population (Pew Oceans Commission, 2003). From 2003 to 2015 alone, the US coastal population increased by 14.3 million people (Martínez et al., 2007), and there is no indication that this growth will slow in the coming decades (Neumann et al., 2015).

Rapid coastal population growth has significant social and environmental implications. The development, resource extraction, and pollution associated with growing populations will place increasing burdens on coastal ecosystems (Martínez et al., 2007; Titus et al., 2009). Population growth is occurring in areas which are highly vulnerable to coastal hazards, posing risks to residents. On the US East Coast, roughly 60% of land lying below the benchmark of one meter above sea level is projected to be developed and populated, according to current state and local government land-use plans (Titus et al., 2009). In these areas of low elevation, the threats of storm surge, sea-level rise (SLR), and flooding are most acute. Even conservative SLR estimates (0.9 meters by 2100) place 4.2 million US coastal residents at risk of inundation in just 80 years (Hauer et al., 2016). Present-day extreme flooding events will occur more commonly in the coming decades due to rising sea levels, with the odds of extreme coastal flooding in most parts of the US doubling every 5 years (Taherkhani et al., 2020). Alterations in storm climatology are also expected to increase the frequency and severity of these flood events (Trenberth, 2005; Elsner et al., 2008).

In what Burby (2006) dubs the "safe development paradox," governments inadvertently facilitate the destruction of hazardous areas by making them appear safe for human development, placing more people and property at risk than would have been endangered without these initial ameliorating actions. For example, construction of the New Orleans levee system spurred unprecedented urbanization in newly protected high-risk, reclaimed wetlands between Lake Pontchartrain and the Mississippi River floodplains. By convincing residents that the region was safe and therefore enabling development, the perceived protection conferred by engineering efforts exacerbated the devastation of Hurricane Katrina (Burby, 2006; Freudenburg et al., 2009); a similar situation has unfolded on Galveston Island, Texas (Dolan and Wallace, 2012).

As the dangers to coastal zones and their inhabitants mount with climate change and continued development, a premium has been placed on coastal protection. Homeowners and developers commonly use shoreline hardening techniques to protect against floods and prevent erosion (Hartig et al., 2011; Dethier et al., 2017), aiming to create a static shoreline. Shoreline hardening is particularly common in coastal urban areas with high housing density (Gittman et al., 2015). Depending on the ecological and hydrodynamic setting, hardened structures may include seawalls, bulkheads, riprap revetments, or breakwaters (*sensu* Figure 1 in Gittman et al., 2015). Shorelines are hardened to provide benefits like flood prevention and erosion control; however, hard structures can have numerous negative impacts on coastal habitats. Shoreline hardening can scour shore zones and contribute to erosion, starve downstream shore zones of sediment, and fragment intertidal habitats (Vona et al., 2020). This fragmentation can lead to reductions in genetic diversity and population stability (Douglass and Pickel, 1999; Hartig et al., 2011). Hardened shorelines can also reduce biodiversity by decreasing the abundance of local flora and fauna (Morley et al., 2012; Gittman et al., 2016). Hard structures can alter the structure and function of local ecological communities by changing food webs from consumer- to producer-dominant (Martins et al., 2009) and facilitating the spread of invasive species (Thompson et al., 2002; Bulleri and Airoldi, 2005).

Although individual hardening projects may have small spatial footprints, their cumulative geomorphological and ecological effects can manifest at the regional scale, illustrating the broad reach of their negative impacts (Peterson and Lowe, 2009; Dethier et al., 2016; Kornis et al., 2017). Coastal managers require detailed shoreline data to effectively manage the coastal zone (Goncalves and Awange, 2017) and to monitor its constituent restored and natural coastal systems (Narayan et al., 2016; Arkema et al., 2017). Without baseline data describing the position, type, and condition of shorelines, it is impossible to estimate the true socio-ecological impacts of human development on coastal ecosystems and supported services (Halpern et al., 2008; Bugnot et al., 2020). Further, identification of possible adaptation pathways for mitigating hazard and climate-change related impacts on coastal communities and ecosystems requires analyses of the uncertainties and risks associated with current coastal conditions (Buurman and Babovic, 2016). Otherwise, incremental efforts taken to reduce risk outside of intentional adaptation pathways, such as construction of traditional shoreline hardening structures to protect coastal communities, may be maladaptive (Magnan et al., 2020). The ability to conduct such analyses is dependent on the availability of accurate and current data on the condition of coastal shorelines. The feasibility and desirability of potential risk reduction tools are not static, but rather fluctuate based on the climatic and socio-economic conditions of the system (Magnan and Duvat, 2020). When they lack dynamic data, coastal communities risk accepting of increasingly degraded coastal zones and increasingly hardened shorelines, a phenomenon known as "shifting baseline syndrome"(Pauly, 1995). Shifting baseline syndrome is the measure of the current state of a system against a reference point (baseline) that is perceived to be the norm, which may not be a historical or accurate reflection of the system's pristine baseline (Soga and Gaston, 2018). Although coastal development has been occurring for centuries along coastlines, having an accurate baseline for current shore conditions would be helpful for management decisions moving forward.

