frontiers | Frontiers in Climate

TYPE Review
PUBLISHED 19 February 2025
DOI 10.3389/fclim.2025.1481824

Check for updates

OPEN ACCESS

EDITED BY
Nadia Seeteram,
Columbia University, United States

REVIEWED BY
Steven Koller,
Harvard University, United States
Abbey Hotard,
University of South Alabama, United States

*CORRESPONDENCE
Benjamin Cross
✉ bcross@uwaterloo.ca

RECEIVED 16 August 2024
ACCEPTED 06 February 2025
PUBLISHED 19 February 2025

CITATION
Cross B, Doberstein B and Lueck V (2025) Improving economic assessment and decision-making for managed retreat through CBA+: a targeted literature review.
Front. Clim. 7:1481824.
doi: 10.3389/fclim.2025.1481824

Improving economic assessment and decision-making for managed retreat through CBA+: a targeted literature review

Benjamin Cross[1]*, Brent Doberstein[1] and Vanessa Lueck[2,3]

[1]Geography and Environmental Management, University of Waterloo, Waterloo, ON, Canada, [2]Pacific Institute for Climate Solutions, University of Victoria, Victoria, BC, Canada, [3]Global Institute for Sustainability and Innovation, Arizona State University, Tempe, AZ, United States

There is growing recognition that managed retreat, also known as strategic relocation, could be an increasingly important adaptation measure in the face of climate change and rising natural hazard risk. However, managed retreat's potential benefits are limited by challenges in funding, negative participant experiences, public and political opposition, uncertainty in long-term climate change and natural hazard risk, and equity concerns, all of which increase the complexity of managed retreat decision-making. While there is some research on how economic assessment tools can be used to aid in managed retreat decision-making, there is a knowledge gap in how these practises contribute to both the causes and potential resolution of the challenges associated with managed retreat. To begin to fill this gap, this paper presents a targeted literature review on the nexus between managed retreat, cost–benefit analysis of climate change adaptation and natural hazard risk reduction, and alternative economic assessment and decision-making tools. We identify connections between economic assessment practises and the primary challenges associated with managed retreat and then present several avenues where changes or additions to standard economic assessment approaches such as cost–benefit analysis (which we collectively refer to as 'CBA+') could lead to better managed retreat outcomes. Finally, we present a framework and 10 key principles that summarise key aspects of CBA+ to help agencies involved in managed retreat improve outcomes through economic assessment and decision-making process design. The most important key principles are the context- and community-specific design of economic assessment and decision-making processes, and the need for ongoing and thorough community engagement and co-production.

KEYWORDS

managed retreat, cost–benefit analysis, strategic relocation, economic assessment, climate change adaptation, disaster risk reduction, decision-making

1 Introduction

Managed retreat – the purposeful, coordinated movement of people and assets out of harm's way (Siders, 2019a) – has received increasing attention among academics and practitioners in the fields of climate change adaptation (CCA) and disaster risk reduction (DRR) in recent years (Pinter, 2021; Boudreault et al., 2023). As flood intensities and losses rise (Dottori et al., 2018), and with climate change projections of increasing storm intensity (Seneviratne et al., 2023) and likely sea level rise of up to 1.1 m by 2,100 (Oppenheimer and Glavovic, 2022), there is growing recognition that managed retreat may play an important role in reducing natural hazard risk and adapting to climate change (Kick et al., 2011; Binder et al., 2015; Siders, 2019a; Mach and Siders, 2021; Taylor Aiken and Mabon, 2024).

Managed retreat has many potential advantages, including avoiding costly repeated loss-rebuild cycles (Greer and Binder, 2017), fully eliminating hazard exposure (Siders and Keenan, 2020), avoiding the negative impacts of flood protection works (Abel et al., 2011; Hino et al., 2017; Mach and Siders, 2021), and providing amenity and protection benefits for the surrounding community through naturalisation of the affected lands (Dedekorkut-Howes et al., 2020; Dodman et al., 2022; O'Donnell, 2022). However, challenges have arisen related to how managed retreat projects are selected, designed, and implemented, and their resulting outcomes. These challenges will be discussed in more depth in Section 2, but include:

- poor participant experiences (e.g., long timelines, confusing bureaucracy, insufficient monetary and other supports) (Siders, 2019b; Nguyen, 2020; Dundon and Abkowitz, 2021; Ehrenfeucht and Nelson, 2023),
- equity concerns over the selection, process, and outcomes of managed retreat (Siders, 2019b; Kraan et al., 2021; Ajibade et al., 2022; Thistlethwaite et al., 2023),
- lack of proactive planning and implementation (Saunders-Hastings et al., 2020; Ajibade et al., 2022; Thistlethwaite et al., 2023) and,
- difficulty acquiring funding and maintaining programmes and institutional knowledge (Greer and Binder, 2017; Shi et al., 2022; Cottar and Wandel, 2024).

These challenges contribute to negative outcomes for many participants and communities (Greer and Binder, 2017; Mach and Siders, 2021) and a failure to fully capitalise on managed retreat's potential benefits (Braamskamp and Penning-Rowsell, 2018), leading to strong public and political opposition in many areas (Dundon and Abkowitz, 2021; Dodman et al., 2022).

One factor contributing to these challenges is the difficulty inherent in managed retreat decision-making. Deciding whether, where, and in what manner to relocate people and infrastructure requires considering a wide range of potential impacts, many of which are intangible and difficult to measure (Kind, 2014; Hudson and Botzen, 2019). Other challenges include trying to accommodate different visions for the community's future (Mach and Siders, 2021), and attempting to evaluate different forms of managed retreat in comparison to each other and against other forms of adaptation [e.g., Turner et al. (2007), Revell et al. (2021)]. It is also difficult to incorporate the many uncertainties related to the timing and magnitude of climatic and social change into decision-making (Lawrence et al., 2020).

Although various economic assessment (EA) tools have been used to help communities evaluate the many factors required in CCA and DRR decision-making in a systematic way, the most common tool has been cost–benefit analysis [CBA; Markanday et al. (2019)]. However, CBA has faced many criticisms related to how it is typically applied to CCA and DRR decision-making. Criticisms of CBA include: its requirement to monetize all impacts; difficulty accounting for the 'deep uncertainty' inherent in long-term climate change; ignoring issues of equity and differential distribution of costs and benefits; undervaluing future generations (Lempert, 2014; Markanday et al., 2019); and being incommensurable with Indigenous value systems (Choy, 2018). These criticisms, described in more detail in Section 3.1, can be particularly impactful when CBA is applied to managed retreat.

When compared to other adaptation measures, managed retreat has a broader range and often greater weight placed on intangible impacts (e.g., attachment to place, community cohesion) (Agyeman et al., 2009; Skidmore and Cohon, 2022), has more significant equity concerns (Siders, 2019b), and is strongly affected by climate change uncertainty (Abel et al., 2011; Dodman et al., 2022; Keeler et al., 2022). Moreover, the risk reduction achieved by managed retreat is permanent, with little or no ongoing costs, making results highly sensitive to the choice of time horizon and discount rate (Boardman et al., 2018).

Despite CBA's shortcomings when applied to managed retreat, and CCA more broadly, it is widely used and often plays a large role in decision-making (Alexander et al., 2016; Markanday et al., 2019). CBAs are also required when applying for funding and other supports in some jurisdictions [e.g., US Federal Emergency Management Agency's (FEMA) Hazard Mitigation Assistance Programme (FEMA, 2024)] and this has further entrenched CBA in those jurisdictions as a widespread and enduring decision-making tool for managed retreat. Therefore, how CBA is designed, implemented, and interpreted for managed retreat programmes may have substantial impacts on programme outcomes. Thus, improving CBA practises is a promising research avenue that may help to achieve better managed retreat outcomes.

To date, there has been minimal examination in the literature of how the use of EA tools like CBA influence the outcomes of managed retreat. This research gap includes both how EAs and decision-making processes could be contributing to poor managed retreat outcomes, and how improvements to these tools and processes could lead to better outcomes.

This paper aims to address this knowledge gap through a targeted literature review and analysis of three bodies of literature: (1) managed retreat, (2) CBA of DRR and CCA, and (3) alternative EA and decision-making tools [e.g., multi-criteria decision analysis (MCDA), robust decision making (RDM), real options analysis (ROA), and dynamic adaptive policy pathways (DAPP) (Haasnoot et al., 2013)]. Searches were conducted using the University of Waterloo's Omni catalogue system, which includes 445 databases (e.g., Web of Science, Scopus, Science Direct). Inclusive search terms were used to account for synonyms of managed retreat (e.g., 'strategic retreat,' 'planned relocation,' 'managed realignment,' 'buyout') and CBA (e.g., 'cost–benefit analysis,' 'benefit–cost analysis,' 'economic assessment'). In addition to individual searches for 'managed retreat' and its many variations, additional searches were conducted combining each of these variations with each of the supplementary economic assessment and decision-making types and their variations (i.e., CBA, MCDA, ROA, RDM, DAPP), as well as citation mining for relevant papers referenced in the primary findings. A total of 128 studies and reports are included in this review, with 14 of those studies presenting an EA of managed retreat. A systematic review was not conducted because of the impracticalities related to the large size of the three individual bodies of literature and the many forms that overlap between these bodies of literature could take. Instead, the targeted review presented here is meant to explore the main themes from each body of literature, identify how the underexplored overlap between these areas could offer insights to improve managed retreat outcomes, and demonstrate the potential value of further research within the three bodies of literature.

The remainder of the paper is organised as follows. Section 2 presents a review of the challenges associated with managed retreat. Section 3 provides an overview of EA's use for managed retreat, beginning with particular challenges and special considerations when using CBA for managed retreat (Section 3.1), followed by a review of current literature on the EA of managed retreat, including alternative and complementary tools, like MCDA, RDM, ROA, and DAPP (Section 3.2). Section 4 provides a discussion of the linkages between EA and managed retreat outcomes, and identifies potential avenues where changes or additions to cost–benefit analysis (which we collectively refer to as 'CBA+') could lead to better managed retreat outcomes. Finally, we present a framework and 10 key principles related to CBA+ which will provide guidance for community- and context-specific decision-making processes that could improve managed retreat outcomes.

A note on terminology and context: The term 'managed retreat' is somewhat controversial and contested, with many alternatives and nuances in definition proposed across the literature (O'Donnell, 2022; Thistlethwaite et al., 2023). This paper uses 'managed retreat' as an umbrella term to broadly capture all programmes which permanently relocate people and infrastructure in a planned and strategic way in order to reduce natural hazard risk and/or adapt to climate change. This includes programmes that may otherwise be described as buyouts, relocation, resettlement, retreat the line, managed realignment, or other similar terms. This paper largely focuses on managed retreat in the context of Western nations where a central organising body is involved (e.g., municipal government) and does not explore climate migration or autonomous relocation. This review also focuses on managed retreat mainly in the context of flooding as that is the most common application in the literature, however we assume the same approaches and concerns could broadly apply to other natural hazards, such as geomorphic hazards (e.g., landslide, coastal erosion) or wildfire (McConnell and Koslov, 2024).

2 Challenges related to managed retreat

In order to evaluate how EA and decision-making practises may affect managed retreat outcomes, it is first necessary to understand the challenges facing managed retreat as a mainstream CCA and DRR strategy. This section provides a summary of the challenges related to managed retreat, however for more detailed discussions please see (Freudenberg et al., 2016; Siders, 2019a, 2019b; Saunders-Hastings et al., 2020), as well as the additional citations below.

2.1 Contested goals and objectives

A fundamental challenge for managed retreat decision-making is a lack of agreement on what it means for retreat to be successful (Hino et al., 2017; Ajibade et al., 2022). CCA is a classic 'wicked problem' (Siders and Pierce, 2021) where 'success' can be defined differently by different parties, or when examined at different scales (Ajibade et al., 2022). Although early managed retreat programmes typically focused on measures of success linked to technical, managerial, and compensation targets, this is now changing (Ajibade et al., 2022). Factors of success now commonly include broader objectives like achieving equitable outcomes, community empowerment, ecosystem restoration, or addressing inequity and injustice (Greer and Binder, 2017; Pinter, 2021; Ajibade et al., 2022; Bower et al., 2023; Ehrenfeucht and Nelson, 2023).

A lack of clarity and agreement on objectives and priorities exacerbates the already challenging decision-making landscape of managed retreat. For example, how various objectives are prioritised can lead to ignoring some values, prioritising some values over others (e.g., intangible community values versus monetized impacts of flood damage) or assessing those values in a different way (e.g., the use of pre-flood versus post-flood property valuations), which can affect the selection, manner of implementation, and participant outcomes of managed retreat.

