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Decisions, options, and actions in the face of uncertainty: a systematic bibliometric and thematic review of climate adaptation pathways

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Abstract

Climate change is already having adverse impacts, with place- and problem-based implications due to higher temperatures, prolonged droughts, and more frequent extremes. Despite uncertainty about the full extent of future change, adaptation will be required. Adaptation pathways (APs) planning is increasingly used as a methodological approach to identify, evaluate, and sequence adaptation options over time. Pathways link critical decisions to future conditions, providing a road map to support planning in the face of uncertainty. This systematic review identifies and assesses the rapidly growing APs literature, focusing on its definition, and application in diverse contexts. Using bibliometric and thematic analysis, we highlight scholarly networks driving innovation in this area, characterise theoretical and conceptual differences in framing, and derive insights for best practice. Results show the evolution in interpretation, framing and practice; from an initial focus on managing uncertainty with technological- and engineered-based approaches, through to more participatory, policy- and decision-relevant pathways. Pathways planning has become increasingly collaborative, and is now used to address climate adaptation outcomes, within the broader context of interacting and compounding stressors. Results also highlight challenges in conceptualising and operationalizing APs, including comprehensive accounting for costs, and navigating social dynamics involved in process development. Based on these findings we propose new avenues for research, to develop methodologies to better engage with stakeholders' social, political, and economic concerns, and enhance learning for climate adapted futures.

1. Introduction

Climate change is inevitable (Keys *et al* 2019). Changing patterns in annual and seasonal rainfall, and increasing likelihood of sudden heatwaves, droughts, storms, and floods, are well documented, the current impacts are widely felt, and future projections point towards widening climate variability, extremes, and slowly emerging impacts (IPCC 2022). While certain effects are able to estimated, large-scale models of an interconnected climate-human-ecological system are only able to provide finite insights into a wide range of plausible futures (Burke *et al* 2014, Harrison *et al* 2016, Kebede *et al* 2018). This implies a need for flexibility in planning for climate change (Folke 2006, Werners *et al* 2021), and building capability and capacity for making

decisions despite uncertainty regarding future conditions.

Within this context, decision making under conditions of deep uncertainty (DMDU) has emerged as a rapidly growing field of research and practice (Marchau *et al* 2019). Deep uncertainty is characterised by situations in which decision makers and stakeholders are faced with an array of plausible future conditions, for which there may be limited information, or high levels of disagreement regarding the consequences or likelihood of different impacts. Here, decision makers aim to develop confidence in a particular decision, rather than focus on the outputs of a particular model or single scenario. Decision making begins with a proposed strategy and tests that strategy to understand how it might perform under different futures; and determine what actions do we need to take now? And which can be postponed to the future?

To assist with decision making, an array of tools and methods have been developed in recent years, from robust decision making, to portfolio analysis, scenario discovery, real options, and adaptation pathways (APs) (Abson *et al* 2013, Kwakkel *et al* 2016, Groves *et al* 2019, Marchau *et al* 2019). Since its introduction in the DMDU literature a decade ago (Haasnoot *et al* 2013), APs has become a popular planning approach in the face of uncertainty regarding the extent, timing and severity of future change (Campos *et al* 2016, Lawrence and Haasnoot 2017, Jacobs *et al* 2019, Ng'ang'a and Crane 2020, Werners *et al* 2021). Pathways planning is broadly understood as process of specifying which adaptation measure(s) are to be taken now and which will be implemented progressively, depending on how the dynamics of climate and other conditions unfold (Kwakkel *et al* 2016). It is a methodological approach to identify, evaluate, and sequence adaptation options over time. Pathways link critical decisions to future conditions, providing a road map to support planning in the face of uncertainty. Instead of being limited to a single adaptation strategy, APs provide a means to consider a range of possible adaptation options, how they will be affected over time, and whether any options have a point at which they are no longer viable. The most suitable combination of options—or pathways—can then be selected. As such, APs explicitly consider uncertainty and embed flexibility within a planning process. Other potential benefits are the ability to identify 'no or low regrets' interventions and to avoid lock-in, threshold effects, and maladaptive consequences (Reeder and Ranger 2011).

Pathways planning was initially focused on technological- and engineered-based applications, for flood control and sea-level rise (Haasnoot *et al* 2013, Ranger *et al* 2013). More recently however, applications of APs have become increasingly conceptually and methodologically diverse, encompassing a wider range of place- and problem-based contexts. The rapid growth in the application of APs, however, has led to a proliferating and potentially confusing terminology (e.g. Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot *et al* 2013), Dynamic Adaptive Pathways Planning (DAPP) (Lawrence *et al* 2019)). Similarly, as the scope of empirical applications of APs has widened from a narrow use of quantitative analysis, to become increasingly diverse, utilising mixed-methods, and involving stakeholder participation, there is a need to better understand the current state of the science and contribute to discussion about mainstreaming pathways in practice.

With this growing number of applied examples, and diverse conceptual, and methodological understandings of APs, there is a need for systematic bibliometric and thematic analysis, reviewing and summarising contemporary pathways literature. Here, we seek to contribute to the literature by focusing on the ways in which APs have been developed for, and applied to, places or problems, building on previous reviews (Bosomworth and Gaillard 2019, Werners *et al* 2021). Following recent studies (Dorr *et al* 2021, Ricart *et al* 2022, Dourado *et al* 2023), two types of analysis were combined: bibliometrics and exploratory content analysis. Bibliometrics is an analytical and mapping method to quantitatively assess the linkages and impact of scientific publications for tracking progress and tracing knowledge of a research field, to identify the temporal trends and regional disparities (Chakraborty *et al* 2021). Exploratory content analysis provides a concept driven approach that allows us to take stock of the field, the strength of evidence for frameworks, and identify avenues for future research (Clark *et al* 2021). Their combination ensures the structural and methodical nature of a systematic review (Badi and Murtagh 2019) and accomplishes the four-step method suggested by Koberg and Longoni (2019), in which material selection, descriptive analysis, category identification, and material evaluation must be achieved. Common to both tools is their ability to simplify the dynamic and complex linkages between different articles and their associated information and to entail visualisation of their knowledge structure using data reduction techniques. The review considers only empirical examples, demonstrating the utility of pathways planning as a concept, tool, or framework. The aim is to document and analyse the genesis and evolution of APs through scholarly and research networks and draw lessons from its application thereby providing ideas and perspectives to guide theoretical and practical advances necessary to realise the full potential of pathways in practice.

The paper is structured as follows: section 2 describes the methodology used for systematically identifying, collecting, and analysing the literature

used in this review. Sections 3 and 4 present the results of the bibliometric and thematic analysis, respectively, including research frontiers and hotspots, and the range and types of APs in practice. Section 5 discusses lessons arising from the development and application of APs, and challenges still needing to be addressed. In section 6, the key findings of the paper are summarised, and future research priorities proposed.