The goal of this study was to critically assess whether coastal managers and scientists are collecting and have access

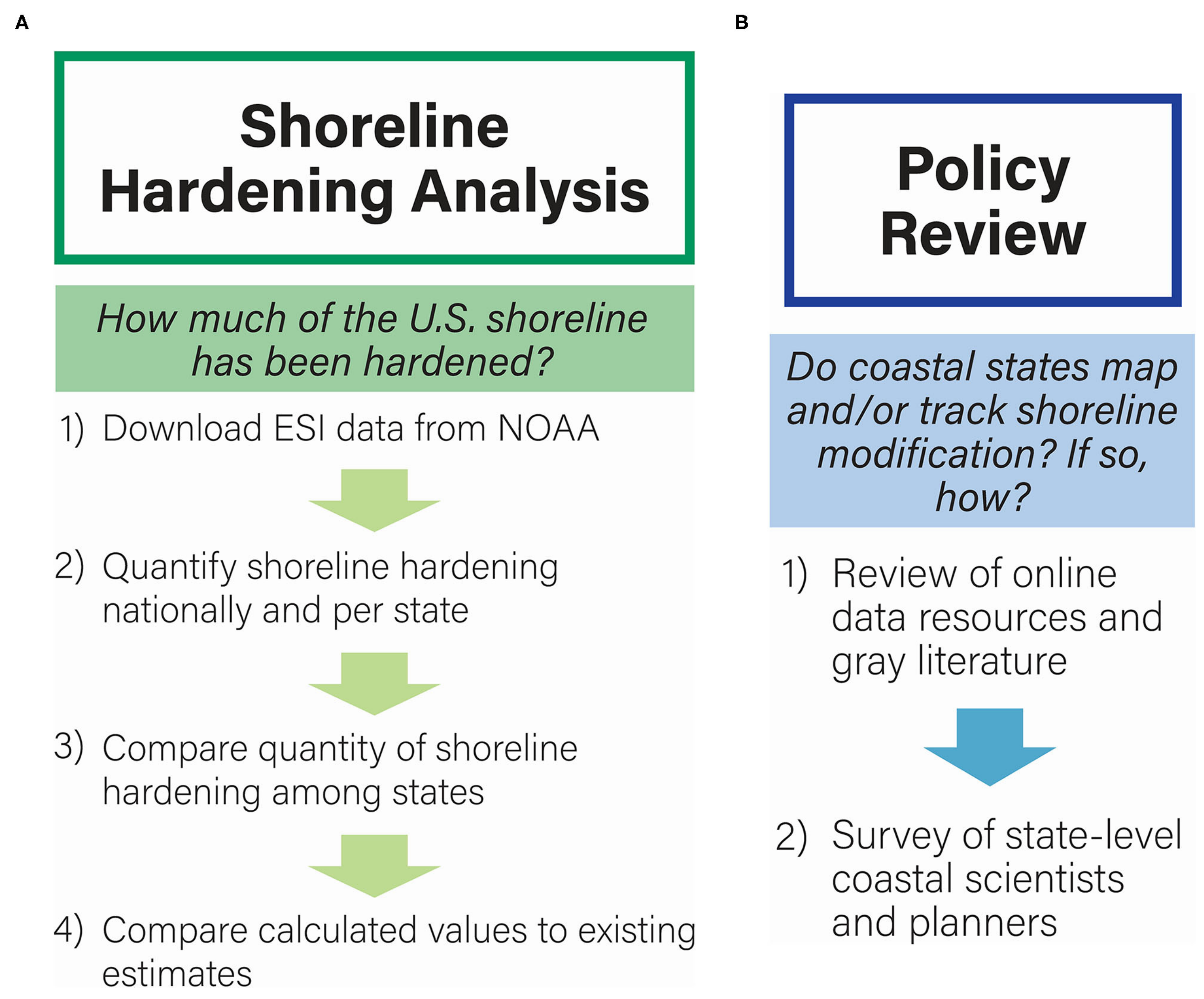

FIGURE 1 | Conceptual diagram outlining the steps used to **(A)** estimate the total (length) and proportion of hardened shoreline to total shoreline for each coastal state based on NOAA ESI data; and **(B)** conduct the state-by-state shoreline mapping review.

to shoreline hardening and modification data necessary to establish baseline shoreline conditions and to quantify changes in shoreline conditions over time in the United States. A comprehensive assessment of shoreline hardening could be used to evaluate complex socio-economic factors influencing coastal development decisions (Scyphers et al., 2014, 2015, 2019; Smith and Scyphers, 2019; Stafford and Guthrie, 2020; Gittman et al., 2021). The ecological effects of shoreline armoring are well-documented, as are the environmental benefits of nature-based alternatives such as living shorelines (Bilkovic and Mitchell, 2013; Mitchell and Bilkovic, 2019). Living shorelines' ability to reduce erosion has also been studied (Gittman et al., 2014; Bilkovic and Mitchell, 2017). However, the lack of side-by-side comparisons of the physical protective capabilities of natural or nature-based vs. hardened shoreline management strategies has been identified as a major hurdle in the wider promotion and adoption of nature-based shoreline management (Arkema et al., 2017; Morris et al., 2018). Comprehensive surveys of shoreline hardening can help facilitate these comparisons.

Here, we assess the current state of shoreline modification mapping across the US. We evaluate publicly available geospatial data to provide an updated estimate of the extent of hardened shoreline along the Atlantic, Pacific, and Gulf coasts of the United States, and to determine whether rates of shoreline modification, particularly shifts from natural to hardened shorelines, can be accurately quantified over time nationally or at the state-level (**Figure 1A**). Further, we present an overview of shoreline mapping efforts within 22 coastal states, drawing on information obtained from a review of state coastal management webpages, online databases, and responses from an email questionnaire sent to coastal managers within each state (**Figure 1B**). Finally, we make recommendations for developing standardized shoreline mapping approaches and highlight specific policies and practices currently being developed that could be used to assist coastal managers in adaptively managing and conserving shorelines.

METHODS

Shoreline Hardening Analysis

Within the US, there is no complete, standardized dataset identifying each stretch of human-modified shoreline and the specific modification that has occurred (e.g., hardening, such as breakwaters, revetment, bulkhead, seawall; or restoration, such as marsh planting and oyster reef restoration). However, some attempts to amalgamate national and state-level shoreline modification monitoring efforts into singular datasets have been made, with varying resolutions, accuracies, degrees of completion, and methodologies. In our attempt to quantify shoreline modifications on a national level, we utilized one of the longest standing and most complete sources of shoreline modification data, the National Oceanic and Atmospheric Administration's (NOAA) Office of Response and Restoration (OR&R) Environmental Sensitivity Index (ESI), first collated in 1982 (NOAA, 2019).