2.2 Equity concerns

Equity and inequity concerns are central themes across the managed retreat literature [e.g., Hino et al. (2017), Siders (2019b), Kraan et al. (2021)]. Land use and housing issues, including location, market value, community characteristics, and natural hazard vulnerability, are strongly tied to economic and social factors, as well as histories of discrimination and forced relocation (Ajibade et al., 2022; Tubridy et al., 2022). Managed retreat directly interacts with these factors and histories through the selective purchase or non-purchase of homes, targeting certain neighbourhoods over others, decisions to pursue other adaptation measures instead of retreat, and in some cases, forced relocation through expropriation. The distribution and characteristics of where managed retreat is considered and implemented therefore has the potential to raise a variety of equity-related concerns.

There are many examples of equity issues identified in the managed retreat literature. Some examples include: the overrepresentation of lower income and minority communities in flood-prone areas, and thus potential for managed retreat, due to histories of racism and colonialism (Hino et al., 2017; Lieberknecht and Mueller, 2023); wealthier neighbourhoods being prioritised for structural protection (Lieberknecht and Mueller, 2023); and reduced 'voluntariness' of buyout programmes in lower income and more vulnerable neighbourhoods (Greer et al., 2022). As the name suggests, buyouts are typically aimed only at property owners, providing little or no support for renters, who are often lower income, and support is typically lacking for mobile home residents who may own their home but not their land, leading to distinct vulnerabilities (Marino, 2018; Dundon and Camp, 2021; Kraan et al., 2021).

When communities actively seek to be relocated, lower income, minority, and Indigenous communities (e.g., Isle de Jean Charles, Louisiana, and Shishmarif and Newtok, Alaska) also have more difficulty accessing government funding and support (Hino et al., 2017; Marino, 2018; Pinter, 2021). Since most buyout programmes focus on the household rather than community scale, Indigenous communities may find it difficult to access funding and support for managed retreat due to their lack of privately owned homes and land.

Taken together, it is not always clear if, or when, managed retreat is working as envisioned by removing the most vulnerable people and structures from hazard exposure, or, if already disadvantaged segments of society are being unfairly targeted and coerced to participate and, in doing so, lose important community supports (Greer and Binder, 2017).

2.3 Poor experiences and implementation issues

Many studies have investigated the challenges of managed retreat from the perspective of both participants and the implementing agencies, identifying a range of common issues related to poor participant experience, some of which can have long-term, negative quality of life impacts. Some common challenges include:

- lengthy timelines, which can affect insurance claims and/or prevent participants from leaving high-risk areas or precarious housing arrangements (Nguyen, 2020; Dundon and Camp, 2021);
- insufficient compensation to relocate to areas with lower natural hazard and social vulnerabilities (McGhee et al., 2020),
- lack of transparency and poor communication (Siders, 2019b),
- feeling pressure to accept buyout offers in nominally 'voluntary' programmes (Greer et al., 2022);
- buyout eligibility based on fixed property damage thresholds that limit homeowner options (Siders, 2019b),
- post-retreat patchwork neighbourhood patterns, resulting in decreased or more costly infrastructure maintenance and negative community impacts (Kraan et al., 2021) and,
- negative income effects following relocation (Hoang and Noy, 2023).

Additional planning challenges have been identified that influence the likelihood of managed retreat being selected over other adaptation alternatives and whether objectives are met during implementation. Funding challenges are common due to high property costs and a lack of funding programmes that allow for property buyouts, particularly without an instigating disaster (Lawrence et al., 2020; Saunders-Hastings et al., 2020; Dodman et al., 2022). Local authorities also often lack the administrative capacity and financial resources to plan managed retreat programmes (Lawrence et al., 2020; Dodman et al., 2022). In post-disaster buyouts, the objective to carry out rapid managed retreat via short programme timelines often conflicts with the need for thorough community engagement and community visioning (Saunders-Hastings et al., 2020; Kraan et al., 2021). In many communities there is a lack of available land and/or housing, especially affordable housing with lower natural hazard and social vulnerability (Abel et al., 2011; Doberstein et al., 2020). And lastly, there are significant challenges related to planning and making decisions under uncertainty, often with different participant objectives and conceptions of success (Eriksen et al., 2015; Bloemen et al., 2019).

2.4 Public and political opposition to retreat

The idea of relocation due to natural hazard risk can be contentious, and managed retreat has become so controversial in some communities that it is difficult or impossible to discuss (Anderson, 2022). The concept of managed retreat raises difficult conversations around community and societal values, and what can or cannot be protected (O'Donnell, 2022). Managed retreat is often downplayed or dismissed due to misperceptions of risk (Driessen et al., 2016; Dundon and Abkowitz, 2021) or viewing managed retreat as a threat to real estate values (Landry et al., 2003; Dedekorkut-Howes et al., 2020; Hashida and Dundas, 2023). The fairness of retreat-related compensation is commonly questioned, which can be seen as either a wealth transfer to affluent homeowners who knowingly took on risk (Siders, 2019b; Tubridy et al., 2022), or as insufficient compensation for households in need (Braamskamp and Penning-Rowsell, 2018; Thistlethwaite et al., 2020; Ehrenfeucht and Nelson, 2023). Discussing managed retreat can also be a political risk as there can be strong pressure to maintain the status quo (Gibbs, 2016; Anderson, 2022; Keeler et al., 2022).

Many residents also have a strong sense of place attachment or place dependency, which may lead to opposition to retreat (Siders, 2019a; Mach and Siders, 2021), and this is often accentuated by fears of community erosion and patchwork retreat patterns (Braamskamp and Penning-Rowsell, 2018; Mach and Siders, 2021). Government-run, non-risk-based insurance and disaster financial assistance programmes can further incentivise living in high-risk areas by shielding residents from the financial consequences of natural disasters (Dundon and Abkowitz, 2021; Dodman et al., 2022), factors which may need to be accounted for in managed retreat planning and EAs.

The main risk posed by public and political opposition is that managed retreat will be left off the table when communities discuss CCA and DRR alternatives. Failing to consider the full suite of adaptation alternatives not only increases the chance of maladaptation and the associated increase in future negative impacts (Wise et al., 2014), but can also cause communities to miss out on the benefits of proactive planning for a potential future where managed retreat might be required, even if it is not the preferred approach at the present time (Lawrence et al., 2020).

2.5 Proactive versus reactive retreat

Although proactive managed retreat is rare (Lawrence et al., 2020; Hanna et al., 2021), there are many benefits of proactive rather than reactive retreat (Saunders-Hastings et al., 2020). Ajibade et al. (2022, p. 8) suggest that pre-emptive managed retreat is more likely to be broadly successful compared to reactive examples as it 'may allow for a variety of logistical, economic, socio-cultural, and intersectional justice concerns to be centred and addressed before a resettlement programme is implemented.' Similarly, Siders et al. (2019, p. 761) observed that 'a preferred alternative is for retreat to be integrated into the pursuit of broader societal goals… and its implementation tailored to context-specific goals.' Relying solely on reactive retreat therefore contributes to path-dependence and potential maladaptation (Kwadijk et al., 2010; Haasnoot et al., 2021; van Alphen et al., 2022). Reactive managed retreat also reduces the possibility of using 'retreat lands' for flood protection and other nature-based solutions like dune or wetland enhancement (Haasnoot et al., 2019; Dodman et al., 2022).

Reactive managed retreat also inherently brings a host of negative impacts related to the double trauma of first experiencing a disaster and then experiencing a reactive buyout. Common negative impacts include: psychological stress and trauma (Hudson et al., 2019);

emergency response and clean-up costs (Nelson and Camp, 2020); environmental contamination (Dedekorkut-Howes et al., 2020); loss or damage of items/resources that could have been relocated (Hudson et al., 2019), some of which cannot be replaced or repaired (Heikkila and Huang, 2014); injury and loss of life (Jonkman et al., 2008); major quality of life impacts, such as triggering homelessness (Kind, 2014); and economic losses from the inefficient nature of recovery spending (Heikkila and Huang, 2014). Many, if not all, of these impacts could be avoided through proactive approaches to managed retreat.

3 Economic assessment of managed retreat

The technical, long-lasting, and uncertain nature of CCA and DRR planning makes managed retreat decision-making a highly complex endeavour. Using established, holistic EA tools can help decision-makers better understand complex situations, facilitate the comparison of different alternatives and trade-offs (Middlesex University Flood Hazard Research Centre, 2014; Boardman et al., 2018), improve communication (De Brito and Evers, 2016; Boardman et al., 2018), and increase transparency (Robertson and Shaw, 1999, 2006). Although many EA tools are available to help make evidence-based, transparent, and efficient CCA and DRR decisions that meet societal objectives, the most common is CBA (Alexander et al., 2016; Markanday et al., 2019). The widespread use of CBA (with its significant criticisms) means that improvements in CBA practises could also confer substantial benefits on managed retreat outcomes. Although this section focuses on CBA, the general concepts and concerns discussed also apply to the practise of EA more broadly. Alternative forms of EA, and their comparative strengths and weaknesses, are discussed in more detail in Sections 3.2 and 4.4.

In its idealised form, CBA's aim is to identify the course of action that maximises total societal welfare by assessing all the costs and benefits of each alternative by converting the potential positive and negative impacts to a common, monetary measure (Kind et al., 2017; Boardman et al., 2018). In practise, CBAs are typically limited in scope to the costs and benefits that can be easily measured/quantified, or that are deemed to be most important to the decision.

The detailed methodology of CBA is beyond the scope of this paper, but broadly, the steps involved include:

1. Identifying alternatives that may fulfil the project's goals and objectives
2. Monetizing relevant costs and benefits for each alternative relative to a baseline scenario
3. Discounting future costs and benefits to their present value
4. Summing the discounted costs and benefits for all 'affected people' included in the analysis
5. Comparing the total costs and benefits to calculate the Net Present Value (NPV), Benefit–Cost Ratio (BCR), and/or Return on Investment of each alternative

In the absence of other considerations, the alternative with the highest NPV is seen as providing the greatest societal benefit and is selected; alternatively, every project where net present benefits outweigh net present costs (i.e., positive NPV or BCR > 1) would be recommended for implementation or further consideration (Boardman et al., 2018).

While this concept seems appealing as a way to simplify complex decision-making and demonstrate efficient use of public funds (Alexander et al., 2016), there are many nuances, challenges, and potential biases that limit CBA's utility, particularly in complex realms like managed retreat.

3.1 Challenges and special considerations for CBA of managed retreat

Section 3.1 summarises criticisms of how standard CBA practises have typically been implemented for CCA and DRR evaluation and identifies special considerations where these approaches may present particular challenges for managed retreat.

3.1.1 Value selection and monetization

A commonly cited limitation of CBA is the requirement to monetize all impacts (positive and negative) and the resulting prioritisation of market values (e.g., infrastructure) over non-market values (e.g., social capital, spiritual values) (Moore, 2012; Li et al., 2014; André et al., 2016; Markanday et al., 2019). Managed retreat CBAs commonly undervalue or omit many potentially important values, such as:

- ecosystem services (Moore, 2012; Li et al., 2014; Markanday et al., 2019; Dodman et al., 2022),
- health impacts (Heikkila and Huang, 2014; Markanday et al., 2019),
- psychological impacts of managed retreat or experiencing a disaster (Hudson and Botzen, 2019; Nelson and Camp, 2020),
- place attachment (Heikkila and Huang, 2014; Nguyen, 2020),
- Indigenous values (Choy, 2018),
- lost social connections and sense of community (Heikkila and Huang, 2014; Hanna et al., 2020),
- planning, public engagement, and other pre-retreat transaction costs (Tubridy et al., 2022),
- co-benefits from the post-retreat lands and reduced residual flood damage (Lawrence et al., 2019) and,
- post-retreat land rehabilitation, social supports, and impacts on the receiving community (Tubridy et al., 2022).

These are potentially serious limitations since including or excluding a given value can change the preferred alternative (Meyer et al., 2012), shift the NPV from negative to positive or vice versa (Brouwer and Van Ek, 2004), or lead to recommendations that do not represent the true costs and benefits of managed retreat (or its alternatives) or that do not represent the values of the affected community. However, measuring these non-market values in a way that is commensurate with easily monetized market values is difficult, requiring additional resources, and is subject to assumptions and uncertainty (Hudson and Botzen, 2019) so it is not always clear or agreed upon which values are appropriate to monetize (Markanday et al., 2019).

3.1.2 Indigenous values and substitutability

The issues of value selection and monetization are particularly challenging when applying CBA to Indigenous communities.

Indigenous communities likely have values that are at odds with CBA's utility theory and welfare economics roots of individual utility maximisation and aggregation (Kind et al., 2017; Boardman et al., 2018), such as Indigenous conceptions of community wellbeing and communal property rights and obligations (Venn and Quiggin, 2007; Choy, 2018).

Traditional CBA, and the Kaldor-Hicks compensation test on which it is based, requires substitutability between sources of utility (i.e., any loss can be exactly offset by any gain of the same value) (Boardman et al., 2018). The non-substitutability typical of many Indigenous values makes it difficult, or potentially impossible, to use CBA to evaluate some impacts on Indigenous peoples and land (Venn and Quiggin, 2007; Choy, 2018; Manero et al., 2022). Opinions differ on whether it is better to attempt to quantify Indigenous values to ensure they are not ignored, or whether these values must be considered outside of CBA due to worldview incompatibility (Venn and Quiggin, 2007; Choy, 2018). Questions of substitutability are also relevant to discussions of 'strong' vs. 'weak' sustainability and whether natural and human capital should be viewed as substitutable in CBAs (Ekins et al., 2003).