2. Methods

Systematic literature reviews (SLRs) use explicit inclusion and exclusion criteria, to collect and assess the literature relevant to a particular topic over a given time (Petticrew and Roberts 2006, Ford *et al* 2011, Booth *et al* 2012, Dixon-Woods *et al* 2016). Such reviews are increasingly common in the social sciences, providing researchers with a method to identify themes and trends (Bilotta *et al* 2014a, 2014b, Adams *et al* 2016) and gain insight into specific problem- or question-framings (Adade Williams *et al* 2020, Reu Junqueira *et al* 2021, Rodrigo-Comino *et al* 2021, Kirk and Cradock-Henry 2022). In climate change research, SLRs have been used to synthesise studies of impacts and implications, and document conceptual and methodological developments (Ford *et al* 2011, Berrang-Ford *et al* 2015, Biesbroek *et al* 2018, Cradock–Henry *et al* 2019). Recent reviews include perceptions of climate change (Ricart *et al* 2022) and climate services (Boon *et al* 2022), serious games for climate adaptation (Flood *et al* 2018), and place- and problem-specific assessments of climate impacts and adaptation actions (Pearce *et al* 2018, Kelman *et al* 2021, Carr *et al* 2022).

2.1. Data collection

We developed the present research investigating how APs have been applied in different settings, using the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) (Liberati *et al* 2009) protocol, including fully documented inclusion criteria in an attempt to eliminate bias and ensure comprehensiveness (Petticrew and Roberts 2006, Petticrew and McCartney 2011, Waddington *et al* 2012). The review is based on systematic searches in two of the most popular multidisciplinary databases: Web of Science™ Core Collection database and the Scopus database from 1 January 2012 to 31 May 2021 (Waltman 2016). The lead author devised a review protocol, with eligibility criteria agreed on by co-authors (table 1). The review was limited to the published, peer-reviewed literature. We acknowledge there are case study examples from the grey literature (e.g. Siebentritt *et al* 2014). However, absent consistent methodological descriptions to enable evaluation of quality, study-specific quality appraisal techniques, and due to limited resources for the review, grey literature was excluded (Adams *et al* 2017).

Two searches were conducted for each database. Search chain 1 = 'adapt* pathway*' AND 'climate', yielded 223 results in WoS and 182 results in Scopus. Search chain 2 = 'adapt* policy pathway*' AND 'climate' yielded 45 and 19 results in WoS and Scopus respectively. Results were combined, and duplicates deleted. Information—including the citation title, abstract, and bibliographic details—for 246 articles were stored in MS Excel spreadsheet, and then repeated for the Scopus searches, leaving a total of 188 results. These results were combined, and duplicates removed. Titles and abstracts of the resulting 257 articles were screened independently by two of the authors. Any citations which did not include the actual application of APs planning (i.e. review articles or commentaries), did not outline a clear AP methodology (i.e. describing the entire process), or lacked enough detail to guide others, were excluded. The final collection included 49 relevant studies for full text screening.

2.2. Data analysis

To analyse the collection, we used 'realist review' methods. Realist reviews are characterised by an explanatory focus (Wong *et al* 2014, Hunter *et al* 2022), allow for both quantitative and qualitative methods to be used (Berrang-Ford *et al* 2015), and are better suited to complex and/or interdisciplinary research (Hunter *et al* 2022). A realist review attempts to understand 'what works where' and develop a fuller understanding of activities or interventions, and outcomes (Hunter *et al* 2022). For the bibliometric analysis, two main tasks have been considered, after Wu *et al* (2021): (1) basic data including descriptive statistics of the sample in terms of annual production, main authors and co-authorships, citations, and most relevant sources, and (2) research hotspot analysis, focusing on trends in keywords and central themes. Performance analysis was conducted to assess the temporal distribution of the most cited publications and their impact in terms of citations, while science mapping was employed to visually depict statistically significant links between publications and content-related conclusions (Rosato *et al* 2021). The WoS–Scopus Bibtex file dataset was analysed in RStudio (R version 4.0) (R Core Team 2022) using the Bibliometrix R package (version 4.1.1) and its web application counterpart called Biblioshiny (Aria and Cuccurullo 2017). Bibliometrix calculates frequency statistics and performs data visualisation of leading authors, conceptual and intellectual maps, collaboration and co-citation networks, and overall trends of APs research framework. Furthermore, VOSviewer (Aria and Cuccurullo 2017) was used to create, visualise, and explore maps based on network data (van Eck and Waltman 2010, 2020 Li and Yan 2018). These tools are readily available, and as a result, increasingly used for systematic and quantitative research to characterise fields of research, and the

Table 1. Inclusion and exclusion criteria used in literature search and document selection.

Inclusion criteria	Exclusion criteria
Empirical application of adaptation pathways or adaptation pathways planning	Does not include case study or empirical application of adaptation pathways or adaptation pathways planning
Broadly undertake the various steps involved in typical adaptation pathways planning processes[6]	Does not undertake steps involved in typical adaptation pathways process
Provides clear instructions on process for developing pathways; able to be replicated	Does not provide sufficiently clear instructions for developing pathways; vague or unclear; not able to be replicated
Type of study: peer-reviewed article	Type of study: NOT peer-reviewed article
English language publication	Non-English language publication
Indexed on either Web of Science (WoS) or Scopus	NOT indexed on either WoS or Scopus
Date range: Published between January 2012 and May 2021	Date range: prior to 2012, or after June 2021

evolution of topics within a domain (Wang *et al* 2018, Hu and Xu 2022, Suhaimi and Mahmud 2022).

In the analysis, a broad interpretation of the term 'keywords' was used, also known as 'keywords+', which encompasses not only the keywords of the selected articles, but also the keywords of the documents that these articles cite. Keywords+ can express article contents more succinctly (Tripathi *et al* 2018). They were automatically generated by a computer algorithm. Burst detection and co-citation clustering analysis were also used to identify APs research hotspots and research frontiers. A clustering algorithm on the keyword+ co-occurrence network analysis elaborated the conceptual structure of the APs collection and helped define key science foci and trends. Bibliometric methods such as these can help readers identify the main research domain variables in a short time, and thus contribute towards integrating these elements in the literature (Secinaro *et al* 2020, Wu *et al* 2021).

For complementary thematic analysis, full text PDF copies of articles were imported into NVivo 12. Manual coding focused on definitions of APs; lessons, insights, or experiences; and challenges of applying pathways. Results of thematic analysis were triangulated between all authors, relying on 'negotiated agreement' to establish intercoder agreement (Campbell *et al* 2013). Accordingly, any disagreements between the authors regarding codes was discussed and resolved. To minimise bias, various measures included investigator triangulation to determine the final selection of articles. This involved reviewers independently reading titles and abstracts of the preliminary final collection and comparing results. Two rounds of review were undertaken. As a result, we are confident we have captured a large portion of available peer-reviewed literature that documents empirical examples of APs. Due to the parameters of the search engine and criteria, however, some relevant literature may have been excluded from this review (e.g. articles for which full text was not available).