ESI data are derived from a variety of sources at the local and national levels; including pre-existing datasets provided by state agencies and universities, aerial imagery, NOAA Continually Updated Shoreline Product (CUSP) data, NOAA national shoreline data, data from NOAA's coastal change analysis program (C-CAP) and data collected specifically for the ESI update effort (Petersen et al., 2019). During the update process, NOAA works with regional resource experts who advise on the use of data from specific regions (Petersen et al., 2019).

In order to provide accurate shoreline classifications, these baseline data are supplemented with specific information on shoreline type. These data are derived from ground and aerial surveys from early ESI classification efforts; low-altitude aerial imagery from Google Earth, Bing, and ShoreZone; and additional coastal habitat maps (Petersen et al., 2019). In some instances where earlier ground data are outdated or aerial imagery is unclear, new overflight data collections or ground observations are performed, but this costly and time-consuming process is limited to select areas (Petersen et al., 2019). The scale for ESI datasets must be 1:24,000 or larger, though published guidelines recommend using a scale no larger than 1:4,000 for shoreline classification (Petersen et al., 2019).

Although originally developed for emergency managers to model impacts from oil spills, previous work by Gittman et al. (2015) determined that ESI data contain the most comprehensive and current shoreline modification information available for US shorelines. As part of the ESI's shoreline sensitivity ranking systems, shorelines are ranked into 29 standardized classifications and subclasses based on their physical and biological characteristics (**Supplementary Table S1**). These characteristics include exposure to wave and tidal energy, shore slope, substrate type, biological productivity and sensitivity, and the presence of anthropogenic modifications. ESI data were first analyzed for the purpose of quantifying shoreline hardening in the US in 2015 (Gittman et al., 2015). Since that study, 19 of the 22 originally analyzed states have provided either partially or completely updated ESI data, with update dates ranging from 2014 to 2016 (**Supplementary Tables S2, S4**—Alabama, California, and Mississippi have not provided updates).

In this study, we examined both (1) whether shorelines are hardened and (2) how they are hardened (e.g., riprap, seawalls, combination). Following methodology by Gittman et al. (2015), we imported ESI data to ArcGIS 10.7 software and calculated linear kilometers of shoreline using the Calculate Geometry tool (ESRI, 2020). ESI shoreline rankings of 1B (exposed, solid man-made structures), 6B (riprap), 8B (sheltered, solid, man-made structures), and 8C (sheltered riprap) were binned as modified shoreline and sub-binned as riprap (6B, 8C), seawall (1B, 8B), or "combination" if the segments of shoreline contained multiple types of hardening techniques (e.g., a segment classified as 6B and 8B). Any segment of shoreline containing one or more of these ESI ranks was binned in one of these categories, even if it also contained natural shoreline types (e.g., a segment classified as 8B and 10A would be classified as 8B). Recent work has suggested that different types of hardening (e.g., seawall vs. riprap) and different combinations of hardening and natural shoreline (e.g., seawall with and without marsh vegetation) do not have equivalent ecological impacts (Bilkovic and Mitchell, 2013; Gittman et al., 2016; Kornis et al., 2017). The intent of this study was to quantify all combinations shoreline hardening to allow for direct comparison with previous work by Gittman et al. (2015). Comparisons of ecological impact of different combinations of hardening is beyond the scope of this study.

Review of State-Level Shoreline Modification Monitoring Efforts

To better understand how individual states map and track shoreline modification and condition, we conducted a gray literature review with keyword searches in common internet search engines (see **Supplemental Materials**), state agency websites, and publicly available digital data. After our initial keyword search, we contacted coastal scientists and planners involved with each state's respective shoreline mapping program (**Supplementary Table S2**). We asked the following questions about each state's shoreline modification monitoring and mapping efforts: (1) Does this state have a coastal mapping program? (2) Does the program track shoreline hardening, shoreline type, shoreline position change all, or none? (3) Are the data from this program publicly available? (4) When were these data last updated? (5) Are the data updated on a set schedule? If we did not receive an initial response, we followed up the initial email with two additional messages.

RESULTS AND DISCUSSION

Shoreline Hardening in the United States

In total, of the 277,633 km of shoreline surveyed in the contiguous US, 28,357 km were modified with hard structures (i.e., seawall, riprap, or combination), representing ∼10% of the contiguous U.S. shoreline (**Figure 2**, **Supplementary Table S3**). Overall, "solid man-made structures" (ESI types 1B and 8B) were