3.1.3 Deep uncertainty

Planning for CCA and DRR involves confronting interacting and compounding uncertainties, such as the effectiveness and cost of adaptation and risk reduction measures, future changes in both climate and social systems, and the measurement of non-market values (Hanna et al., 2020). Additional technical uncertainties arise from challenges in downscaling climate change projections, particularly for extreme events and small-scale watersheds (Hinkel et al., 2019; Haasnoot et al., 2021), and in damage modelling that translates flood depths into societal impacts (Merz et al., 2010; Woodward et al., 2014; Nelson and Camp, 2020).

Although CBAs account for uncertainties with known probabilities by using expected value calculations (i.e., the weighted average of the possible values an uncertain parameter could take, weighted by the probability of each outcome), this approach is challenging or impossible to use when faced with complex, compounding uncertainties (Hanna et al., 2020), and does not work at all for 'deep uncertainties' where probabilities cannot be assigned due to uncertainty about basic mechanisms and relationships (Hinkel and Bisaro, 2015; Buurman and Babovic, 2016). As future climate and cultural conditions depend on unknowable future societal choices, rates of technological progress, and poorly understood climate change feedbacks, CCA and DRR planning is fraught with 'deep uncertainties' (Buurman and Babovic, 2016; Bloemen et al., 2019; Haasnoot et al., 2019). CBAs may therefore provide inadequate information to understand the nature and consequences of uncertainty and whether any given adaptation measure will be robust to the range of potential futures (e.g., rates of climate change, changing societal risk tolerance). CBAs may even lead to decisions based on 'spurious certainty' and an overreliance on a single source of information (Biggs et al., 2009).

3.1.4 Discount rates and time horizons

The practise of discounting within CBA is used to make the value of future costs and benefits more comparable to those incurred today, considering both the opportunity cost of the chosen alternative and humanity's inherent immediacy preference. The discount rate determines the magnitude of the preference for the near over the far future; the 'present value' of future costs and benefits decreases with larger discount rates and as impacts move further into the future (Boardman et al., 2018). It is important to recognise that traditional discount rates based on expected investment returns can strongly bias CBA results against alternatives with high immediate costs but larger long-term benefits, such as managed retreat (Dennig, 2018; Markanday et al., 2019).

Many proposals have been made to address the challenge of assigning discount rates for CCA, such as low, declining, zero, or even negative discount rates (Turner et al., 2007; Li et al., 2014; Dennig, 2018; Markanday et al., 2019; Nelson and Camp, 2020). In contrast to these views, Dudley et al. (2019) argue that discounting theory is sound and adopting different discount rates for temporally remote events introduces bias. With no consensus, government-prescribed or typical discount rates are commonly used, often without consideration of the decision context, and sensitivity analyses are performed to examine how different discount rates would change the resulting rankings (Kind, 2014; Li et al., 2014; Dawson et al., 2018; Nelson and Camp, 2020).

Since the benefits of managed retreat typically continue far in the future, time horizon and discount rate choices can substantially impact CBA outcomes (Hino et al., 2017; Dennig, 2018; Dudley et al., 2019; Haasnoot et al., 2020) and can have large intergenerational equity implications (Markanday et al., 2019). The time horizon for EAs is often set as the lifespan of the proposed infrastructure investment (Boardman et al., 2018). However, since managed retreat is often compared to infrastructure-based alternatives, such as a protective floodwall, it is common to use time horizons based on those infrastructure lifespans, despite managed retreat's benefits accruing in perpetuity.

3.1.5 Scenario, boundary, and baseline selection

The design and selection of EA scenarios are important for all EAs since excluded scenarios are automatically precluded from analysis, and analyzing unfeasible or unrealistic scenarios does not aid in planning (Dawson et al., 2018; Li et al., 2014). Note that within this paper the term 'alternative' is used to describe the overarching adaptation measure being considered (e.g., managed retreat, seawall construction, beach nourishment), while 'scenario' includes both the adaptation alternative and all the additional specifications (e.g., timing, staging, and scale of implementation, comparing different compensation schemes) that differentiate each of the variations being assessed within an EA.

CBAs also require setting geographic and political boundaries and identifying who has status as an 'affected person' (Li et al., 2014; Boardman et al., 2018). These choices dictate the scale at which costs and benefits are assessed, and influence which effects are interpreted as transfers or redistributions within the system, and therefore as net-neutral (Boardman et al., 2018). For example, CBAs at the scale of a local government may view post-retreat property tax reductions as a cost (i.e., if relocated individuals move out of the community), while at a higher-scale this would be viewed as a net-zero change (i.e., tax payments by relocated households continue, but in another community). Similarly, some land uses may continue elsewhere following relocation or rezoning, which could be a low- or zero-cost effect at a higher scale but may appear as a loss at a local scale (Brouwer and Van Ek, 2004).

Finally, scenarios should be compared to an approximation of a future where none of the alternatives are implemented, known as the baseline, rather than assuming that conditions will remain unchanged (Boardman et al., 2018). In the case of a post-disaster CBA for managed retreat, the baseline would be a community in which flooded homeowners rebuild in place and then continue to suffer flood risks or periodic loss/rebuild cycles. Setting realistic baselines is a difficult process: uncertainties in future economic growth, technological innovation, cultural change, and the degree to which individuals take on autonomous adaptation independent of community initiatives add further uncertainty, particularly for the long time frames involved in managed retreat (Moore, 2012; Li et al., 2014; Watkiss et al., 2015).

3.1.6 Non-marginal impacts, equity, and risk aversion

Traditional CBA theory assumes that costs and benefits are marginal (i.e., they are incremental changes small enough not to disrupt larger systems), however, this assumption can be broken by the disruptive impacts of extreme events (Adler, 2016; Dudley et al., 2019). This is particularly important for low income and other vulnerable populations where disasters may have disproportionately large effects, such as inducing homelessness or triggering large out-migrations (Kind et al., 2020). One solution is the use of risk aversion and/or equity weights, which assign greater value to impacts that make up a large percentage of total wealth, or to all impacts experienced by lower-income households, respectively (Kind et al., 2017, 2020). However, the use of equity and risk aversion weights is uncommon because assigning weights can be seen as imposing an external value system, CBAs typically assume redistribution will occur elsewhere in society (e.g., via the tax system), and using weights requires expert judgement and additional information on the affected population and the distribution of impacts, which may not be available (Kind et al., 2017, 2020; Markanday et al., 2019; US Office of Management and Budget, 2023).

3.1.7 Subjectivity and comparisons

The sometimes subjective and inconsistent choice of discount rates, values, time horizons, and other CBA parameters makes it difficult to compare and extrapolate results from one study to another (Dedekorkut-Howes et al., 2020). While a standardised CBA process for CCA and DRR could help overcome these challenges, prescriptive CBA methods may prevent the necessary community- and context-specific aspects of good CBA design, and could entrench poor practises, such as excluding particular non-market values (André et al., 2016). CBA's subjectivity, enacted through many parameter and value choices, can also reinforce local or institutional biases, preventing new perspectives or more transformational changes from being considered or implemented (Siders and Keenan, 2020). For example, selecting a short time horizon and high discount rate, and focusing on real estate value and other market impacts, could be used to bias decision-making away from considering managed retreat.

3.1.8 Optimism bias and overreliance on cost–benefit analysis

Despite the issues discussed in Sections 3.1.1–3.1.7, there is a common overreliance on CBAs in decision-making processes (Hinkel and Bisaro, 2015). For example, a UK flood protection funding programme required an 8:1 BCR, which prevented some beneficial projects from proceeding and caused other projects to reduce protection levels to fit the arbitrary threshold (Alexander et al., 2016). Similarly, eligibility for national buyout funding in the United States is often based on a prescribed CBA focused on house value and level of damage, which preferentially targets lower income neighbourhoods for buyouts without considering broader contexts (Siders, 2019b). In an analysis of over 2000 CBAs for public investment projects, researchers found evidence that CBAs consistently underestimated costs and overestimated benefits, and placed unfounded confidence in the accuracy and 'unbiased' nature of these estimates, resulting in overestimating BCRs by an average of 50–200% depending on the investment type (Flyvbjerg and Bester, 2021).

3.2 Current literature on the economic assessment of managed retreat

3.2.1 Economic assessment tools and approach

Although the body of managed retreat literature has grown rapidly in recent years, the number of papers on the EA of managed retreat remains small (Boudreault et al., 2023). In total, we found just 14 papers that presented an EA of managed retreat as a CCA or DRR measure (Table 1). In all 14 cases the natural hazard being addressed was flooding, with 5 studies addressing riverine flooding and the other 9 studies addressing sea level rise and coastal flooding. The 14 studies had a global spread, including 4 in North America, 6 in Europe, 3 in Oceania, and 1 in Asia. However, within this small body of literature is a wide range of approaches and levels of detail, indicating that this is still an emerging field, and that researchers and practitioners are experimenting with novel approaches. Also of note is that all 14 studies presented EAs of hypothetical cases or as a demonstration of new techniques or practises that could be used in real-world cases. No studies were found which reported on EA practises that were used in real-world managed retreat programmes.

While nine studies utilised largely traditional CBA methodology to compare alternatives, the remaining five studies combined CBA with one or more complementary tools. To improve uncertainty analysis, three studies also used real options analysis (ROA) (Lawrence et al., 2019; Stroombergen and Lawrence, 2022), two used robust decision making (RDM) (Ramm et al., 2018; Boudreault et al., 2023), and three used dynamic adaptive policy pathways (DAPP) (Ramm et al., 2018; Lawrence et al., 2019; Stroombergen and Lawrence, 2022). Similarly, three studies also incorporated multi-criteria decision analysis (MCDA) to better capture intangible impacts (Lawrence et al., 2019; Skidmore and Cohon, 2022; Stroombergen and Lawrence, 2022). Please see Section 4.2 for further discussion of these complementary tools and their impact on managed retreat decision-making and outcomes.

3.2.2 Value selection, monetization, and estimation

Across the 14 studies, there was large variation in the values considered, as well as the selection of values that were monetized or not monetized. Construction and implementation costs (e.g., buyout costs, demolition, operation and maintenance of protection infrastructure), and the benefit of avoided flood losses (typically measured as a reduction in average annual damage) were the most common values considered, but this was not universal. For example,

TABLE 1 Summary of economic assessment approaches used across the 14 cost–benefit assessment studies reviewed.

Study references	Tools used in addition to CBA	Adaptation measures considered	Alternative forms of retreat considered	Case study location	Treatment of intangible impacts
André et al. (2016)	N/A	Protect Retreat Status Quo	- Division of Ownership ('Usufruct') - Buy and Lease Back	Hypothetical town, France	Monetized select impacts (e.g., loss of seagrass meadows, psychological effects)
Boudreault et al. (2023)	RDM	Retreat Status Quo	- Pre-Disaster Buyout - Post-Disaster Buyout - Division of Ownership ('Usufruct') - Neighbourhood-Level - Property-Level	Southwest Quebec, Canada	Two scenarios: Intangible flood losses insignificant or equal to property damage
Cardona et al. (2020)	N/A	Protect Accommodate Retreat	N/A	Furadouro Beach, Portugal	N/A
Creach et al. (2020)	N/A	Accommodate Retreat	N/A	La Gueriniere, France	Reduction in risk of death
Dottori et al. (2023)	N/A	Protect Accommodate Retreat	N/A	All of Europe	N/A
Finn et al. (2024)	N/A	Protect Retreat	N/A	Sumas Lake (*Xhotsa*), British Columbia, Canada	N/A
Lawrence et al. (2019)	ROA DAPP MCDA	Protect Retreat Status Quo	- Full Scale Retreat - Limited retreat following natural shoreline adjustment	Hawke's Bay, New Zealand	Qualitative factors included in MCDA (e.g., socio-economic and environmental impacts, Maori relationship with their ancestral lands)
Meyer et al. (2012)	N/A	Accommodate Retreat	N/A	Erlina and Grimma, Germany	Transaction costs (e.g., planning and design, communications) measured qualitatively separate from CBA
Ramm et al. (2018)	RDM DAPP	Protect Accommodate	N/A	Lakes Entrance, Australia	Qualitative 'Lived Values' assessment of 5 factors: Scenery, Natural Environment, Safety, Proximity to Water, Lifestyle
Revell et al. (2021)	N/A	Protect Retreat	- Buy and Lease Back	Imperial Beach, California, USA	Monetized select impacts (ecosystem services, change in recreational value)
Skidmore and Cohon (2022)	MCDA	Retreat Accommodate Status Quo	- 6 Different Receiving Locations	Kivalina, Alaska	Four categories of qualitative factors in MCDA: Risk to Humans, Environmental Protection, Convenience, Equity and Social Justice
Stroombergen and Lawrence (2022)	ROA DAPP	Protect Retreat	- Full Scale Retreat - Partial Retreat	Hutt River and Hawke's Bay, New Zealand	N/A