[6] Adaptation pathways approaches generally follow a similar process, comprised of five- to upwards of ten steps, based on a version of an adaptive management cycle, beginning with defining objectives and outcomes (Cradock-Henry *et al* 2018, 2020, 2021, Bosomworth and Gaillard 2019), through to monitoring and evaluation. Other authors use a more detailed but comparable process (Haasnoot *et al* 2013, Lawrence and Haasnoot 2017, Bloemen *et al* 2018) which was consistent with our approach, and so these articles were included.

3. Bibliometric results and exploratory findings

APs planning is a relatively new approach but has grown rapidly from a small, closely connected cohort of researchers/institutions, focused on flood control, and coastal processes, to encompass a wide range of place- and problem-based analyses. We begin with a discussion of the bibliometric analysis, and the institutional and disciplinary landscape as the starting point for the exploratory analysis.

3.1. Basic data

In 2013, the first article on APs was published, with numbers rising from 2017 onwards as the approach was adopted and results published. Although the annual production index (figure 1(a)) is inconstant: 2018 accounts for almost one-quarter of the total production of articles, while two-thirds (66%) have been published in the last four years, confirming the growing interest in, and the relevance of, pathways planning approaches and applications. This timeline aligns with APs rising on the global agenda with key global agreements reached in 2015 such as the Sendai Framework for Disaster Risk Reduction, reiterating the commitment to building disaster resilience, the launch of the Sustainable Development Goals (SDG) including SDG 13 Climate action and 13.1 'Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries', and the Paris Agreement defining a global goal on 'enhancing adaptive capacity and resilience'.

The 49 articles in our collection include 210 authors from 15 countries. There are no single-authored articles. A co-authors ratio per document

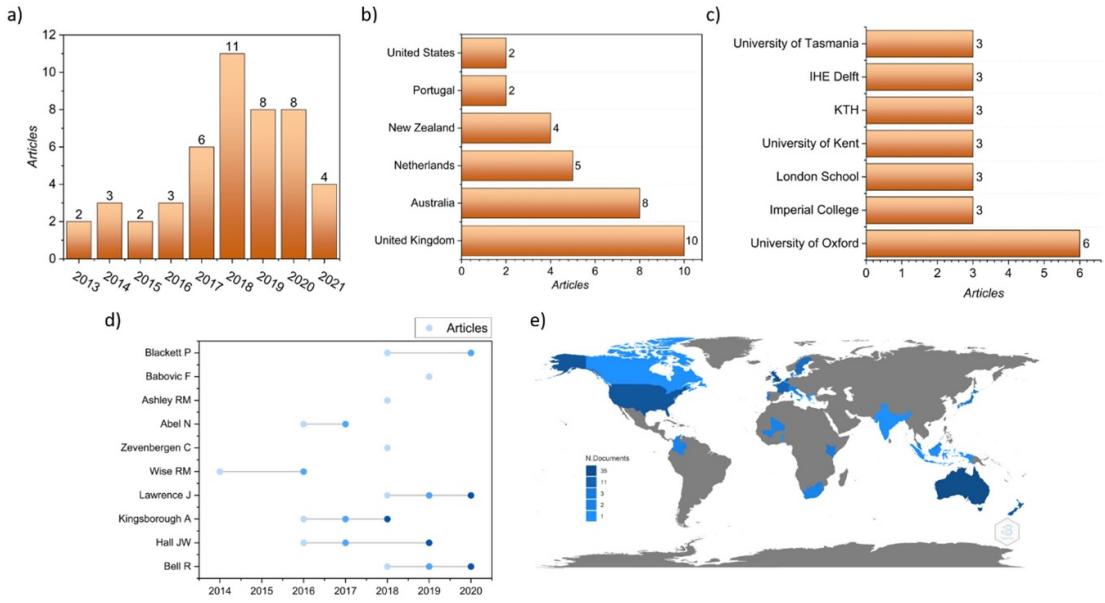

Figure 1. Authors' output by (a) annual production, (b) most relevant country, (c) main affiliation, (d) top10 authors by distribution over time, and (e) production by country.

of 5.2 and a collaboration index of 4.5 reflect trends in the broader literature towards multi-authored articles, and inter- and transdisciplinary collaborations with a larger group of incidental or early-career contributors (Haghani *et al* 2022). The author productivity calculated through Lotka's Law shows 182 authors (86.7%) have contributed to a single article, while six authors have written three articles: Robert Bell (National Institute of Water and Atmospheric Research, NZ), Jim W. Hall and Ashley Kingsborough (University of Oxford, UK), Judy Lawrence (Victoria University of Wellington, NZ), Russell M. Wise (CSIRO Land and Water, AUS) and Chris Zevenbergen (IHE Delft Institute for Water and Education, NL). Although authors' output by annual production is led by 2018, the majority of the top10 most relevant authors concentrated their activity between 2016 and 2020 (figure 1(d)). Likewise, of 20 institutions, the University of Oxford leads the authors' affiliations ranking, followed by other three UK institutions (Imperial College London, London School of Economics and Political Science, and the University of Kent), and two in the Netherlands: KTH Royal Institute of Technology, and the IHE Delft Institute for Water and Education (figure 1(c)). The diffused blue colour in figure 1(e) demonstrates a remarkable development in the topic in different countries (France, Sweden, Japan, Kenya, South Africa, Colombia) beyond those of the corresponding authors (figure 1(b)). However, the figure also shows that many areas have still not engaged with pathways approaches. Each country developing pathways seems to pursue individual objectives, in some cases even developing 'bespoke' pathways approaches (e.g. Lawrence *et al* 2018) as per national interests and priorities. The underlying rationale and motivations behind this should be further explored to better coordinate APs' development, especially the Global South, where insufficient resources, inadequate management of climate risks, and lack of focus on APs have been identified as barriers in the literature (Sen Roy 2018).

Co-authorship is one of the most visible forms of collaboration and a hallmark of contemporary research (Carchiolo *et al* 2022). Co-authorship network analysis considers authors' articles published and citations received. Figure 2(a) shows authors' collaboration organised in seven clusters, most of them built after 2017. The two most important clusters are those led by Chris Zevenbergen (e.g. Zevenbergen *et al* 2015) and Jim W. Hall (e.g. Hall *et al* 2019), and Nick Abel (e.g. Abel *et al* 2016). The whole collection was cited 2154 times and five articles have received, at least, hundred citations at a rate of ten citations per year. Likewise, the top3 most cited authors (figure 2(b)) are Marjolijn Haasnoot (Haasnoot *et al* 2013, 643 citations, 71.4 citations/year), Russell Wise *et al* (2014, 507 citations, 63.4 citations/year), and Nicola Ranger (Ranger *et al* 2013, 148 citations, 16.4 citations/year).