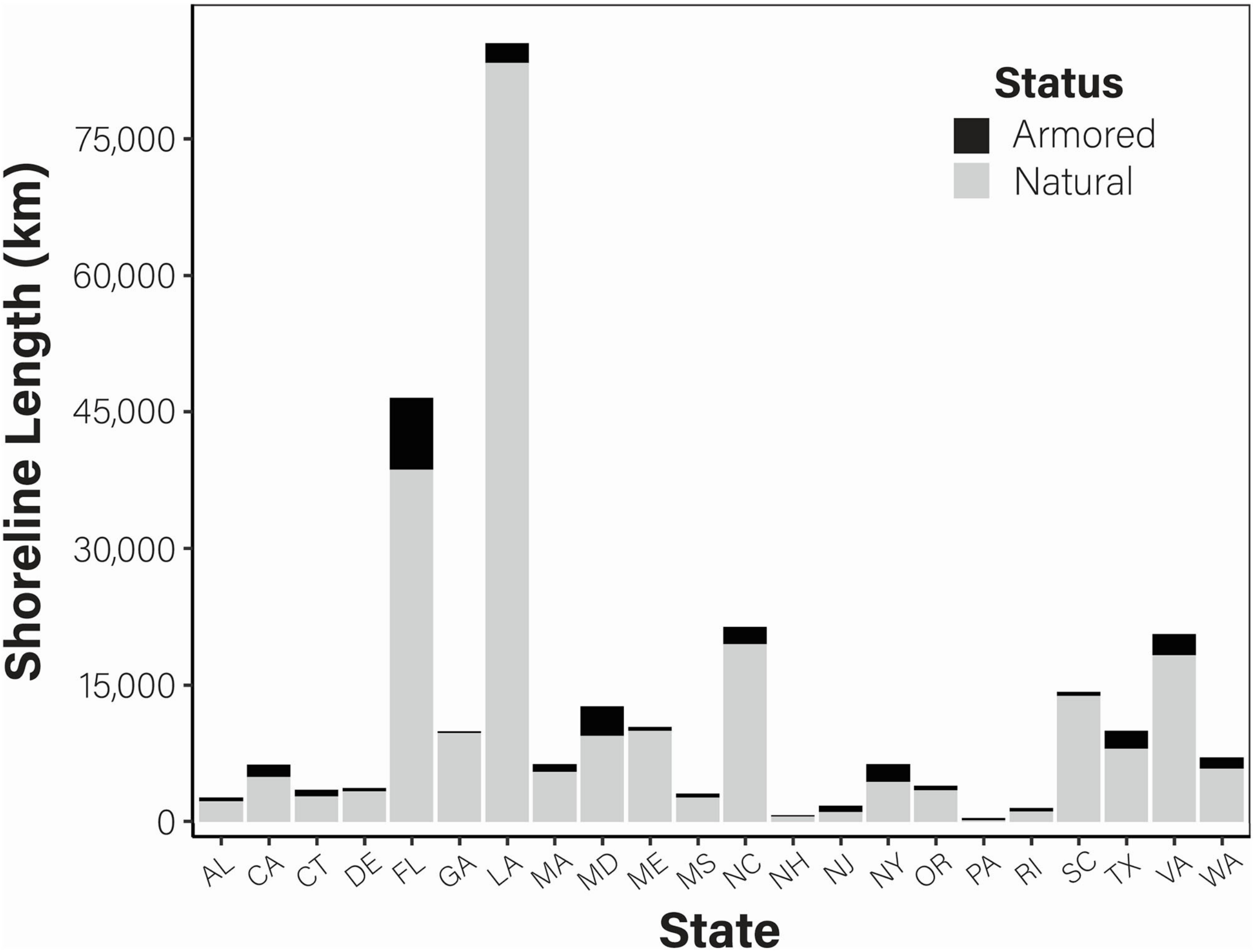

FIGURE 2 | Total length of natural (gray) and armored (black) shoreline in each U.S. coastal state. Note that direct comparisons of shoreline estimates across states are limited because the most recent update year and methodologies for mapping the shoreline varies from state to state. These data represent the best available national estimate of shoreline hardening in the United States.

the most prevalent type of shoreline modification, representing 17,211 km or 61% of hard structures; this category includes "[solid, non-riprap] revetments, seawalls, piers, and docks constructed of concrete or wood" (NOAA, 2019). Riprap (types 6B and 8C) and combinations of multiple shoreline types composed the remaining hardened structures (10,305 and 844 km, respectively). The majority (13,431 km) of solid, man-made structures were classified as ESI type 8B, meaning they are located on shorelines sheltered from wave energy and strong tidal currents rather than exposed shorelines (**Supplementary Table S1**).

Despite these national trends, the most common type of hardening varied among states (**Supplementary Table S1**). The state with the greatest amount of hardened shoreline relative to its total shoreline was Pennsylvania, with 54%, followed by New Jersey (36%) and New York (30%) (**Figure 3**). North Carolina and New Hampshire had the least hardening relative to their total shorelines, with around 8% of their shorelines hardened (**Figure 3**, **Supplementary Table S3**). However, it should be noted that states with large amount of shoreline have more to harden and thus the total length of hardened shoreline is also important to consider (**Figure 2**, **Supplementary Table S3**). Further, the shorelines of the Great Lakes were not included in this analysis, thus estimates of shoreline length and hardening for states bordering the Great Lakes will not include those shorelines. The state with the greatest amount of hardened shoreline overall was Florida (7,848 km) while the state with the smallest amount was New Hampshire (53 km). Previous work suggests that shoreline hardening is often associated with densely populated coastlines (e.g., around New York City), to protect both commercial and residential development and infrastructure (Dugan et al., 2011; Gittman et al., 2015). Outside of metropolitan areas, shoreline hardening may be occurring in response to heightened vulnerability of coastal development and infrastructure to storm events, such as hurricanes on the Atlantic Coast.