(Continued)

TABLE 1 (Continued)

Study references	Tools used in addition to CBA	Adaptation measures considered	Alternative forms of retreat considered	Case study location	Treatment of intangible impacts
Turner et al. (2007)	N/A	Protect Retreat Status Quo	- Scale of Retreat Varies Across 5 Scenarios - Scenarios differ in balance of Economic Growth and Habitat Creation	Humber Estuary, UK	Monetized select impacts (habitat creation, carbon sequestration)
Zeng et al. (2023)	N/A	Retreat	N/A	Jiangxi, China	N/A

The categorisation of adaptation measures is based on the PARA framework (Doberstein et al., 2019).

in Lawrence et al.'s (2019) MCDA of six scenarios made up of different combinations and sequences of large- and small-scale managed retreat, protection, and 'do nothing' alternatives over a 100-year period, all monetary costs were excluded in an attempt to increase focus on typically undervalued considerations such as socio-economic impacts and Indigenous relationships with the land. However, this led to an implicit assumption that the structural protection alternative was 100% effective, introducing a bias against the non-protection measures. Similarly, Cardona et al. (2020) did not assess the reductions in average annual damage associated with each adaptation alternative considered (protect, accommodate, retreat) and instead only monetized project costs. This made all adaptation measures appear equally effective in reducing hazard risk, which is unlikely to be the case. Finn et al. (2024), took another approach and only calculated the total assessed value of all properties within the historical boundaries of a flood-prone area (i.e., the base financial cost of retreating 100% of those properties) and compared that to the costs of four proposed alternatives focused on protection; this exercise demonstrated that managed retreat costs were within the range of the four protection alternatives and was therefore worth further consideration. Finally, when assessing various flood risk reduction alternatives (protection, managed retreat, and two forms of accommodation), rather than calculating expected reductions in flood damage, Creach et al. (2020) quantified the reduction in the number of homes that posed a high-risk of death during flood events, as measured using the Extreme Inherent Vulnerability index.

A variety of methods were also used to assess the direct costs and benefits of the managed retreat programmes themselves. Some examples of costs considered in addition to property purchase and demolition included: damage to home contents and additional living expenses during temporary displacement (Boudreault et al., 2023); transaction costs (e.g., communication, negotiation) (Meyer et al., 2012; Zeng et al., 2023); opportunity cost of lost agricultural land (Turner et al., 2007); and loan interest (Zeng et al., 2023). Examples of additional market costs and benefits assessed include the economic impacts of changes in recreation and tourism (André et al., 2016; Revell et al., 2021), carbon sequestration (Turner et al., 2007), lower maintenance costs due to wave attenuation (Turner et al., 2007), and predictions of increased post-relocation wages in rural China (Zeng et al., 2023).

The inclusion or exclusion of intangible, or otherwise difficult to monetize values (e.g., reductions in emergency response costs), also varied widely among studies. Most studies simply listed potential non-market impacts that were not quantitatively assessed, and for some studies this list was the only acknowledgement of intangible impacts (e.g., Cardona et al., 2020). Other studies monetized some intangible values, with the choice of which values to monetize likely due to perceived community interest or easy data availability. Some examples include the enjoyment of wider beaches (André et al., 2016; Revell et al., 2021), increased post-flood use of psychotropic drugs as a proxy for psychological distress (André et al., 2016), replacement costs of impacted ecosystems (Revell et al., 2021), and habitat creation (Turner et al., 2007). Boudreault et al. (2023) also assessed one scenario where intangible flood losses were assumed to be equal to property damage.

In addition to selecting which values to assess, the choice of monetization method can also significantly influence EA outcomes. Avoided flood losses are typically the largest benefit in managed retreat CBAs, and there were large variations across the studies in the approach and level of detail used for the two main aspects of damage estimation: flood modelling and converting flood depths to property damage (Meyer et al., 2012; Revell et al., 2021; Dottori et al., 2023; Zeng et al., 2023). Boudreault et al. (2023) explored the impact of the choice of flood loss estimation methods by using two different damage modelling approaches when generating RDM scenarios.

3.2.3 Scenario design and comparisons

While most studies shared a common goal of comparing managed retreat with alternative forms of adaptation, each study took a different approach to defining and assessing these alternatives. Several studies included a baseline scenario (André et al., 2016; Ramm et al., 2018; Creach et al., 2020; Skidmore and Cohon, 2022; Boudreault et al., 2023), while the remaining studies only compared scenarios that included adaptation measures. Geographic and scale considerations differed across the studies, ranging from hyper-local to continent-scale analyses; one study examined both property-level and neighbourhood-level scales (Boudreault et al., 2023), another study used a hypothetical analysis of a fictional town (André et al., 2016), others focused on regional-scale (Humber Estuary, UK; Turner et al., 2007) or continent-scale EAs (Europe; Dottori et al., 2023), and some studies included analysis of different potential receiving areas (Skidmore and Cohon, 2022) or pre-disaster vs. post-disaster managed retreat (Boudreault et al., 2023). Several studies compared different forms of managed retreat, such as buy and rent back programmes (André et al., 2016; Revell et al., 2021), or usufruct arrangements that separated bare ownership (typically held by a public authority) from use rights maintained by the residents until managed retreat is triggered (André et al., 2016; Boudreault et al., 2023). Although many studies assessed each adaptation alternative independently, some studies assessed scenarios with different combinations (Turner et al., 2007) or sequencing of alternatives (Lawrence et al., 2019; Stroombergen and Lawrence, 2022).

There was no consistency in how studies identified the number, range, and types of alternatives being assessed alongside managed retreat. Approaches used included only assessing the managed retreat component of an established flood risk reduction plan (Zeng et al., 2023), comparing managed retreat to 'do nothing' approaches with continued post-disaster assistance (Boudreault et al., 2023), comparing one simple representative of each of adaptation category (e.g., protection, accommodation, and retreat) (Cardona et al., 2020), comparing managed retreat to various forms of coastal modification (e.g., beach nourishment, living dunes, groynes with sand nourishment) (Revell et al., 2021), scaling the use of each adaptation alternative to meet varying policy targets (Turner et al., 2007), and comparing managed retreat to different forms of accommodation (e.g., warning and evacuation programmes, second story shelters) (Creach et al., 2020).

As discussed in Section 3.1.5, the scope and boundaries of EA studies play large roles in determining the EA's perspective, and therefore how impacts are measured. An explicit statement of scope and boundary was absent from most of the studies, leaving the reader to infer them from study details (e.g., value selection, valuation methods). This lack of specificity can lead to inconsistencies, such as labelling decreased local tax revenue as a cost of managed retreat (implying a localised scope and narrow boundaries) while also assessing increased recreation for the wider region as a benefit (implying a regional/societal-scale scope) (André et al., 2016). Boudreault et al. (2023) was the only study to directly address the issue of different perspectives and scopes, presenting results from the perspectives of both a public authority and a homeowner (the primary distinction being whether government payments for rebuilding/relocation were treated as a benefit or a cost), and also evaluating managed retreat at both property- and neighbourhood-levels. Similarly, only Skidmore and Cohon (2022) attempted to address the specific perspective, and noted challenges, of managed retreat for an Indigenous community where viable relocation sites were limited. Finn et al. (2024) presented an extended discussion of Indigenous jurisdiction and law related to their case study in Sumas Lake, British Columbia, but did not incorporate any Indigenous values or perspective into the CBA itself.

3.2.4 Discount rate and time horizon

The choice of time horizon and discount rate was highly variable across the 14 EA studies. Of the 14 studies, the two most common time horizons used for the main analysis were 50–60 years (André et al., 2016; Cardona et al., 2020; Boudreault et al., 2023; Zeng et al., 2023) and 85–100 years (Turner et al., 2007; Meyer et al., 2012; Lawrence et al., 2019; Creach et al., 2020; Revell et al., 2021; Stroombergen and Lawrence, 2022). Discount rates for the main analysis also varied, from a low of 1% (Revell et al., 2021), to a middle range of 2.5–4% (Turner et al., 2007; André et al., 2016; Cardona et al., 2020; Creach et al., 2020; Stroombergen and Lawrence, 2022; Dottori et al., 2023), to higher rates more representative of anticipated market returns from 5 to 8% (Boudreault et al., 2023; Zeng et al., 2023). As mentioned in Section 3.1.4, a lower discount rate (e.g., 1%) will tend to favour projects with long-term benefits and will be supportive of addressing intergenerational equity concerns, while a higher discount rate (e.g., 8%) will favour projects with lower immediate costs and high immediate benefits, both of which will tend to place a lower value on significant future benefits and intergenerational equity.

For studies that combined CBA with MCDA (Lawrence et al., 2019; Skidmore and Cohon, 2022; Stroombergen and Lawrence, 2022), the timeframe considered by participants when evaluating qualitative impacts was not specified and may not have matched the timeframe of the financial assessment (e.g., participants may have considered multi-generational environmental and social impacts while the financial assessment had a shorter, fixed time horizon). This lack of timeline specificity makes interpreting the results more difficult and may have unintentionally distorted participant responses depending on their interpretation of the assessment's timeframe.

3.2.5 Uncertainty and sensitivity analysis

The treatment of uncertainty varied substantially across the 14 studies. Following best practises for dealing with uncertainty in EAs, all studies other than Cardona et al. (2020) performed some level of sensitivity analysis. This involves recalculating assessment results while varying values and parameters about which there is uncertainty in order to test the results' robustness to uncertainty in parameter values (Boardman et al., 2018). The most common factors used in the sensitivity analyses were discount rate (Turner et al., 2007; Meyer et al., 2012; Revell et al., 2021; Stroombergen and Lawrence, 2022; Boudreault et al., 2023), and the assessed value of one or more of the monetized impacts (Turner et al., 2007; Meyer et al., 2012; André et al., 2016; Revell et al., 2021; Boudreault et al., 2023; Dottori et al., 2023; Zeng et al., 2023; Finn et al., 2024). There was no consistency across studies as to which values were included or the range of uncertainty that was tested.

The RDM studies had the most thorough treatment of uncertainty, using Monte Carlo simulation to assess thousands of hypothetical scenarios, each using a different combination of parameters within a predetermined, expected range of values (Ramm et al., 2018; Boudreault et al., 2023). In addition, the two RDM studies and one of two ROA studies (Stroombergen and Lawrence, 2022) were the only studies to include different rates and severities of climate change in their scenario designs. The other ROA study (Lawrence et al., 2019) considered only a single rate of sea level rise, reducing ROA's advantages in planning for an uncertain future through the ability to postpone investment. Similarly, all three DAPP studies (Ramm et al., 2018; Lawrence et al., 2019; Stroombergen and Lawrence, 2022) used a set number of dates and fixed dates as opportunities to switch adaptation strategies, a choice which reduced flexibility about switching to a new adaptation strategy as and when climate conditions change.

4 Discussion

The targeted review of managed retreat and EA of CCA and DRR literature helped to identify several avenues where changes and additions to CBA and decision-making processes may help to facilitate improved managed retreat outcomes. These changes, which we collectively refer to as 'CBA+', are discussed in detail in the following section.

4.1 Context-specific economic assessment and decision-making processes

Arguably the greatest opportunity to improve managed retreat outcomes through changes to EA and related decision-making is to align these processes with the specific community and decision-making contexts. Except for Boudreault et al. (2023), managed retreat EAs in the literature were typically presented from one perspective (e.g., the local government) and with the goal of providing a single, holistic evaluation of the program's societal effects. However, given the many different participants in managed retreat programmes (e.g., community members, local government or other organising bodies, higher-level government funders, non-government organisations), each with their own values, objectives, and priorities, a single EA is unlikely to align with all parties, and may not perfectly align with any of them. This issue is further complicated by the heterogeneity that typically exists within communities, groups, and organisations. This heterogeneity means that different values, objectives, and priorities can exist not only between groups but also within them, and can affect the level of engagement and representation of different participants' viewpoints within the EA process (Costa and Kahn, 2003).

As suggested by Brouwer and Van Ek (2004), multiple separate or sub-assessments may be needed to fully understand the costs, benefits, and tradeoffs of the proposed alternatives. For example, a neighbourhood deciding whether to accept a buyout offer, a municipal government selecting amongst multiple adaptation alternatives, and a higher-level government weighing the costs of managed retreat against future recovery spending would each have a different perspective on the nature and scope of the decision at hand, and would benefit from an EA that included different values and parameters. This distinction could help identify how a managed retreat programme, or a specific form of managed retreat, may be beneficial for one party and detrimental to another. In those cases, the programme design could be altered to account for these differences, such as changing the scale or timing of managed retreat or providing additional compensation or supports for certain populations. However, the time, effort, and cost of assessment should also be commensurate with the importance of the decision in question and the resources available. Conducting additional assessments has costs, including opportunity costs, which should be considered against the value of information to be gained and the benefits of more rapid decision-making and action.