The collection covers 30 journals, three of which (*Environmental Science & Policy, Climate Risk Management*, and *Global Environmental Change*) account for over one-third of the articles. These journals are indexed in the Environmental Sciences category in Clarivate Analytics 2021 and cover topics ranging from sustainable development to natural resources management and climate change adaptation with an emphasis on pathways oriented towards policy action. According to Bradford's law

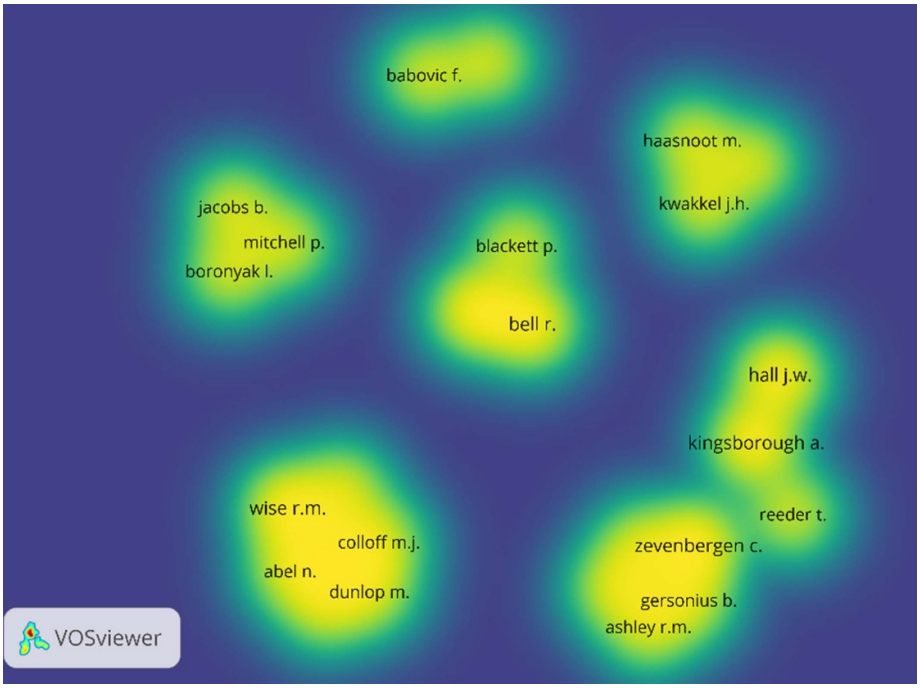

Figure 2. Network analysis of co-authorship according to authors' documents (articles) for the whole period 2013–2021[7].

for distribution frequency, seven journals are considered core sources (zone 1) (figure 3(a)). In 2018, seven journals published at least one pathways article, and source dynamics showed significant growth in the number of publications in subsequent years. Regarding the citation's records, local citations (citations received from the set) and global citations (citations received outside the set) follow a similar trajectory, for which works published in 2013 and 2014 are the collection' most cited ones (figure 3(b)). Interestingly, the top five articles (table 2) were published in this period and accounted for 86% of total citations. These articles are foundational articles in the field, which have provided inspiration for later research, and a solid basis for further exploration and maturation.

3.2. Hotspot analysis

Content analysis techniques map the strength of association between information items in textual data, dealing directly with sets of terms shared by documents (Cobo *et al* 2011). The analysis identified 648 unique keywords (keywords+), of which 246 were listed by the articles themselves. Although 'climate change' ranked first, its use can be directly focused on 'adaptation' (Burnham and Ma 2018), or fixed on 'risk', especially to flood risk (e.g. Radhakrishnan *et al* 2018). Similar results were obtained at the title and abstract level, although some new keywords appeared, such as 'participatory approach' (Babovic and Mijic 2019a) and 'strategies' (Petr *et al* 2015). Furthermore, as shown in figure 4(a), keywords use has changed over time. Researchers initially tried to relate 'climate change' and 'adaptation management' with 'decision making' processes (e.g. Tanaka *et al* 2015) but have been progressively incorporating 'risk assessment' and 'flood control' to address 'uncertainty' issues (e.g. Babovic and Mijic 2019b) (figure 4(b)). Although at keywords+ level the term 'pathways' is not mentioned, the keyword dynamics at abstract level highlighted 'adaptation pathways' as the second most used keyword (Carstens *et al* 2019, Cradock-Henry *et al* 2020). The corresponding increase in the share of publications using 'adaptive management' and 'decision-making' definition indicates that the shift to more complex resilience pathways is part of an evolution that has happened after the concept of APs has first emerged in the literature in 2013.

Co-occurrence of terms represents cases in which two keywords occur simultaneously in multiple manuscripts. Analysis of the co-occurrence of terms can reflect the frontiers and hotspots during different research periods, revealing changes in the popularity of certain research topics (Radhakrishnan *et al* 2017). Co-occurrence analysis from keywords+ structure was also applied to identify major thematic clusters. Figure 5 identifies four main thematic clusters from 49 keywords+, highlighting three items directly associated with 'pathways' patterns: 'adaptation pathways', 'dynamic adaptive policy pathways', and 'transformation pathway'. Clusters focus on risk management and planning, especially for flooding (red

[7] Full counting method applied; min. number of authors and documents (articles) = 2.

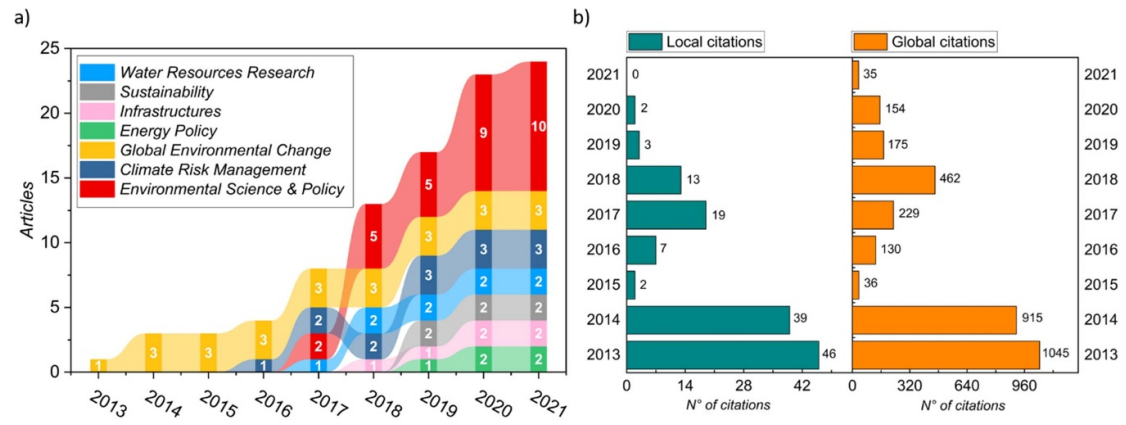

Figure 3. (a) Annual production of most relevant sources and (b) local/global citations per year[8].

Table 2. Top10 most cited documents considering local/global citations[9].