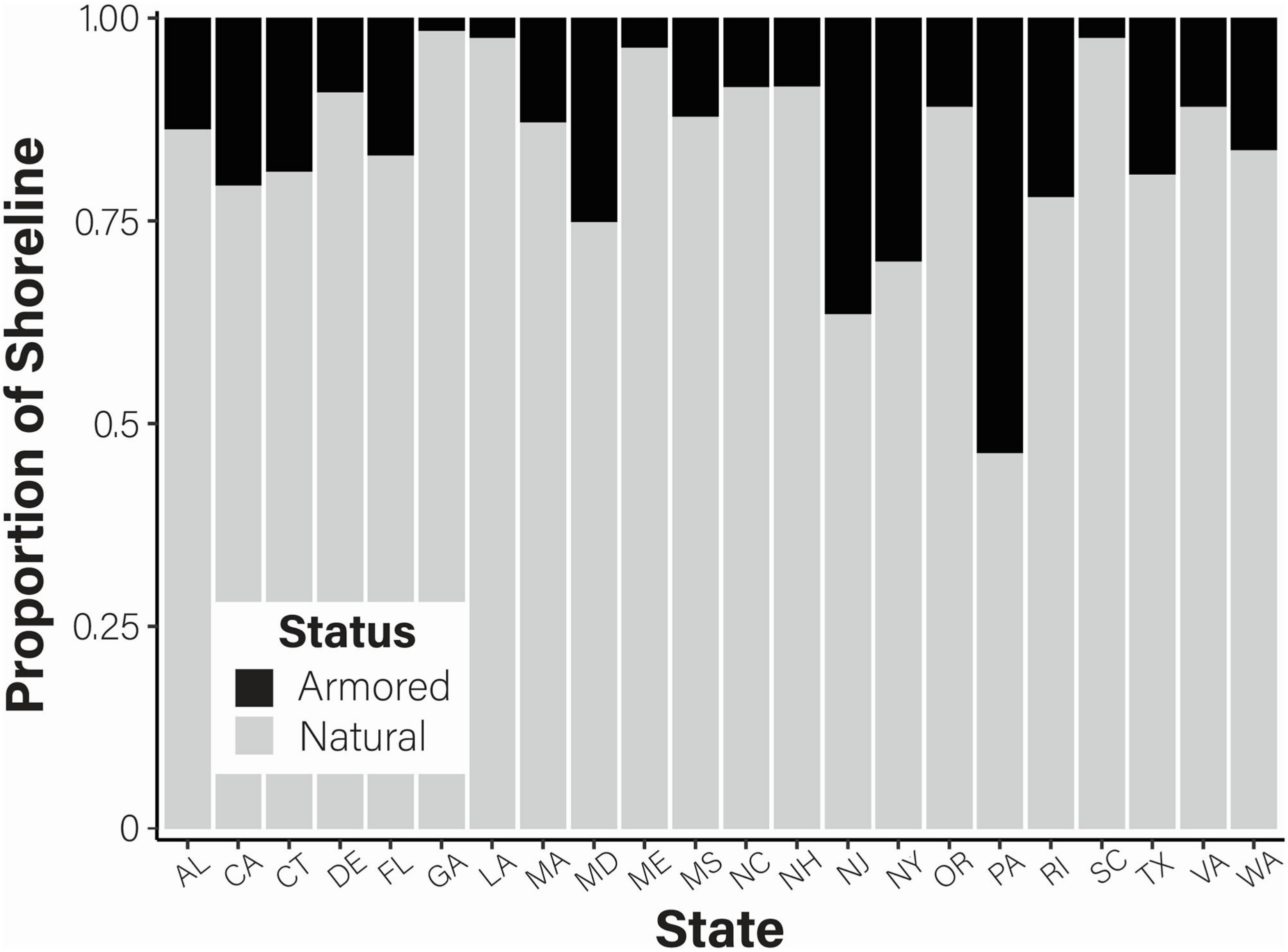

FIGURE 3 | Proportion of natural (gray) and armored (black) shoreline in each U.S. coastal state. Note that direct comparisons of shoreline estimates across states are limited because the most recent update year and methodologies for mapping the shoreline varies from state to state. These data represent the best available national estimate of shoreline hardening in the United States.

Comparison to Previous Shoreline Hardening Estimates

Since the original study conducted by Gittman et al. (2015), the relative amount of hardened shoreline in the U.S. has declined by ∼4%, from 14 to 10%. However, our study expanded the amount of shoreline analyzed by 117,465 km (173%) and found that the absolute length of armoring increased by 5,515 km (124%). Therefore, although hardening percentages decreased based on the updated data, the total amount of hardening increased. An expanded mapping range (e.g., mapping further upstream) and changes in map resolution likely contributed to this discrepancy. When small stretches of the same shoreline (1–5 km) were compared between this study and the 2015 study datasets for different years (e.g., 2011 vs. 2016 in North Carolina, **Supplementary Table S2**) they differed in resolution, with more detailed reticulation of the shoreline being represented in 2016 data. Further, when a shoreline is hardened, the shoreline length can change, *via* reduced reticulations of the shoreline, thus making shoreline comparisons over time challenging. While ESI data provide an overview of shoreline type and armoring throughout the US, our results show that they cannot be used to easily—or accurately—track alteration in the extent of hardening over time. Comparison of individual state datasets from different time periods that use different shoreline delineation and characterization methodology, in combination with differing resolution of data can result in the "coastline paradox." The coastline paradox posits that the delineation of shoreline length is characterized by fractal dimension, whereby shoreline length increases as data resolution increases and vice versa (Mandelbrot, 1967). These differences in shoreline length and resolution prevented us from estimating changes in hardening over time or calculating annual rates of shoreline hardening. These data discrepancies and availability issues are not unique to our study. Rather, US states and federal agencies consistently fail to collect the types (or quantities) of data necessary to evaluate program outcomes and efficacy (Bernd-Cohen and Gordon, 1999).

State-Level Shoreline Mapping Review

Although shoreline mapping and data management methods varied across states, our review of state-level shoreline mapping

TABLE 1 | Summary of state-level shoreline mapping programs.