Stroombergen and Lawrence (2022) presented a case where an ROA indicated that delaying a large CCA investment was more economical, but the community opted for immediate implementation due to political preferences and the results of public consultation. The community was risk averse and feared that future councils may not follow through on the plan, so immediate implementation was seen as fairer to current homeowners. If the EA had incorporated these perspectives from the beginning, the process could have been used to better refine the alternatives under consideration, or perhaps resurrect a preferable alternative that was previously omitted from consideration because of the initial focus on economic efficiency rather than the community's stated priorities.

The above example also highlights the importance of predetermining a clear role for EA in the broader decision-making process (Shi et al., 2022). In some cases, a decision where non-economic community values are prioritised over a traditional CBA may signify a successfully functioning decision-making process, while in other cases it may demonstrate a failure to account for appropriate values in the CBA design, resulting in wasted time and resources. The distinction between these two cases would be whether decision-making and the consideration of different types of values followed a thoughtful, pre-determined process, or was a surprise result undermining previous work. Even where flexibility in the design and role of EAs in the decision-making process is limited by legal and regulatory structure [e.g., the CBA requirement and guidance in FEMA's Hazard Mitigation Assistance Programme (FEMA, 2024)], it is beneficial to maintain transparency and be thoughtful in the choices that are made.

The selection of values and decisions about how values are considered in the decision-making process could also have large impacts on EA and managed retreat outcomes. As discussed in Section 2, many of the challenges related to manage retreat involve impacts and values that traditional CBAs would not typically capture. Failure to account for the most important values related to managed retreat outcomes could lead to making decisions without the appropriate information, a false sense of confidence in a purportedly holistic EA, and/or selecting adaptation measures that have unintended negative consequences, particularly on the most vulnerable populations. In addition, technical nuances in value selection and measurement can have substantial effects on assessment outcomes, such as how property values are estimated in compensation and flood impact calculations (e.g., pre- vs. post-flood valuations, assessed value, replacement cost).

The research revealed that the measurement and representation of key financial costs may also affect the viability and ultimate implementation of managed retreat. For example, the design and costing of the proposed compensation scheme (e.g., pre- vs. post-disaster valuation, 'home for a home' assessments or top-ups, legal and moving expenses, pre- and post-relocation support programmes) can have a large effect on the total cost of the programme, and therefore whether it appears 'economically efficient' and thus eligible for funding. Where EAs are the basis for funding decisions, this may also effectively determine the level of compensation and supports received by the participating households, thereby affecting relocation options and quality of life outcomes.

Not all values must (or should) be included in an EA, but there should be an explicit recognition of the values that are *not* formally assessed within the decision-making process to ensure they are not ignored. For example, Boudreault et al. (2023) intentionally omitted the effects of land-use change following relocation despite acknowledging that changes in land use powerfully impact the cost-effectiveness of managed retreat. While this omission greatly limits the study's ability to assess the societal impacts of managed retreat against its alternatives, the explicit recognition of the omission is important for appropriately interpreting and using the study results in decision-making.

If equity impacts and considerations of Indigenous values and history are community priorities, and it is decided not to quantitatively assess these, better managed retreat outcomes related to these values are more likely to be achieved if their place in the decision-making process is made explicit from the outset. Indigenous values may be better represented through a systematic process or tool such as MCDA, or through qualitative reporting and consideration by the decision-making body, depending on the community needs and preference.

Context-specific considerations potentially affect many other aspects of EA design as well, including discount rates, time horizons, and boundary and baseline selection. A shorter time frame and/or higher discount rate may be appropriate in some contexts (e.g., primarily financial or short-term decision contexts), while longer time frames and/or lower discount rates may be appropriate in others (e.g., decisions focused on ecological restoration or long-term community planning and CCA). Similarly, EA boundaries should match the decision-making context, whether that be of individual homeowners, neighbourhoods, towns, or society as a whole.

4.2 Community engagement and co-production of managed retreat programmes

An almost ubiquitous theme in the managed retreat literature is the benefit of, and need for more, community engagement and co-production of managed retreat programmes (Dodman et al., 2022; O'Donnell, 2022; Bower et al., 2023; Dundon and Abkowitz, 2024), a theme that could also be applied to the design and execution of managed retreat EA and decision-making processes (Brouwer and Van Ek, 2004). EA design based on community engagement and co-production helps to align the assessment with the context-specific needs and perspectives of the community and decision-makers, ensures that the community's values are captured and prioritised appropriately, and builds buy-in for the final EA results and decision. Engaging the community early in the EA process can also be an important step in the design of creative and realistic scenarios (Hanna et al., 2021), which is discussed in more detail in Section 4.3. Community engagement processes should also recognise the heterogeneity of communities and the multiple voices that exist within organisations to diversify the voices heard and encourage discussion between parties (Golden and Bencherki, 2021).

The process of conducting EAs, particularly those that involve direct community engagement, is often as valuable as the assessment results, and therefore EA processes should be designed to maximise these benefits (Brouwer and Van Ek, 2004). Community engagement, and EA more broadly, also benefit from an iterative process, whereby new information and early assessment results feed back into the design and modification of the scenarios under consideration and the assessment design itself (Brouwer and Van Ek, 2004; Sayers et al., 2015). An iterative, participatory process may be particularly impactful for avoiding unforeseen equity impacts and providing different groups the opportunity to identify additional or misrepresented impacts, which could then influence both the project design and later iterations of the EA and final decision (Ehrenfeucht and Nelson, 2023).

Co-production and deep community engagement will be especially important for managed retreat projects led by or involving Indigenous groups. As discussed in Sections 3.1.2 and 4.1, traditional EA methods often do not align with Indigenous world views (Venn and Quiggin, 2007; Choy, 2018; Manero et al., 2022), and EA and decision-making processes that do not involve and empower Indigenous communities may be more likely to entrench, rather than resolve, histories of colonialism and forced relocation (Marino, 2018; Siders et al., 2021; Jessee, 2022).

4.3 Creative and realistic scenario design

As the number and complexity of scenarios under consideration is necessarily limited, creative and realistic scenarios should be chosen to provide the most usable information for decision-makers. This helps to avoid missing out on the benefits of novel solutions and wasting resources evaluating impractical proposals (Mach and Siders, 2021). For example, including alternative forms of managed retreat, such as usufruct arrangements and buy and rent back (Abel et al., 2011; André et al., 2016; Keeler et al., 2022; Boudreault et al., 2023), can help reduce community opposition, fund property purchases through rental income, encourage consideration of pre-emptive managed retreat, and provide timing flexibility in the face of uncertain rates of climate change. Failing to include and assess creative designs like these may result in selecting a less desirable, higher-cost alternative.

The use of DAPP to show how managed retreat can be used alongside and in sequence with other adaptation measures is another example of how scenario choice and design may broaden community discussions and considerations (Ramm et al., 2018; Lawrence et al., 2019; Stroombergen and Lawrence, 2022). The combination of DAPP and EA tools such as CBA also encourages long-term planning. This may help reduce the reliance on, and the negative impacts of, post-disaster retreat, either by increasing the desirability of pre-emptive retreat or by demonstrating the value of pre-planning even if a disaster is ultimately needed to trigger managed retreat.

However, the literature review revealed that there is still room for improvement in the inclusion of different scales and staging of managed retreat within EAs. Most managed retreat EAs were framed as a single decision of whether to relocate a pre-determined community or set of homes at a single time. Boudreault et al. (2023) compared property-level to neighbourhood-level managed retreat scenarios, and other studies utilised DAPP or alternative purchase arrangements to make some allowance for staging managed retreat, but there are opportunities to explore scenarios that better preserve community cohesion and reduce uncertainty and funding limitations.

4.4 Selecting and combining the appropriate tool(s)

Although there is extensive literature critiquing and identifying the limitations of CBA for CCA and DRR [e.g., Markanday et al. (2019)], the continued widespread use of CBA despite these critiques means that improving CBA methods might confer significant benefits to programme outcomes. One avenue for improvement is to combine CBA with other tools. Although the details of these complementary tools are beyond the scope of this paper, this section will outline how MCDA, ROA, RDM, and DAPP could compensate for CBA's weaknesses and contribute to better managed retreat outcomes.

One approach to overcome CBA's requirement to monetize impacts is to combine CBA with MCDA, as demonstrated by Lawrence et al. (2019) and Skidmore and Cohon (2022). MCDA's primary benefit is the ability to account for and compare quantitative and qualitative assessments of scenario impacts in the same analysis (Dittrich et al., 2016). MCDA is also highly flexible, with many variations that can accommodate different types of values, measurement techniques, scoring and tradeoff philosophies, complexities, and level of community and expert involvement needed (Siders and Pierce, 2021; Cinelli et al., 2023). Combining CBA and MCDA allows for the tangible, financial effects of managed retreat to be estimated using a tool designed for that purpose (i.e., CBA), while using MCDA to capture and compare additional values that the community identifies as inappropriate for monetization. An MCDA co-designed with the community could identify impacts that would otherwise be ignored, rebalance the relative priority of impacts in line with the community's values, and build trust and buy-in to the process, all of which could lead to better managed retreat experiences and outcomes.

However, MCDA is not a panacea and is susceptible to bias and manipulation by influential parties if the process is not designed with equity and equitable participation in mind (Lawrence et al., 2019; Skidmore and Cohon, 2022). Additionally, MCDAs can be complex processes that require a lot of resources and community participation, and some forms of MCDA suffer from the same limitations as CBA (e.g., lack of substitutability of values, disagreement on value weightings/priorities) so it is important to design an appropriate approach and to understand its nuances when interpreting the results (Dittrich et al., 2016; Zhu et al., 2017).

ROA, RDM, and DAPP all provide additional tools to make better decisions under uncertainty and can easily be combined with CBA for managed retreat decision-making. ROA and RDM are technical EA approaches that adapt CBA to account for the potential benefit of delaying decisions or staging implementation to take advantage of new information as it becomes available [ROA; Kind et al. (2018)], or to test alternatives against a wide range of potential futures (typically thousands) to see how robust they are too unpredictable events, such as long-term climate change [RDM; Lempert, 2014; Dittrich et al., 2016). In contrast, DAPP is a planning tool that helps communities map out how CCA measures could be combined and sequenced in different ways over time, identify triggers for when changing approaches may be warranted, and develop an adaptive management plan to assist in monitoring conditions and implementing supporting actions (Haasnoot et al., 2013).

Despite the advantages these additional tools provide, they are not yet standardised and can require substantial cost, expertise, time, and data to execute well. Given that local authorities often lack these resources, there is a need to balance practicality with sufficient complexity and community engagement to capture the most important impacts of managed retreat. For example, Lawrence et al. (2020) and Stroombergen and Lawrence (2022) used a novel 'cut-off' probability approach to ROA to address a major drawback of traditional ROA, the need to assign probabilities to each potential future, which is generally considered impossible for the long-term effects of climate change (Hinkel and Bisaro, 2015; Kind et al., 2018). However, it is unlikely that local government staff would have the capacity to implement this type of newer approach. Dittrich et al. (2016) suggested that using simplified versions of ROA and RDM which take advantage of key benefits while sacrificing some rigour may be a good compromise. The need for simplified but appropriate EA methodologies also applies to CBA itself, since capturing the full impacts of managed retreat may become too complex to effectively analyze. This need for simplicity was demonstrated in the limited range of values and scenarios explored in all the CBA studies reviewed, highlighting the need for careful scenario and parameter selection and the importance of community involvement from the beginning of study design.

4.5 Balancing guidance, standardisation, and flexibility

In addition to the studies reviewed, managed retreat practitioners have access to a range of guidance documents on how to conduct EAs for CCA and DRR, not to mention the extensive literature on EA more broadly. Various government entities have produced detailed guidance on the EA of CCA and DRR programmes, including Canada (Muir et al., 2021), the United States (Federal Emergency Management Agency, 2024), and the United Kingdom (HM Treasury, 2021, 2022, 2024). Additional guidance in the form of a detailed review of available costing approaches for managed retreat impacts (Olufson, 2019) or more general guidance on managed retreat planning and implementation (Freudenberg et al., 2016; Saunders-Hastings et al., 2020; Thistlethwaite et al., 2023; Dundon and Abkowitz, 2024) is also beginning to emerge. However, there may be an opportunity to improve managed retreat outcomes through more effective EA and decision-making guidance. For example, it has been observed that managed retreat programmes often lack sufficient guidance and capacity (Ramm et al., 2018; Hanna et al., 2020; Curran-Groome et al., 2021), designing complex processes from scratch is costly and time consuming (André et al., 2016; Greer and Binder, 2017), and FEMA's CBA requirements have been criticised for having negative equity outcomes (Siders, 2019b).