Article	Journal	Local citations	Global citations
Haasnoot *et al* (2013)	Global Environmental Change	34	875
Wise *et al* (2014)	Global Environmental Change	19	617
Barnett *et al* (2014)	Nature Climate Change	13	143
Ranger *et al* (2013)	EURO Journal on Decision Processes	12	170
Rosenzweig and Solecki (2014)	Global Environmental Change	7	155
Bloemen *et al* (2018)	Mitigation and Adaptation Strategies for Global Change	5	64
Bosomworth *et al* (2017)	Environmental Science & Policy	5	60
Hermans *et al* (2017)	Environmental Science & Policy	5	47
Kingsborough *et al* (2017)	Climate Risk Management	5	30
Ramm *et al* (2018)	Environmental Science & Policy	4	40

cluster), climate change adaptation and the human-environment nexus (green cluster), decision-making and water management (blue cluster), and APs and resilience (yellow cluster). The red cluster has the largest number of terms ($n = 16$), some of which (e.g. 'adaptive management', 'risk assessment', 'risk management') are strongly linked to 'flooding' or 'planning process'. The red cluster is largely focused on two issues. The first issue relates to strategies for managing climate change risk and uncertainty for public conservation areas and flood risk management. For instance, managers of protected areas have begun to recognise the inevitability of ecosystem change and the need to embrace dynamic approaches to intervention, but the onset and severity of some impacts remain uncertain (Jacobs *et al* 2019), therefore requiring the use of participatory planning processes to capture contested stakeholder priorities (Ramm *et al* 2018). The second identifies the importance of sensitivity in scenario discovery for flood risk management, such as multi-layered frameworks considering cost-effective and robustness (Hall *et al* 2019) or resilience indicators built from informant interviews or participatory workshops (Roy *et al* 2021).

The green cluster captures literature on the human-environment interactions, with two major themes: climate change vulnerability, and flood risk planning and governance. Here, linkages between vulnerability and other factors are elaborated, including loss of biodiversity (Thornton *et al* 2019), sea-level rise (Aerts *et al* 2018) and infrastructure (Kool *et al* 2020). Mixed evidence was found among red and green clusters report on the biophysical impacts of climate change and adaptative capacity, and the effects of natural risks on planning strategies, as well as the need for improving anticipatory governance and adaptation strategies (Lawrence *et al* 2018). Building capability and capacity for anticipatory adaptation in relation to water management and governance can inform decision-making processes (Skrimizea and Parra 2020), the focus of the blue cluster. The blue cluster includes 'stakeholder engagement', 'government', and 'effective response', indicating the importance of planning and policies in minimising vulnerabilities and improving response and adaptation capacities. Here studies focus on providing new

[8] Data for year 2021 includes only the first half of the year.
[9] Global citations have been updated to April 2023.

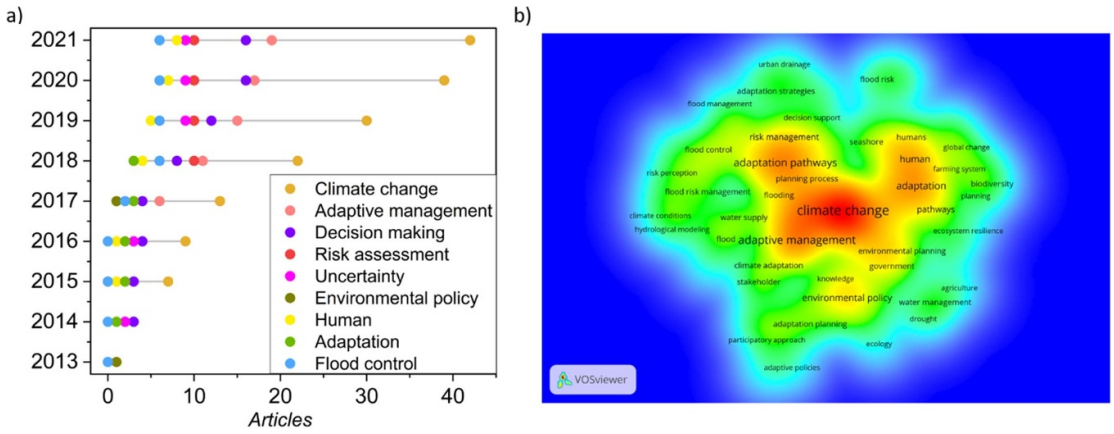

Figure 4. Main keywords combined in abstracts as keywords+ (a) and co-occurrence evolution (b) for the whole period[10].

tools for data-poor contexts to integrate stakeholders' knowledge and values in decision making (e.g. Asset Drivers Well-being Interaction Matrix) (Skewes *et al* 2016), while others focus on new concepts and holistic approaches (e.g. Room for the River) embracing multifunctionality from flood safety in combination with landscape, environmental and cultural values (Zevenbergen *et al* 2015). Finally, the yellow cluster is the only one including the term 'adaptation pathway' (Bloemen *et al* 2018), being connected to the red cluster through climate change adaptation strategies for water and flood management. Here, there is a clear emphasis on strategies for transformation, highlighting the vast body of research on interactions between adaptation and complex socioeconomic and environmental dynamics (Abel *et al* 2016). Presence of the terms 'economic' and 'social effects' could indicate that research on APs may capture and deepen the increasingly differentiated adaptation capacity across the community (Ng'ang'a and Crane 2020).

Thematic analysis results are reinforced by applying Callon's centrality and density indexes. Callon's centrality measures the intensity of links between a given community and other communities (Callon *et al* 1991). This value can be represented as a proxy measure for the importance of a theme in a collection of literature. Callon's density measures the internal strength of a collection and can be represented as a measure of the theme's development (Yu *et al* 2021). Results depict a matrix in which nine clusters can be identified, three of which—'climate change', 'risk assessment' and 'adaptive management'—are evolving together and in conjunction with red and green clusters topics (table 3). The findings demonstrate how topics have evolved, moving from *basic themes* (essential but not yet developed issues) to *motor themes* (well-developed topics used for structuring a research field) and have shaped the structure of the research field during the time span. Results show 'local government' is ranked first in terms of centrality and density, while 'climate change adaptation' is the main *emerging theme* during the specified timeframe. In the last decade, this implies the presence of significant debates within policy and planning regarding the value and implementation of APs, particularly for addressing slow-onset hazards such as 'drought risk'. Conversely, some top10 most used keywords+ at title and abstract level (e.g. 'pathways', 'uncertainty', 'strategies') are only included as clusters' sub-themes (table 3).

Consequently, when viewing trends in the literature and the field's development, there is clear evidence for a gradual shift in the centre of gravity. Pioneering studies focused on vulnerability and resilience agenda-setting, using data collection methods to characterise uncertainty and suggest potential solutions. Once the relevance of the climate change impacts-risk assessment nexus was established (with particular attention on flood risk and control), the focus shifted again to understanding and exploring the extent to which participatory, policy- and decision-relevant APs can be developed and applied in other settings. While the shift in focus is clear, the three waves of research (from top-3 themes) share one important characteristic: in a fundamental sense, they all include a degree of understanding of human behaviour and social research.