State	Extent of shoreline mapping program	Program maps shoreline type?	Program maps shoreline change?	Frequency of updates
Alabama	Statewide	Yes	Yes, segments	Type: no regular updates Change: updated annually
California	Statewide	Yes*	No	No regular updates
Connecticut	Statewide	Yes	Yes	No regular updates
Delaware	Segments	Yes, segments[a]	No[e]	Wetlands data: updated every 10–15 years.
Florida	Statewide	No	No[e]	Update frequency unavailable.
Georgia	Statewide	Yes	Yes	Change/type: updates are funding dependent.
Maine	Statewide (length) and segments (change)[b]	No	Yes, segments[c]	Change: updated monthly. Highest astronomical tide, marsh migration, and coastal bluff mapping: updated approximately every 4 years.
Maryland	Statewide	Yes	Yes	No regular updates
Massachusetts	Statewide	Yes	Yes	Type: no regular updates Change: updated bi-annually
Mississippi	Statewide	Yes	Yes[e]	No regular updates
New Hampshire	Statewide	Yes	Yes[c]	Type: update planned Change: no regular updates
New Jersey	Statewide and segments	Yes, segments[d]	No[e]	Type: updated as new projects emerge Profile: updated as new base data become available (semi-regularly)
New York	Segments	No	Yes, segments	Update frequency unavailable.
North Carolina	Statewide	Yes	Yes	Type: updated as data becomes available
Oregon	Statewide and segments	Yes	Yes, segments	Type: no regular updates Change: updates vary by location Profile: updated with NOAA CUSP
Rhode Island	Statewide	Yes	Yes*	No regular updates
South Carolina	Statewide	Yes	Yes	Update frequency unavailable.
Texas	Statewide	Yes, segments	Yes	Change/type: Coastwide surveys performed approximately every 10 years and after major storms.
Virginia	Statewide	Yes	Yes	No regular updates
Washington	Segments	Yes	Yes, segments[e]	Update frequency unavailable.

Superscripts a–e specify what type of shoreline is mapped if mapping only occurs on specific, high-priority segments of shoreline. (a) Inland bays (b) Shorelines dedicated as high erosion risk (c) Beaches (d) Living shorelines. Superscript e indicates that although the state does not track shoreline change, historic shoreline maps are publicly accessible online. Asterix (*) indicates that the maps and/or databases in question are still in development.

efforts revealed that 20 coastal states have mapped either their entire shoreline or a portion of their shorelines at least once. More specifically, 16 states track shoreline type and/or modification in a variety of ways, with states creating modification databases, mapping nearshore habitats, tracking shoreline structure permits, or mapping hard shore structures (**Table 1**, **Supplementary Table S4**). Additionally, 15 states track changes to shoreline profiles over time. Of those, nine states map positional change over their entire coastline, while six states calculate positional change rates only for select shoreline segments, usually in areas of high erosion risk, like beaches.

We initially attempted to distinguish between states that had ongoing coastal mapping initiatives and those that had mapped their shorelines in the past; however, we found it difficult to make this distinction. Some states have several, disparate and separately funded shoreline mapping efforts, of which some are active and others inactive, and other states have programs that are inactive due to funding availability. Despite the large number of mapping programs across the 22 states surveyed, only a few of the resulting shoreline maps and databases have plans for updates (**Table 1**, **Supplementary Table S4**). Out of the state shoreline mapping programs examined, nine are either continuously updated or updated on a regular interval, while another nine states have plans for updates which depend upon funding and the availability of parent datasets (**Table 1**, **Supplementary Table S4**). Many states supplement their mapping efforts with data from nationwide efforts to track shoreline type and positional change, including ESI data, the United States Geological Survey (USGS) National Assessment of Shoreline Change (NASC), the NOAA National Shoreline, and NOAA CUSP.

Like state-specific datasets, these national shoreline mapping efforts have their own unique methodologies, resolutions, and update frequencies. For example, NASC is an effort to calculate shoreline change rates and trends for open-ocean coasts, using shoreline data from NOAA historical survey topographic sheets, USGS Light Detection and Ranging (LIDAR), data from the

Army Corps of Engineers, and digitized shorelines from various coastal management departments in specific states (Hapke et al., 2010). Although the data sources vary, the methods that NASC researchers employ to assess rates of shoreline change are internally consistent (Hapke et al., 2010). The Army Corps of Engineers (USACE) is utilizing this USGS shoreline change data in its ongoing National Shoreline Management Study (NSMS). The policy-focused national project involves a series of regional reports on the mechanisms behind coastal erosion, the economic and environmental effects of these shoreline changes, and existing federal, state, and local erosion management initiatives (Grandpre et al., 2018). Another national mapping initiative, NOAA National Shoreline, is a vector shoreline map based on converted NOAA National Ocean Service historical survey topographic sheets and aerial imagery. Mapping dates range from 1855 to the present, with differential update schedules based on geographic segment (National Geodetic Survey, 2021a). Lastly, NOAA CUSP is a continuous map of the US shoreline; generally delineated based on the Mean High-Water line. It covers a wider area than the NOAA National Shoreline and is updated more frequently (National Geodetic Survey, 2021b). CUSP draws on both NOAA and non-NOAA sources, including vectors and lidar from the National Geodetic Survey, USGS, NOAA Digital Coast, the National Wetlands Inventory, the US Department of Agriculture, and commercial satellites (National Geodetic Survey, 2021a). Due to the broad data sources used to create each of these respective datasets, standardization is limited across data sources. For example, the scale of individual sources of data can influence the overall accuracy and completeness of the collated information (e.g., NOAA CUSP source scales can range from 1:1,000 to 1:24,000, full or partial shoreline delineation by individual states); which can result in increased risk of error and broader interpretation of shoreline characteristics like location, habitat type, and presence and type of shoreline modification (Moore, 2000).

In our correspondence with state coastal managers, several challenges related to shoreline mapping recurred. These challenges included (1) a lack of funding for mapping and classification efforts; (2) lack of a consistent update schedule (intertwined with challenge 1); (3) non-intuitive data storage conventions or locations (e.g., data were often hard to find, even when they existed); and (4) incompatibility between various maps and datasets, given that mapping products are often produced by different organizations and not standardized. With the exception of Massachusetts' MORIS and Alabama's Center for the Advancement of Science in Space (CASIS), most states lacked a central coastal data repository. Thus, we cannot ensure that all relevant state datasets were identified and included. Additional coastal datasets, which were not identified by our standardized search terms, posted on state websites, or brought to our attention by coastal managers, may likely exist and limit the extent of this review of monitoring efforts. Similarly, while state shoreline profile maps could often be obtained upon request, they were not always readily available through online portals, which can be an impediment to data accessibility and may in turn influence shifting baseline syndrome. These data acquisition challenges highlight the need for a comprehensive central repository of shoreline monitoring data at the state and/or national levels.