One challenge in developing improved EA guidance will be to balance the provision of useful direction that raises standards, allows greater inter-study comparisons, and reduces barriers for lower-capacity communities, while maintaining the flexibility to design context-specific assessments that are likely to improve managed retreat outcomes. Establishing a standardised EA approach also risks entrenching poor practises (e.g., excluding particular values, introducing bias) (André et al., 2016), so any standard should be designed and implemented with care and with opportunities for wide ranging community engagement and iterative improvement. These challenges highlight the subjective nature of both EA design and managed retreat decision-making more broadly, which is also demonstrated by the many options and choices in EA design and use discussed in this paper. The ability to bias managed retreat decisions and outcomes, whether intentional or not, through subjective EA and decision-making choices emphasises the importance of well-considered, transparent processes that balance standardisation and flexibility.

4.6 Framework for managed retreat economic assessment and decision-making

To collect and synthesise the observations presented above, a framework was developed to provide a high-level process that

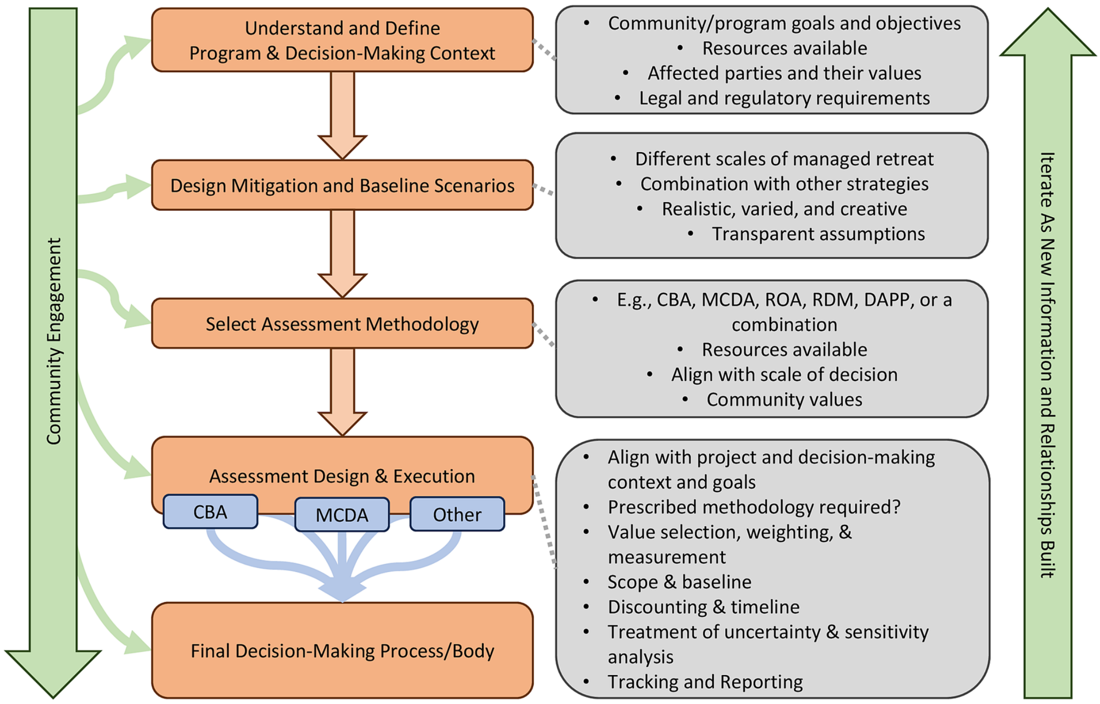

FIGURE 1
This framework provides organisations involved in managed retreat with a high-level process to follow for designing an improved economic assessment and decision-making process (CBA+), based on the key principles drawn from our review of the managed retreat and economic assessment literature, with the goal of improving managed retreat programme outcomes.

organisations involved in managed retreat can follow to design an EA and decision-making process using a CBA+ approach, with the goal of achieving more positive programme outcomes (Figure 1). This framework captures the key principles presented in this paper, which are summarised in the next section.

We believe that following this framework will help practitioners to resolve the five main managed retreat challenges discussed in Section 2. For example, conducting multiple context-specific EAs based on community engagement and co-production can help to recognise and address the heterogeneous nature of communities and provide a tool to work through contested goals, objectives, and values (Section 2.1). Equity concerns (Section 2.2) can be addressed through the use of equity weights, inclusive community co-production, and the design of creative managed retreat solutions that shift where programme benefits and costs accrue. Poor managed retreat experiences and implementation issues (Section 2.3) could be reduced by capturing a wider breadth of monetary and non-monetary impacts of retreat when comparing alternatives and by building in efforts to reduce negative outcomes (e.g., higher compensation levels, social supports). Similarly, public and political opposition to retreat (Section 2.4) may be reduced through enhanced community engagement/co-production, better-designed managed retreat programmes, and more transparent and relevant EAs that reflect community values and account for uncertainty using tools like MCDA, ROA, and RDM. Finally, the negative effects of reactive post-disaster retreat (Section 2.5) could be reduced by facilitating pre-disaster planning through EAs based on the CBA+ framework. The CBA+ concepts could help communities grapple with the benefits and costs of managed retreat in a productive, inclusive, and non-threatening way.

5 Conclusion

While there is a thoroughly developed body of literature detailing the benefits and challenges of managed retreat, and a growing literature on EA applications for retreat, there remains a gap between these two areas of research and an open question of how EA practises may be affecting managed retreat outcomes. This paper attempts to identify where in the design of managed retreat EAs there may be opportunities to increase the benefits and resolve some of the challenges associated with managed retreat, with the goal of encouraging discourse and collective efforts to fill this research gap.

The following are 10 key principles for managed retreat EA and decision-making to accompany the framework from Section 4.6. These principles, which we collectively refer to as CBA+, succinctly summarise the main conclusions of this study:

Community engagement and co-production: Community engagement and co-production should be incorporated as fully and at as many stages as possible in both developing and executing the EA and decision-making processes.

Contextual relevance: EA and decision-making processes for managed retreat should be specific to the context and nature of the decisions being made. Even within the same managed retreat project, an EA or decision-making process intended for one purpose or group may be inappropriate for another. Key areas for contextualization include: the level of effort, time, and resources required; the tools/

techniques that are chosen and in what combination; which values are considered, how they are measured, and how they are weighed/prioritised against each other; who is involved and what roles they play; the generation and selection of the scenarios being assessed; and, how the final adaptation decision is ultimately made.

Importance of process: The process of conducting an EA (e.g., community consultation, selection of methodology, values, and valuation approaches, conducting valuation studies, iterative methodology refinement) is often more valuable than the final outcome, and it is important to design the process to maximise these benefits.

Scenarios driven by community values: The development and comparison of scenarios under consideration should encourage creative and varied solutions that are driven by the full spectrum and heterogeneity of community values and input, and that achieve other societal goals where possible.

Expose and address uncertainty: Major sources of uncertainty should be identified and systematically addressed in all EAs.

Conduct sensitivity analyses: Sensitivity analyses should be conducted for all parameters and metrics where the EA outcome could be substantially affected by reasonable variations. The range of values tested within a sensitivity analysis will depend on the risk tolerance of the decision-maker and should typically be within a realistic range of variation.

Consider multiple tools, approaches, and inputs: A CBA will provide useful information in most decision-making contexts but should not be the only input to a decision. Instead, CBAs, and other similar EAs, should be used alongside other tools and techniques, such as MCDA and DAPP, in a broader and inclusive decision-making process.

Understand limitations: It is important to understand and consider the choices, assumptions, uncertainties, and limitations involved in all EAs when interpreting and comparing results, and when deciding whether the assessment is relevant to the decision at hand.

Proactively consider retreat: Where possible, planners and decision-makers should attempt to complete as much communication, community engagement, planning, and EA as possible prior to experiencing a disaster, regardless of whether pre-emptive retreat is desired or realistic.

Build learning and adaptive management into the process: Decision-making processes surrounding managed retreat are likely to be iterative and require repeating steps or stages as new information becomes available and new relationships are built. Build learning, adaptive management, tracking, and reporting into the process to ensure that these opportunities are not lost, that programme evaluation is possible, and that lessons are captured and implemented for future projects.

While we believe following these 10 key principles would help to achieve better managed retreat outcomes, there are still knowledge gaps on how EAs are being used in managed retreat decision-making and how they are affecting programme outcomes. To begin filling these gaps we suggest several avenues for future research, including: (1) interviews with managed retreat practitioners and policy makers to better understand the role of EAs in managed retreat decision-making, and to identify what needs are not currently being met; (2) analyses of the connection between particular EA and decision-making processes and the resulting managed retreat outcomes to identify both best- and potentially problematic practises; (3) using the results of (1) and (2) to design and test alternative EA and decision-making processes, such as the framework presented in Section 4.6, with managed retreat practitioners and policy makers to further iterate and refine the practises and guidance. Additionally, there is little to no research that analyzes EA processes in previously implemented managed retreat programmes, which makes it difficult to assess whether the practises described in the literature accurately reflect what is being done in practise. Research collecting and describing real-world EA processes for managed retreat is another research avenue that would be beneficial to the field.

Author contributions

BC: Conceptualization, Investigation, Writing – original draft. BD: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. VL: Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The authors acknowledge support from the Pacific Institute for Climate Solutions through the Living with Water theme project grant, and the Province of B.C. Agreement #TP23WMB0006 administered through the University of British Columbia.

Acknowledgments

The authors would like to acknowledge and thank the Pacific Institute for Climate Solutions (PICS)-funded Living with Water project team for their ongoing support in exploring values-based solutions to improve flood resiliency and coastal adaptation.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., et al. (2011). Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. *Environ. Sci. Pol.* 14, 279–288. doi: 10.1016/j.envsci.2010.12.002

Adler, M. D. (2016). Benefit-cost analysis and distributional weights: an overview. *Rev. Environ. Econ. Policy* 10, 264–285. doi: 10.1093/reep/rew005

Agyeman, J., Devine-Wright, P., and Prange, J. (2009). Close to the edge, down by the river? Joining up managed retreat and place attachment in a climate changed world. *Environ. Plan. A* 41, 509–513. doi: 10.1068/a41301

Ajibade, I., Sullivan, M., Lower, C., Yarina, L., and Reilly, A. (2022). Are managed retreat programs successful and just? A global mapping of success typologies, justice dimensions, and trade-offs. *Glob. Environ. Chang.* 76:102576. doi: 10.1016/j.gloenvcha.2022.102576

Alexander, M., Priest, S., and Mees, H. (2016). A framework for evaluating flood risk governance. *Environ. Sci. Pol.* 64, 38–47. doi: 10.1016/j.envsci.2016.06.004

Anderson, R. B. (2022). The taboo of retreat: the politics of sea level rise, managed retreat, and coastal property values in California. *Econ. Anthropol.* 9, 284–296. doi: 10.1002/sea2.12247

André, C., Boulet, D., Rey-Valette, H., and Rulleau, B. (2016). Protection by hard defence structures or relocation of assets exposed to coastal risks: contributions and drawbacks of cost-benefit analysis for long-term adaptation choices to climate change. *Ocean Coast. Manag.* 134, 173–182. doi: 10.1016/j.ocecoaman.2016.10.003

Biggs, R., Carpenter, S. R., and Brock, W. A. (2009). Spurious certainty: how ignoring measurement error and environmental heterogeneity may contribute to environmental controversies. *Bioscience* 59, 65–76. doi: 10.1525/bio.2009.59.1.10

Binder, S. B., Baker, C. K., and Barile, J. P. (2015). Rebuild or relocate? Resilience and Postdisaster decision-making after hurricane Sandy. *Am. J. Community Psychol.* 56, 180–196. doi: 10.1007/s10464-015-9727-x

Bloemen, P., Hammer, F., van der Vlist, M. J., Grinwis, P., and van Alphen, J. (2019). "DMDU into practice: Adaptive Delta Management in the Netherlands" in Decision making under deep uncertainty. ed. V. A. M. Marchau (Cham: Springer International Publishing), 321–351.

Boardman, A. E., Greenberg, D. H., Vining, A. R., and Weimer, D. L. (2018). Cost-benefit analysis: Concepts and practice. Cambridge: Cambridge University Press.