3.3. Pathways contexts and methods

APs planning emerged in both the UK and Netherlands at approximately the same time, as part of a wider set of tools and approaches for decision making under conditions of uncertainty (Marchau *et al* 2019). Subsequently, APs have been applied in increasingly diverse settings, in both place- and problem-based studies. Five primary settings for APs were identified from the articles reviewed. These

[10] Legend: Coldwarm plot (b) shows high (red) and low (blue) concurrence. Notes: Min. num. of occurrences was two. Association strength normalization was applied. Max. lines: 1,000. Small clusters have been merged. Data for year 2021 is incomplete.

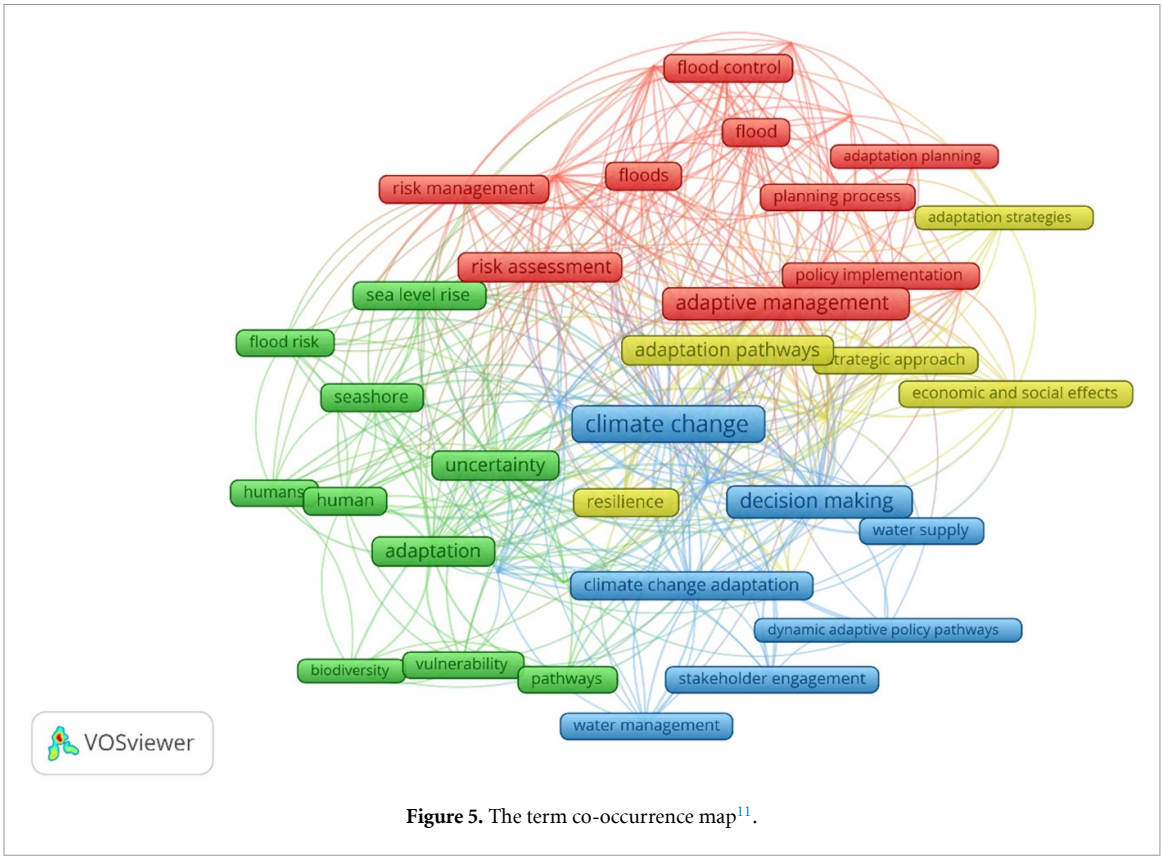

Figure 5. The term co-occurrence map[11].

Table 3. Thematic and co-occurrence clustering topics comparison.

Main themes from the thematic map (top 3 themes)	Main sub-themes from co-occurrence clustering
Climate change	Water resources, sustainable development, urban drainage, economic and social effects
Risk assessment	Flood control, sea level rise, adaptation pathways, economics, infrastructure planning
Adaptative management	Stakeholders, governance, local government, participation, policy implementation

included flood or water management ($n = 16$), sea level rise ($n = 11$), primary industries ($n = 9$), natural resource management ($n = 3$) and energy ($n = 2$) (table 5). Seven articles did not fit into these themes and are listed in the 'Other' section of table 2. One further article, Wise *et al* (2014) was more conceptual in its approach and therefore did not have a specific context but is listed under 'Other' too.

Water issues are complex and require not just technical solutions but an understanding of social–ecological systems, adaptation dynamics, and governance issues (Skrimizea and Parra 2020), and are good fit with pathways approaches. Of the 16 articles focused on floods or water management, half were from Australia ($n = 2$), the United Kingdom ($n = 3$) and the Netherlands ($n = 3$) (table 5). Seven studies report on the application of APs for managing flood risk on the River Thames, London (TE2100 project) (Ranger *et al* 2013, Kingsborough *et al* 2016, Babovic and Mijic 2019a, 2019b) and the Rhine Delta in the Netherlands (Haasnoot *et al* 2013, Zevenbergen *et al* 2015, Hermans *et al* 2017). The articles in this theme either focused on management of water resources under climate change pressures ($n = 9$) or flood risk management systems to reduce vulnerability and increase resilience ($n = 7$). This includes studies of contested rights for land and water use (Abel *et al* 2016, Bhave *et al* 2018), the difficulty of making long-term decisions for drainage systems in the face of uncertainty (Babovic and Mijic 2019b) and approaches for managing flood risk when there is an increased frequency and intensity of rain events (Ranger *et al* 2013, Radhakrishnan *et al* 2018) affecting household livelihoods (Roy *et al* 2021).

Future sea level rise is also a significant concern for many coastal communities, and in particular, pathways planning has been used in Australia and

[11] A co-occurrence relationship is defined between n-units when appearing together in one article. Each cluster is composed of several frequently co-occurring terms. The minimum threshold of $n = 3$ occurrences of a keyword has been fixed. Node size and link thickness are proportional to the term frequency and link strength, respectively, in this figure.

Table 4. A summary of the context or setting for the 49 adaptation pathways articles.