Shifting Baselines in Shoreline Management

Coastal development and change occur over multiple temporal scales, from the short-term storm surge and damage caused by extreme storms to the long-term change due to ambient wave attack of a shoreline. Over time, increasing amounts of unsustainable coastal development and concomitant degradation of natural resources can result in shifting baseline syndrome (Sundblad and Bergström, 2014). The three primary causes of shifting baseline syndrome are: (1) lack of data; (2) loss of familiarity; and (3) loss of interaction (Soga and Gaston, 2018). This study has elucidated the lack of recognized standards for shoreline delineation and characterization at both the national and state levels. This study has also illuminated limitations to state-driven monitoring efforts due to challenges that include lack of funding, inconsistent update schedules, data storage issues, and compatibility issues related to varying data management standards. Coastal managers and scientists involved with shoreline monitoring programs further identified issues associated with inconsistent data, poor resolution, and data gaps, inhibiting transfer of data to coastal communities regarding hardening of their shorelines and, therefore, the loss of intertidal habitats that can support local economies. Without accurate data quantifying how the amount and location of shoreline modifications is changing over time, coastal managers cannot make informed decisions about the socio-ecological impacts of shoreline modification. Further, community perceptions of what constitutes a natural or socio-ecologically acceptable shoreline condition may shift over time, resulting in continued degradation of coastal ecosystems.

With a lack of data comes a loss of knowledge of an area's natural history. Select groups within a community (e.g., scientists, academics, naturalists, coastal managers) serve as warehouses of natural history knowledge (Soga and Gaston, 2018). However, the presence of these experts within a community does not necessarily translate to knowledge transference to the broader population (Fanini et al., 2019). Current and projected immigration of populations to coastal zones are resulting in more and newer coastal community members who may not have generational or local historic knowledge of an area's ecological baselines, resulting in a shifting of these baselines in the community consciousness. This loss of knowledge is further complicated by individual property management decisions and subsequent legacy effects. When individual homeowners choose to harden their shorelines, their neighbors are more likely to harden their shorelines as well, resulting in cascading impacts within an area (Scyphers et al., 2015; Gittman et al., 2021). Waterfront homeowners are also more likely to prefer to repair or keep their existing hard structure (e.g., revetment, bulkhead, seawall; Scyphers et al., 2015) rather than replace it with a more natural alternative; despite the negative ecological and geomorphological impacts of hard structures. Accurate data and improved understanding of shoreline hardening impacts, particularly threshold effects at regional scales, could better enable coastal managers and private landowners to weight the costs and benefits in shoreline stabilization decisions (Dayton et al., 2000; Soga and Gaston, 2018).

A Call for Improved Shoreline Mapping and Monitoring Programs

As coastal populations grow and development follows, hardening will continue to impact US shorelines. Recent analysis indicates that there is a serious lack of data describing the extent of coastal armoring (Bugnot et al., 2020). In fact, Gittman et al.'s (2015) assessment of US shoreline armoring is one of the few recent attempts to quantify the total amount of armoring. Today, 86% of national exclusive economic zones lack data on shoreline armoring (Bugnot et al., 2020). Efforts must therefore be made to improve the quality and degree of shoreline mapping. Without detailed, consistent data, managers and scientists will be unable to reliably track increased construction of armored structures. At best, the body of knowledge assessing links between human activity and shoreline hardening has been described as "patchy and insufficient" (Paterson et al., 2014). Indeed, the information pertaining to shoreline armoring and more specifically, seawalls and groins, represent a gap in the coastal management knowledge base (Paterson et al., 2014). Marine spatial planning (MSP) hinges on the ability to determine which coastal systems are—and more importantly, are not—compatible with human use. Continuous classification data are therefore critical to spatio-temporal assessment of coastal ecosystems as part of MSP (Crowder and Norse, 2008; Frazão Santos et al., 2013). Ehler and Douvere (2009) set a high bar for coastal management bodies, arguing that data used in MSP efforts must be "up-to-date, objective, reliable, relevant, and comparable." Without the necessary data to illustrate or measure hardening, coastal managers and residents may not recognize the shifted baselines that normalize increasingly developed and armored coastlines over time (Sundblad and Bergström, 2014). Fortunately, several innovative coastal programs across the country can provide models for mapping at the local, state, and federal levels that could mitigate these concerns.

At the national scale, in their quest to "map once, use many times," NOAA and the Inter-agency Working Group on Ocean and Coastal Mapping advocates for data sharing and the use of standards in data collection, processing, and storage to reduce redundancy and promote widest possible use of marine mapping data (NOAA, 2021). A key component of such efforts is NOAA's spatial prioritization process. When planning marine mapping and research efforts, NOAA may choose to identify regional mapping priorities by dividing the project area into subregions and designating an advisory team composed of regional stakeholders (Costa et al., 2019). These stakeholders can review existing data and communicate to NOAA any gaps and/or areas of priority. Using an online application, participants use virtual "coins" to identify and comment on their priority areas, including requests for the data needed (Costa et al., 2019). NOAA can therefore maximize its ability to collect and provide useful, relevant marine, and coastal data. Such efforts to promote integrated ocean and coastal mapping foster effective collaboration and communication between state and federal governments, while reducing the likelihood of collecting unnecessary or redundant data (*pers. comm.* A. Lanier).