Boudreault, M., Bourdeau-Brien, M., and Milot, N. (2023). Comparison of three flood-related relocation programs with probabilistic cost-benefit analyses. *Int. J. Disaster Risk Reduc.* 96:103950. doi: 10.1016/j.ijdrr.2023.103950

Bower, E. R., Badamikar, A., Wong-Parodi, G., and Field, C. B. (2023). Enabling pathways for sustainable livelihoods in planned relocation. *Nat. Clim. Chang.* 13, 919–926. doi: 10.1038/s41558-023-01753-x

Braamskamp, A., and Penning-Rowsell, E. C. (2018). Managed retreat: a rare and paradoxical success, but yielding a dismal prognosis. *Environ. Manage. Sust. Dev.* 7:108. doi: 10.5296/emsd.v7i2.12851

Brouwer, R., and Van Ek, R. (2004). Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecol. Econ.* 50, 1–21. doi: 10.1016/j.ecolecon.2004.01.020

Buurman, J., and Babovic, V. (2016). Adaptation pathways and real options analysis: an approach to deep uncertainty in climate change adaptation policies. *Polic. Soc.* 35, 137–150. doi: 10.1016/j.polsoc.2016.05.002

Cardona, F. S., Ferreira, J. C., and Lopes, A. M. (2020). Cost and benefit analysis of climate change adaptation strategies in coastal areas at risk. *J. Coast. Res.* 95, 764–768. doi: 10.2112/SI95-149.1

Choy, Y. K. (2018). Cost-benefit analysis, values, wellbeing and ethics: an indigenous worldview analysis. *Ecol. Econ.* 145, 1–9. doi: 10.1016/j.ecolecon.2017.08.005

Cinelli, M., Kadzinki, M., Miebs, G., Stowinski, R., Gonzalez, M., and Burgherr, P. (2023). MCDA methods selection software. Available at: https://mcda.cs.put.poznan.pl/ (Accessed July 11, 2024).

Costa, D. L., and Kahn, M. E. (2003). Civic engagement and community heterogeneity: An Economist's perspective. *Persp. Politics* 1, 103–111. doi: 10.1017/S1537592703000082

Cottar, S., and Wandel, J. (2024). Municipal perspectives on managed retreat and flood mitigation: a case analysis of Merritt, Canada after the 2021 British Columbia flood disaster. *Clim. Chang.* 177:50. doi: 10.1007/s10584-024-03707-4

Creach, A., Bastidas-Arteaga, E., Pardo, S., and Mercier, D. (2020). Vulnerability and costs of adaptation strategies for housing subjected to flood risks: application to La Guérinière France. *Mar. Policy* 117:103438. doi: 10.1016/j.marpol.2019.02.010

Curran-Groome, W., Haygood, H., Hino, M., BenDor, T. K., and Salvesen, D. (2021). Assessing the full costs of floodplain buyouts. *Clim. Chang.* 168:3178. doi: 10.1007/s10584-021-03178-x

Dawson, D. A., Hunt, A., Shaw, J., and Gehrels, W. R. (2018). The economic value of climate information in adaptation decisions: learning in the sea-level rise and coastal infrastructure context. *Ecol. Econ.* 150, 1–10. doi: 10.1016/j.ecolecon.2018.03.027

De Brito, M. M., and Evers, M. (2016). Multi-criteria decision-making for flood risk management: a survey of the current state of the art. *Nat. Hazards Earth Syst. Sci.* 16, 1019–1033. doi: 10.5194/nhess-16-1019-2016

Dedekorkut-Howes, A., Torabi, E., and Howes, M. (2020). When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. *J. Environ. Plan. Manag.* 63, 2102–2143. doi: 10.1080/09640568.2019.1708709

Dennig, F. (2018). Climate change and the re-evaluation of cost-benefit analysis. *Clim. Chang.* 151, 43–54. doi: 10.1007/s10584-017-2047-4

Dittrich, R., Wreford, A., and Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: are robust methods the way forward? *Ecol. Econ.* 122, 79–89. doi: 10.1016/j.ecolecon.2015.12.006

Doberstein, B., Fitzgibbons, J., and Mitchell, C. (2019). Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience. *Nat. Hazards* 98, 31–50. doi: 10.1007/s11069-018-3529-z

Doberstein, B., Tadgell, A., and Rutledge, A. (2020). Managed retreat for climate change adaptation in coastal megacities: a comparison of policy and practice in Manila and Vancouver. *J. Environ. Manag.* 253:109753. doi: 10.1016/j.jenvman.2019.109753

Dodman, D., Hayward, B., Pelling, M., Castan Broto, V., Chow, W., Chu, E., et al. (2022). "Cities, settlements and key infrastructure" in Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. eds. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck and A. Alegriaet al. (Cambridge: Cambridge University Press).

Dottori, F., Mentaschi, L., Bianchi, A., Alfieri, L., and Feyen, L. (2023). Cost-effective adaptation strategies to rising river flood risk in Europe. *Nat. Clim. Chang.* 13, 196–202. doi: 10.1038/s41558-022-01540-0

Dottori, F., Szewczyk, W., Ciscar, J. C., Zhao, F., Alfieri, L., Hirabayashi, Y., et al. (2018). Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Clim. Chang.* 8, 781–786. doi: 10.1038/s41558-018-0257-z

Driessen, P. P. J., Hegger, D. L. T., Bakker, M. H. N., van Rijswick, H. F. M. W., and Kundzewicz, Z. W. (2016). Toward more resilient flood risk governance. *Ecol. Soc.* 21:453. doi: 10.5751/ES-08921-210453

Dudley, S. E., Pérez, D. R., Mannix, B. F., and Carrigan, C. (2019). Dynamic benefit-cost analysis for uncertain futures. *J. Benefit Cost Anal.* 10, 206–225. doi: 10.1017/bca.2019.13

Dundon, L. A., and Abkowitz, M. (2021). Climate-induced managed retreat in the U.S.: a review of current research. *Clim. Risk Manag.* 33:100337. doi: 10.1016/j.crm.2021.100337

Dundon, L. A., and Abkowitz, M. (2024). Turning 'managed retreat' research into practice ready tools: needed guidelines to reach stakeholders. *Environ. Res. Lett.* 19:041003. doi: 10.1088/1748-9326/ad300d

Dundon, L. A., and Camp, J. S. (2021). Climate justice and home-buyout programs: renters as a forgotten population in managed retreat actions. *J. Environ. Stud. Sci.* 11, 420–433. doi: 10.1007/s13412-021-00691-4

Ehrenfeucht, R., and Nelson, M. (2023). Towards transformative climate relocation initiatives. *J. Plan. Lit.* 38, 395–407. doi: 10.1177/08854122221130287

Ekins, P., Simon, S., Deutsch, L., Folke, C., and De Groot, R. (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecol. Econ.* 44, 165–185. doi: 10.1016/S0921-8009(02)00272-0

Eriksen, S. H., Nightingale, A. J., and Eakin, H. (2015). Reframing adaptation: the political nature of climate change adaptation. *Glob. Environ. Chang.* 35, 523–533. doi: 10.1016/j.gloenvcha.2015.09.014

Federal Emergency Management Agency (2024). FEMA: Benefit-cost analysis. FEMA. Available at: https://www.fema.gov/grants/tools/benefit-cost-analysis (accessed February 17, 2024).

FEMA (2024). Hazard mitigation assistance program and policy guide. Washington, DC: FEMA.

Finn, R. J. R., Ned-Kwilosintun, M., Ballantyne, L., Hamilton, I., Kwo, J., Seymour-Hourie, R., et al. (2024). Reclaiming the Xhotsa: climate adaptation and ecosystem restoration via the return of Sumas Lake. *Front. Conserv. Sci.* 5:1380083. doi: 10.3389/fcosc.2024.1380083

Flyvbjerg, B., and Bester, D. W. (2021). The cost-benefit fallacy: why cost-benefit analysis is broken and how to fix it. *J. Benefit Cost Anal.* 12, 395–419. doi: 10.1017/bca.2021.9

Freudenberg, R., Calvin, E., Tolkoff, L., and Brawley, D. (2016). Buy-in for buyouts the case for managed retreat from flood zones buy-in for buyouts. Available at: www.lincolninst.edu (Accessed October 24, 2022).

Gibbs, M. T. (2016). Why is coastal retreat so hard to implement? Understanding the political risk of coastal adaptation pathways. *Ocean Coast. Manag.* 130, 107–114. doi: 10.1016/j.ocecoaman.2016.06.002

Golden, A. G., and Bencherki, N. (2021). "I'm Just Saying': Multivocal Organizing in a Community Health Initiative" in Speaking with One Voice: Multivocality and Univocality in Organizing. eds. C. Benoit-Barné and T. Martine (New York, NY: Taylor and Francis), 41–64.

Greer, A., and Binder, S. (2017). A historical assessment of home buyout policy: are we learning or just failing? *Hous. Policy Debate* 27, 372–392. doi: 10.1080/10511482.2016.1245209

Greer, A., Binder, S., and Zavar, E. (2022). From Hazard mitigation to climate adaptation: a review of home buyout program literature. *Hous. Policy Debate* 32, 152–170. doi: 10.1080/10511482.2021.1931930

Haasnoot, M., Brown, S., Scussolini, P., Jimenez, J. A., Vafeidis, A. T., and Nicholls, R. J. (2019). Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environ Res Commun* 1:ab1871. doi: 10.1088/2515-7620/ab1871

Haasnoot, M., Kwakkel, J. H., Walker, W. E., and ter Maat, J. (2013). Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Chang.* 23, 485–498. doi: 10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., van Aalst, M., Rozenberg, J., Dominique, K., Matthews, J., Bouwer, L. M., et al. (2020). Investments under non-stationarity: economic evaluation of adaptation pathways. *Clim. Chang.* 161, 451–463. doi: 10.1007/s10584-019-02409-6

Haasnoot, M., Winter, G., Brown, S., Dawson, R. J., Ward, P. J., and Eilander, D. (2021). Long-term sea-level rise necessitates a commitment to adaptation: a first order assessment. *Clim. Risk Manag.* 34:100355. doi: 10.1016/j.crm.2021.100355

Hanna, C., White, I., and Glavovic, B. (2020). The uncertainty contagion: revealing the interrelated, cascading uncertainties of managed retreat. *Sustainability* 12:736. doi: 10.3390/su12020736

Hanna, C., White, I., and Glavovic, B. C. (2021). Managed retreats by whom and how? Identifying and delineating governance modalities. *Clim. Risk Manag.* 31:100278. doi: 10.1016/j.crm.2021.100278

Hashida, Y., and Dundas, S. J. (2023). The effects of a voluntary property buyout and acquisition program on coastal housing markets: evidence from New York. *J. Environ. Econ. Manag.* 121:102873. doi: 10.1016/j.jeem.2023.102873

Heikkila, E. J., and Huang, M. (2014). Adaptation to flooding in urban areas: an economic primer. *Public Works Manag. Policy* 19, 11–36. doi: 10.1177/1087724X13506559

Hinkel, J., and Bisaro, A. (2015). A review and classification of analytical methods for climate change adaptation. *Wiley Interdiscip. Rev. Clim. Chang.* 6, 171–188. doi: 10.1002/wcc.322

Hinkel, J., Church, J. A., Gregory, J. M., Lambert, E., Le Cozannet, G., Lowe, J., et al. (2019). Meeting user needs for sea level rise information: a decision analysis perspective. *Earths Future* 7, 320–337. doi: 10.1029/2018EF001071

Hino, M., Field, C. B., and Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. *Nat. Clim. Chang.* 7, 364–370. doi: 10.1038/nclimate3252

HM Treasury (2021). Wellbeing Guidance for Appraisal: Supplementary Green Book Guidance. Available at: www.gov.uk/official-documents (Accessed February 18, 2024).

HM Treasury (2022). The green book (2022). *HM Treasury*. Available at: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020 (accessed February 17, 2024).

HM Treasury (2024). Green Book supplementary guidance: climate change and environmental valuation. Available at: https://www.gov.uk/government/publications/green-book-supplementary-guidance-environment (accessed February 17, 2024).