Context (BOLD) or setting	No. of articles	References
Flood or water management	**16**	
Australia	2	Abel *et al* (2016), Radhakrishnan *et al* (2019)
Netherlands	3	Haasnoot *et al* (2013), Hermans *et al* (2017), Zevenbergen *et al* (2015)
United Kingdom (UK)	4	Babovic and Mijic (2019a, 2019b), Kingsborough *et al* (2016), Ranger *et al* (2013)
Bangladesh, Greece, India, Portugal, United States (US), Vietnam	6	Roy *et al* (2021), Skrimizea and Parra (2020), Bhave *et al* (2018), Dias *et al* (2020), Radhakrishnan *et al* (2018), Rosenzweig and Solecki (2014)
UK & Netherlands	1	Bloemen *et al* (2018)
Sea level rise	**11**	
Australia	3	Barnett *et al* (2014), Bosomworth *et al* (2017), Ramm *et al* (2018)
New Zealand (NZ)	3	Lawrence *et al* (2018), (2019), Kool *et al* (2020)
France, Sweden, UK, US, Vietnam	5	Rocle *et al* (2020), Carstens *et al* (2019), Hall *et al* (2019), Aerts *et al* (2018), Scussolini *et al* (2017)
Primary industry adaptation	**9**	
Australia	2	Bardsley *et al* (2018), Prober *et al* (2017)
China, India, Kenya, Mali, multi-national, NZ, Portugal	7	Burnham and Ma (2018), Singh and Chudasama (2021), Nga'ang'a and Crane (2020), Totin *et al* (2021), Tanaka *et al* (2015), Cradock-Henry *et al* (2020), Vizinho *et al* (2021)
Natural resource management	**3**	
Australia, US		Jacobs *et al* (2018, 2019), Murphy *et al* (2017)
Energy sector	**2**	
Colombia, Greece		Arango-Aramburo *et al* (2019), Michas *et al* (2020)
Other	**8**	
Australia, India, Indonesia, UK, multi-national, not applicable*		Mathew *et al* (2016), Thornton *et al* (2019), Skewes *et al* (2016), Kingsborough *et al* (2017), Petr *et al* (2014), Quinn *et al* (2018), Sadr *et al* (2020)*, Wise *et al* (2014)*

Note: *The country for the research was not specified.

New Zealand, to inform decisions on the type and timing of the adaptation to reduce flood risk from future sea level rise (Scussolini *et al* 2017, Lawrence *et al* 2019), often with community input and participation. Six of the eleven articles in this theme are derived from Oceania case studies (table 5). Increasingly, policies and decision-making challenges relating to sea-level rise and coastal hazards are implemented alongside AP approaches, which is able to account for the dynamics associated with uncertainty to address these concerns (Lawrence *et al* 2018, 2019) in both developed (e.g. Gippsland Lakes, Victoria, Australia (Ramm *et al* 2018), Los Angeles County's coastal areas (Aerts *et al* 2018)) and developing country settings (e.g. the Mekong Delta in Vietnam (Scussolini *et al* 2017)).

Primary economic activities including agriculture and horticulture, are similarly well suited for APs. Agricultural producers face a range of climate-related stressors, adaptation decisions make have long-lead times—especially for a change in land use to better suit future climatic conditions—and there are often clear phenological or biophysical thresholds, such as growing degree days, or winter chilling hours, which can be linked to changes in management (Cradock-Henry *et al* 2021). The nine articles in the primary industries theme, span diverse countries and contexts, and one is multi-national in scope (Prober *et al* 2017). Pathways have been applied to viticulture (Bardsley *et al* 2018, Cradock-Henry *et al* 2020), pastoral farming (Ng'ang'a and Crane 2020, Singh and Chudasama 2021), cropping (Burnham and Ma 2018, Totin *et al* 2021) and agro-forestry (Vizinho *et al* 2021) at the scale of farms, regions and sectors; while Tanaka *et al* (2015) develop an AP for the global production of wheat. Research by Prober *et al* (2017) use APs together with the values-rules-knowledge (VRK) framework to in a case study of cropping and livestock production to identify potential constraints to implementation. Using the VRK framework helped balance the trade-offs between agriculture and environmental conservation and connected biophysical knowledge of the ecological system with social changes.

Finally, two Australian articles used APs for biodiversity and cultural heritage in public conservation reserves and National Parks in New South Wales, Australia (Jacobs *et al* 2018, 2019). Murphy *et al* (2017) uses scenarios and participant engagement to respond to future community vulnerabilities and conservation initiatives in the Big Hole valley in the northern Rocky Mountains of Montana. These comprise the 'natural resource management' theme.

Articles which were included in the 'other' contexts ranged from urban wastewater management (Sadr *et al* 2020) and heat risk (Kingsborough *et al* 2017) to native bush food production (Mathew *et al* 2016), transport infrastructure (Quinn *et al* 2018), livelihoods (Skewes *et al* 2016), and the biosecurity of an invasive weed (Thornton *et al* 2019) (table 4).

Results also highlight the range of methods used in pathways planning, including case studies, quantitative, and mixed methods analysis. While

Table 5. Methods used to derive adaptation pathways.

Method	No. of articles
Modelling	**11**
Workshops	10
Mixed qualitative–quantitative methods	8
Mixed qualitative methods	5
Interviews	4
Surveys	2
Economic Analysis	1
N/A (e.g. conceptual articles, hypothetical case studies)	8

pathways planning was originally used for large-scale infrastructure, relying on probabilistic, economic, and engineering models and analysis, qualitative and other approaches are now used more frequently. Emergent methods, such as simulation- or serious games (Huggins *et al* 2015) or analyses of historical materials (King 2015), provide potential avenues for further methodological advancement. Table 5 summarises the different methods used to develop APs across the collection.

Due in part to its origins as a technical, engineering-oriented approach for dealing with large uncertainties, modelling continues to underpin most APs development. The modelling is diverse, however. For example, Kingsborough *et al* (2017) used downscaled probabilistic climate change models to inform long-term adaptation planning for heat risk management, while in Hall *et al* (2019), a suite of models including flood hazard analysis, flood damage assessment, and sensitivity analysis were used to derive different pathways of tidal flood risk in London. Many of the articles using modelling were inspired by Dynamic Adaptive Policy Pathways (DAPP), which links adaptation decisions to policy 'triggers'. One of the earliest examples was the development of the Thames Barrier, discussed in Ranger *et al* (2013) who used numerical models to develop sea-level rise scenarios from which they developed APs for flood-risk. Others have combined modelling with pathways planning to determine the most effective mix of short- and long-term policy actions. Michas *et al* (2020) demonstrate the utility of this approach through a study exploring the adoption of small-scale solar photovoltaics in Greece using a combination of agent based and economic modelling. Elsewhere, Petr *et al* (2015) use a woodland carbon calculator and probabilistic climate change data to develop 'action expiration' dates for forestry management actions using ecosystem services delivery thresholds.