Once collected, the utility of coastal and marine data can be maximized through application of data standards like the Coastal and Marine Ecological Classification Standard (CMECS). CMECS is a nested, hierarchical classification system which includes assessment of anthropogenic substrates and structures in its "geoform" category. CMECS is the national standard for describing ecological data, having been endorsed by the Federal Geographic Data Committee (2012). As of 2020, federal agencies and research funded by them are required to use classification standards like CMECS (US Ocean Policy Committee, 2020). Although the US National Estuarine Research Reserve System (NERRS) maintains its own classification system, CMECS and this NERRS standard can now be crosswalked (*pers. comm.* K. Rose). CMECS has been successfully used to describe data collected by both individual researchers and larger state- or national-level efforts (Wright, 2020). As compared to ESI data, CMECS provides a more rigorous and appropriate methodology of shoreline classification, especially given the goal of tracking and mapping shoreline armoring.

Finally, updates to shoreline modification maps could be completed by linking shoreline modification permitting to mapping efforts at the national level. Section 404 of the Clean Water Act authorizes the US Army Corps of Engineers to issue general permits for actions which the Corps has determined will have "minimal adverse environmental effects," both individually and cumulatively (Brandon, 2016). Despite its central role in permitting and regulating shoreline hardening the Corps collects little, if any, data regarding the shore modifications permitted. Given that the cumulative negative impacts of shoreline hardening manifest on a larger scale than that on which the projects are built (Peterson and Lowe, 2009; Dethier et al., 2016; Kornis et al., 2017), such data are vital to quantify and remediate the negative impacts of armoring. All individual permit applications and nationwide permit verification requests are processed through an automated internal system, where requested amounts of impacts and proposed compensatory mitigation are also recorded (Federal Register, 2016). Amending current permitting regulations to require pre-construction notifications (PCNs) for all bank stabilization and shoreline hardening projects would provide the Corps with valuable data regarding the type, location, and size of armored structures that have been granted permits (Brandon, 2016). Such data would be instrumental in the Corps' assessment of the cumulative impacts of hardening, fulfilling the requirements of the National Environmental Policy Act (NEPA). Greater knowledge of armoring extent might also allow for strategic future permitting decisions, perhaps assisting in the promotion of nature-based stabilization techniques (Brandon, 2016).

Given the challenges of standardizing and funding shoreline mapping at the national or even international level, several coastal states have also developed innovative strategies to leverage existing coastal data or resources to improve shoreline modification mapping efforts. For example, as permits for new structures are approved and construction is completed, Oregon's Parks and Recreation Department updates the state's "shoreline armoring line" dataset, thus facilitating regularly updated geospatial tracking of shoreline armoring in the state (*pers. comm*. M. Reed). Between 2009 and 2012, the Geological Survey of Alabama (GSA) mapped 829 miles of Alabama's coast, classifying shorelines in real time during vessel-based surveys (Jones et al., 2009; Jones and Tidwell, 2011, 2012). The resolution of the AL shoreline data produced exceeds that of ESI data and is used for shoreline vulnerability assessments (*pers. comm.* S. Jones).

Within coastal states, local and county governments are also taking action to map and characterize their shorelines with the goal of identifying viable climate-adaptation pathways. For example, extensive high-resolution shoreline mapping and characterization revealed that reconstructing dunes and cobble beaches are viable options for sea-level rise hazard protection along the Stinson Beach shoreline in lieu of hardening in Marin County, CA (Marin County Community Development Agency, 2018). Although local or grassroots shoreline mapping efforts will likely result in discrepancies in methodology and resolution that will make state or national level comparisons of shoreline condition challenging, consensus building in support of funding and development of a shoreline mapping plan may be more easily achieved at the local level. Barnett et al. (2014) suggest that if individuals within a community can identify common goals for the future of their community, local governments have improved chances of garnering support for risk reduction and adaptation to protect the future of that community. Thus, local coastal adaptation planning efforts should be considered and incorporated, when possible, into future shoreline mapping approaches and funding plans.

Creating consistent, reliable shoreline maps on a large scale is a challenge, so drawing inspiration from successful efforts is an important way to tackle the issue. Identifying mapping priorities can help ensure that limited resources are being used to map the most relevant areas, while employing standardized classification systems can make data easier to compare across time and location, mitigating the risk of shifting baseline syndrome. Linking permitting and mapping systems and utilizing local mapping and adaption efforts can also make it easier to map shorelines and track change efficiently and comprehensively over large geographic areas.

CONCLUSION

Unfortunately, even the most comprehensive shoreline mapping plans can be hindered by the absence of a consistent update schedule, complicating efforts to understand shoreline change at the local, regional, and national levels. Shoreline mapping and assessment efforts could be improved through several avenues. First, the extent and resolution of data should be standardized to facilitate easy comparisons between different areas and timepoints. In an effort to guide and assist state-level or local coastal managers, we recommend creation of a set of detailed guidelines to instruct managers in methods to implement suggested improvements to their mapping programs (structural and budgetary). Second, when possible, both federal agencies and states should commit to regular update intervals and secure funding for these mapping efforts using classification standards (for example, CMECS, as described above) to enhance utility of mapping data for multiple uses and promote consistency among mapping bodies. Finally, state-level and national-level permitting of shoreline modification should be directly linked to shoreline mapping updates. Although many of these strategies have been piloted at the local or state-level, these strategies must be scaled up and adequately funded to ensure effective management and conservation of shorelines.

AUTHOR CONTRIBUTIONS

RC-B and RG conceived and outlined the framework for this research. RC-B extracted and summarized the NOAA ESI data, conducted the shoreline mapping search, and contacted the coastal managers with the assistance of RG. RC-B, EW, and RG wrote the initial draft of the manuscript. All authors contributed to writing, editing, and revising subsequent drafts of the paper. EW created the figures. RC-B, EW, and RG created the tables.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2022.719109/full#supplementary-material

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