Hoang, T., and Noy, I. (2023). The income consequences of a managed retreat. *Reg. Sci. Urban Econ.* 100:103896. doi: 10.1016/j.regsciurbeco.2023.103896

Hudson, P., and Botzen, W. J. (2019). Cost–benefit analysis of flood-zoning policies: a review of current practice. *Wiley Interdiscip. Rev. Water* 6:1387. doi: 10.1002/WAT2.1387

Hudson, P., Botzen, W. J. W., Poussin, J., and Aerts, J. C. J. H. (2019). Impacts of flooding and flood preparedness on subjective well-being: a monetisation of the tangible and intangible impacts. *J. Happiness Stud.* 20, 665–682. doi: 10.1007/s10902-017-9916-4

Jessee, N. (2022). Reshaping Louisiana's coastal frontier: managed retreat as colonial decontextualization. *J. Polit. Ecol.* 29, 277–301. doi: 10.2458/jpe.2835

Jonkman, S. N., Vrijling, J. K., and Vrouwenvelder, A. C. W. M. (2008). Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method. *Nat. Hazards* 46, 353–389. doi: 10.1007/s11069-008-9227-5

Keeler, A. G., Mullin, M., McNamara, D. E., and Smith, M. D. (2022). Buyouts with rentbacks: a policy proposal for managing coastal retreat. *J. Environ. Stud. Sci.* 12, 646–651. doi: 10.1007/s13412-022-00762-0

Kick, E. L., Fraser, J. C., Fulkerson, G. M., Mckinney, L. A., and De Vries, D. H. (2011). Repetitive flood victims and acceptance of FEMA mitigation offers: an analysis with community-system policy implications. *Disasters* 35, 510–539. doi: 10.1111/j.1467-7717.2011.01226.x

Kind, J. (2014). Economically efficient flood protection standards for the Netherlands. *J. Flood Risk Manag.* 7, 103–117. doi: 10.1111/jfr3.12026

Kind, J., Baayen, J., and Botzen, W. J. W. (2018). Benefits and limitations of real options analysis for the practice of river flood risk management. *Water Resour. Res.* 54, 3018–3036. doi: 10.1002/2017WR022402

Kind, J., Botzen, W. J. W., and Aerts, J. C. J. H. (2020). Social vulnerability in cost-benefit analysis for flood risk management. *Environ. Dev. Econ.* 25, 115–134. doi: 10.1017/S1355770X19000275

Kind, J., Wouter Botzen, W. J., and Aerts, J. C. J. H. (2017). Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management. *Wiley Interdiscip. Rev. Clim. Chang.* 8:446. doi: 10.1002/wcc.446

Kraan, C. M., Hino, M., Niemann, J., Siders, A. R., and Mach, K. J. (2021). Promoting equity in retreat through voluntary property buyout programs. *J. Environ. Stud. Sci.* 11, 481–492. doi: 10.1007/s13412-021-00688-z

Kwadijk, J. C. J., Haasnoot, M., Mulder, J. P. M., Hoogvliet, M. M. C., Jeuken, A. B. M., van der Krogt, R. A. A., et al. (2010). Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdiscip. Rev. Clim. Chang.* 1, 729–740. doi: 10.1002/wcc.64

Landry, C. E., Keeler, A. G., and Kriesel, W. (2003). An economic evaluation of beach Erosion management alternatives. *Mar. Resour. Econ.* 18, 105–127. doi: 10.1086/mre.18.2.42629388

Lawrence, J., Bell, R., and Stroombergen, A. (2019). A hybrid process to address uncertainty and changing climate risk in coastal areas using dynamic adaptive pathways planning, multi-criteria decision analysis & real options analysis: a New Zealand application. *Sustainability* 11:406. doi: 10.3390/su11020406

Lawrence, J., Boston, J., Bell, R., Olufson, S., Kool, R., Hardcastle, M., et al. (2020). Implementing pre-Emptive managed retreat: constraints and novel insights. *Curr. Clim. Chang. Rep.* 6, 66–80. doi: 10.1007/s40641-020-00161-z

Lempert, R. J. (2014). Embedding (some) benefit-cost concepts into decision support processes with deep uncertainty. *J. Benefit Cost Anal.* 5, 487–514. doi: 10.1515/jbca-2014-9006

Li, J., Mullan, M., and Helgeson, J. (2014). Improving the practice of economic analysis of climate change adaptation. *J Benefit Cost Anal.* 5, 445–467. doi: 10.1515/jbca-2014-9004

Lieberknecht, K., and Mueller, E. J. (2023). Planning for equitable climate relocation: gaps in knowledge and a proposal for future directions. *J. Plan. Lit.* 38, 229–244. doi: 10.1177/08854122221147696

Mach, K. J., and Siders, A. R. (2021). Reframing strategic, managed retreat for transformative climate adaptation. *Science* 372, 1294–1299. doi: 10.1126/science.abh1894

Manero, A., Taylor, K., Nikolakis, W., Adamowicz, W., Marshall, V., Spencer-Cotton, A., et al. (2022). A systematic literature review of non-market valuation of indigenous peoples' values: current knowledge, best-practice and framing questions for future research. *Ecosyst. Serv.* 54:101417. doi: 10.1016/j.ecoser.2022.101417

Marino, E. (2018). Adaptation privilege and voluntary buyouts: perspectives on ethnocentrism in sea level rise relocation and retreat policies in the US. *Glob. Environ. Chang.* 49, 10–13. doi: 10.1016/j.gloenvcha.2018.01.002

Markanday, A., Galarraga, I., and Markandya, A. (2019). A critical review of cost-benefit analysis for climate change adaptation in cities. *Clim. Chang Econ.* 10:1950014. doi: 10.1142/S2010007819500143

McConnell, K., and Koslov, L. (2024). Critically assessing the idea of wildfire managed retreat. *Environ. Res. Lett.* 19:041005. doi: 10.1088/1748-9326/ad31d9

McGhee, D. J., Binder, S. B., and Albright, E. A. (2020). First, do no harm: evaluating the vulnerability reduction of post-disaster home buyout programs. *Nat. Hazards Rev.* 21:05019002. doi: 10.1061/(asce)nh.1527-6996.0000337

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A. (2010). Review article "assessment of economic flood damage.". *Nat. Hazards Earth Syst. Sci.* 10, 1697–1724. doi: 10.5194/nhess-10-1697-2010

Meyer, V., Priest, S., and Kuhlicke, C. (2012). Economic evaluation of structural and non-structural flood risk management measures: examples from the Mulde River. *Nat. Hazards* 62, 301–324. doi: 10.1007/s11069-011-9997-z

Middlesex University Flood Hazard Research Centre (2014). Support tool no. 2: Multi-criteria analysis (MCA) guidelines of flood risk management (FRM). London: Middlesex University Flood Hazard Research Centre.

Moore, F. C. (2012). Costing adaptation: revealing tensions in the normative basis of adaptation policy in adaptation cost estimates. *Sci. Technol. Hum. Values* 37, 171–198. doi: 10.1177/0162243911402364

Muir, R., Papa, F., Inc, F. H., Markham, C., Limited, D. C., Limited, R. V. A. A., et al. (2021). Guidelines on undertaking a comprehensive analysis of benefits, costs and uncertainties of storm drainage and flood control infrastructure in a changing climate. Ottawa, ON: National Research Council of Canada Construction.

Nelson, K. S., and Camp, J. (2020). Quantifying the benefits of home buyouts for mitigating flood damages. *Anthropocene* 31:100246. doi: 10.1016/j.ancene.2020.100246

Nguyen, C. N. (2020). Homeowners' choice when the government proposes a managed retreat. *Int. J. Disaster Risk Reduc.* 47:101543. doi: 10.1016/j.ijdrr.2020.101543

O'Donnell, T. (2022). Managed retreat and planned retreat: a systematic literature review. *Philos. Trans. Soc. B Biol. Sci.* 377:20210129. doi: 10.1098/rstb.2021.0129

Olufson, S. E. (2019). Managed retreat components and costing in a coastal setting. Wellington: Victoria University of Wellington.

Oppenheimer, M., and Glavovic, B. C. (2022). "Sea level rise and implications for low-Lying Islands, coasts and communities" in The ocean and cryosphere in a changing climate: Special report of the intergovernmental panel on climate change. eds. H. O. Pörtner, D. C. Roberts and V. Masson-Delmotte (Cambridge: Cambridge University Press), 321–446.

Pinter, N. (2021). The lost history of managed retreat and community relocation in the United States. *Elementa* 9:36. doi: 10.1525/elementa.2021.00036

Ramm, T. D., Watson, C. S., and White, C. J. (2018). Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environ. Sci. Pol.* 87, 92–101. doi: 10.1016/j.envsci.2018.06.001

Revell, D., King, P., Giliam, J., Calil, J., Jenkins, S., Helmer, C., et al. (2021). A holistic framework for evaluating adaptation approaches to coastal hazards and sea level rise: a case study from imperial beach, California. *Water* 13:1324. doi: 10.3390/w13091324

Robertson, A. M., and Shaw, S. C. (1999). "A multiple accounts analysis for tailings site selection," in *Mining and the environment II*, 883–891.

Robertson, A., and Shaw, S. S. (2006). Use of the multiple-accounts-analysis process for sustainability optimization. *Min. Eng.* 58, 33–38.

Saunders-Hastings, P., Bernard, M., and Doberstein, B. (2020). Planned retreat approaches to support resilience to climate change in Canada. Ottawa, ON: Natural Resources Canada.

Sayers, P., Galloway, G., Penning-Rowsell, E., Yuanyuan, L., Fuxin, S., Yiwei, C., et al. (2015). Strategic flood management: ten 'golden rules' to guide a sound approach. *Int. J. River Basin Manag.* 13, 137–151. doi: 10.1080/15715124.2014.902378

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynki, C., Di Luca, A., et al. (2023). "Weather and climate extreme events in a changing climate," in *Climate Change 2021 – The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press), 1513–1766.

Shi, L., Fisher, A., Brenner, R. M., Greiner-Safi, A., Shepard, C., and Vanucchi, J. (2022). Equitable buyouts? Learning from state, county, and local floodplain management programs. *Clim. Chang.* 174:29. doi: 10.1007/s10584-022-03453-5

Siders, A. R. (2019a). Managed retreat in the United States. *One Earth* 1, 216–225. doi: 10.1016/j.oneear.2019.09.008

Siders, A. R. (2019b). Social justice implications of US managed retreat buyout programs. *Clim. Chang.* 152, 239–257. doi: 10.1007/s10584-018-2272-5

Siders, A. R., Ajibade, I., and Casagrande, D. (2021). Transformative potential of managed retreat as climate adaptation. *Curr. Opin. Environ. Sustain.* 50, 272–280. doi: 10.1016/j.cosust.2021.06.007

Siders, A. R., Hino, M., and Mach, K. J. (2019). The case for strategic and managed climate retreat. *Science* 1979, 761–763. doi: 10.1126/science

Siders, A. R., and Keenan, J. M. (2020). Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean Coast. Manag.* 183:105023. doi: 10.1016/j.ocecoaman.2019.105023

Siders, A. R., and Pierce, A. L. (2021). Deciding how to make climate change adaptation decisions. *Curr. Opin. Environ. Sustain.* 52, 1–8. doi: 10.1016/j.cosust.2021.03.017

Skidmore, T. A., and Cohon, J. L. (2022). A multicriteria decision analysis framework for developing and evaluating coastal retreat policy. *Integr. Environ. Assess. Manag.* 19, 83–98. doi: 10.1002/ieam.4662

Stroombergen, A., and Lawrence, J. (2022). A novel illustration of real options analysis to address the problem of probabilities under deep uncertainty and changing climate risk. *Clim. Risk Manag.* 38:100458. doi: 10.1016/j.crm.2022.100458

Taylor Aiken, G., and Mabon, L. (2024). Where next for managed retreat: bringing in history, community and under-researched places. *Area* 56:12890. doi: 10.1111/area.12890

Thistlethwaite, J., Henstra, D., and Ziolecki, A. (2020). Managed retreat from high-risk flood areas: Design considerations for effective property buyout programs. Waterloo, Canada: Centre for International Governance Innovation.

Thistlethwaite, J., Le Geyt, M., Martin, G., Cottar, S., and Whittaker, L. (2023). Buying out the floodplain: Recommendations for strategic relocation programs in Canada. Waterloo, Canada: Partners for Action.

Tubridy, F., Lennon, M., and Scott, M. (2022). Managed retreat and coastal climate change adaptation: the environmental justice implications and value of a coproduction approach. *Land Use Policy* 114:105960. doi: 10.1016/j.landusepol.2021.105960

Turner, R. K., Burgess, D., Hadley, D., Coombes, E., and Jackson, N. (2007). A cost-benefit appraisal of coastal managed realignment policy. *Glob. Environ. Chang.* 17, 397–407. doi: 10.1016/j.gloenvcha.2007.05.006

US Office of Management and Budget (2023). Circular A-4. Available at: https://www.whitehouse.gov/wp-content/uploads/2023/11/CircularA-4Explanation.pdf (Accessed December 27, 2024).

van Alphen, J., Haasnoot, M., and Diermanse, F. (2022). Uncertain Accelerated Sea-level rise, potential consequences, and adaptive strategies in the Netherlands. *Water* 14:1527. doi: 10.3390/w14101527

Venn, T. J., and Quiggin, J. (2007). Accommodating indigenous cultural heritage values in resource assessment: Cape York peninsula and the Murray-Darling basin, Australia. *Ecol. Econ.* 61, 334–344. doi: 10.1016/j.ecolecon.2006.03.003

Watkiss, P., Hunt, A., Blyth, W., and Dyszynski, J. (2015). The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability. *Clim. Chang.* 132, 401–416. doi: 10.1007/s10584-014-1250-9

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., et al. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ. Chang.* 28, 325–336. doi: 10.1016/j.gloenvcha.2013.12.002

Woodward, M., Kapelan, Z., and Gouldby, B. (2014). Adaptive flood risk management under climate change uncertainty using real options and optimization. *Risk Anal.* 34, 75–92. doi: 10.1111/risa.12088

Zeng, P., Fang, W., Zhang, H., and Liang, Z. (2023). Cost-benefit analysis of the Wuxikou integrated flood management project considering the effects of flood risk reduction and resettlement. *Int. J. Disaster Risk Sci.* 14, 795–812. doi: 10.1007/s13753-023-00520-y

Zhu, F., Zhong, P. A., Sun, Y., and Yeh, W. W. G. (2017). Real-time optimal flood control decision making and risk propagation under multiple uncertainties. *Water Resour. Res.* 53, 10635–10654. doi: 10.1002/2017WR021480