As pathways approaches have become more problem- and place-based, workshops have been incorporated into the methodological toolbox with greater frequency. Workshops enable the public and affected stakeholders to input into the development and assessment of different APs, critical in situations characterised by uncertain knowledge or diverse values. For example, in Bosomworth *et al* (2017), workshops were used to develop APs for natural resource management organisations under climate change, and the authors concluded that negotiation of goals and objectives was important due to high levels of uncertainty. Workshops also enabled people to develop pathways in collaboration with those who might have different perspectives or objectives. In other examples, public participation was affected by the highly technical discussion. Carstens *et al* (2019) note that formulating objectives that were both specific and general was difficult but ultimately argued the method provides 'a means of integrating robust decision support in municipal planning' (p11). Balancing participation within workshops is a challenge however, and not unique to pathways planning. For example, in a case study from rural Mali (Totin *et al* 2021), workshops were dominated by the most influential and educated voices, and hindered by a lack of gender diversity. In Skewes *et al* (2016) the authors highlighted that, due to the technical nature of the workshops, they needed to be held over multiple days, which may limit who can participate. Evidence from the broader literature on collaborative decision making is clear that the composition or inclusiveness of the groups is highly correlated to levels of stakeholder satisfaction with the process. In practice however, there may be a much broader range of criteria of which convenors should be aware when deciding on group composition.

In nine articles, mixed qualitative–quantitative methods were used. Typically, these AP processes would combine some form of quantitative numerical modelling to develop or inform scenarios of long-term futures, or for assessing costs and benefits associated with different options. Modelling results would be used in conjunction with qualitative methods such as workshops, focus groups, and interviews to gain insight into the perceived suitability- and/or limitations of options from the perspective of affected stakeholders and the public. In Cradock-Henry *et al* (2020), workshops and interviews with different primary sector representatives was combined with top-down modelling of climate change projections, as well as biophysical and crop modelling, to develop and assess APs. Similar combinations were also present in Prober *et al* (2017), Radhakrishan *et al* (2019), and Lawrence *et al* (2019). Some of these articles, such as Dias *et al* (2020), also took inspiration in DAPP and combined those stakeholder engagement methods with hydrological modelling.

Other APs processes used a combination of different qualitative techniques. Typically, these combined collective qualitative data collection methods such as focus groups or workshops, alongside one-on-one interviews, or surveys. For example, Aerts *et al* (2018) developed APs through a series of bilateral

expert consultations and seminars with stakeholders, an approach inspired by DAPP and Haasnoot *et al* (2013). Kool *et al* (2020) used new and novel qualitative techniques like serious games in combination with workshops. Others used a combination of semi-structured interviews followed up with focus groups (Ng'ang'a and Crane 2020).

Some articles relied solely on interviews to collect qualitative data. Bardsley *et al* (2018) collected data through walk-and-talk interviews with farmers about business risks and opportunities to adapt agricultural systems to future climate change. Burnham and Ma (2018) used interviews to discuss adaptation options among household farmers in China. Kingsborough *et al* (2016) collected data through semi-structured interviews to identify acceptable levels of risk regarding sea-level rise and flood management in London. Lastly, in Thornton *et al* (2019) the authors used semi-structured interviews to understand the trajectory of biological plant invasions in India in the adoption of a pathways approach to adaptation.

Two articles relied on survey material and one on economic analysis to derive APs. One survey-based article, Radhakrishan *et al* (2018), closely followed a five step pathways process, with surveys revealing that people could cope with flood levels in Can Tho City in Vietnam if they were at manageable levels. Babovic and Mijic (2019a) used economic analysis combined with climate change scenarios to see which options implemented affected the financial performance of different APs.

There were eight articles in the collection we could not classify. These references were either conceptual studies looking at APs or were hypothetical case studies of how to apply APs in different contexts. Some articles, such as Bloemen *et al* (2018), presented lessons and challenges about the use of pathways for flood management.

4. Thematic analysis

Following the bibliometric analysis, thematic analysis was used to code and extract qualitative data from the articles. Themes were defined in advance and include: defining APs, lessons and insights from pathways' application, and challenges for development and implementation.

4.1. Defining pathways

Given the rapid proliferation of APs, there were different definitions of pathways, ranging from reference to a very specific methodological approach, to more generic adaptive management processes to APs as a metaphor for change. Thirty-eight of the articles were grouped into four categories to provide a referenced definition of APs, and/or described how APs were understood (table 6).

Table 6. Categorisation of definitions of adaptation pathways used in the 49 articles.

Category	No. of articles
Dynamic Adaptive Policy Pathways (DAPP)	29
Pathways as a metaphor for transformative change	6
Action(s) to respond to a specific threat	2
Vulnerability and risk assessments	1
Did not provide a definition	11

4.1.1. Dynamic Adaptive Policy Pathways (DAPP)

Twenty-nine of the articles defined APs with reference to the pioneering work of Haasnoot and colleagues on Dynamic Adaptive Policy Pathways in the Netherlands (2013). Traditionally, decision-making has been based on static plans that were considered the 'most suitable' for the 'most likely' future conditions. The DAPP process, however, addresses the vulnerability to changes in conditions by focusing on the design of short-term policies, in conjunction with identifying long-term interventions. Articles included definitions that emphasise the way pathways planning shifts the focus to the process of decision making, rather than pre-determined outcomes. This involves identifying a range of options across multiple plausible futures and using triggers (such as changes in environmental conditions) and tipping points (when something is no longer tolerable) to indicate when decisions will need to be made and transitions started. The options and plausible futures generally require significant investment and expert knowledge to create plausible scenarios and evaluate trade-offs and the impacts of different choices. The pathways and decision process are represented visually to help identify how decisions could play out over time. This is done to identify initial decisions that can be made that will have low regrets and preserve options for the future, thereby avoiding the potential for lock-in and maladaptation. As part of the process, monitoring is required to identify when environmental conditions change and when trigger or tipping points are reached. Because the emphasis is on the process (rather than any specific outcome), decision makers can evaluate changes in social and political issues over time, and in the process build consensus around decisions, linking these to specific policy changes.

4.1.2. Pathways as a metaphor for transformational change

Six of the articles defined APs broadly, as a metaphor or approach to more sustainable decision making that helps foster transformative social and/or systems change. While these definitions included many of the aspects of DAPP above, APs were described

as broader, holistic, and to address system changes beyond single stressors (such as flooding or sea level rise) in local contexts. These definitions suggested APs could be used as iterative planning cycles at scale that integrate social, environmental, technical, and political elements, while also addressing social equity and path dependency. Consequently, there is more of a focus on complex and dynamic multi-scalar ecological systems instead of their individual components.

4.1.3. Action(s) to respond to a specific threat

Two articles defined APs as a series of specific actions that could be sequenced to respond to a specific and single-stressor threat, such as sea level rise or flooding. These definitions focus exclusively on the potential practical or technical actions (such as sea walls or beach nourishment) that can be used to respond to the single threat. The actions are then sequenced to show how pathways can be created between the various options to ensure future flexibility and avoid lock-in/mal-adaptation.

4.1.4. Risk and vulnerability assessment

One article defined APs as part of an approach to undertaking vulnerability and risk assessments in relation to climate change. This approach emphasises the need for vulnerability and risk assessments to evolve over time, as new information and threats/stressors from climate change develop. Part of this approach includes identifying evaluation and adaptation strategies and monitoring the impacts of these and changing socio-environmental conditions.

4.2. Challenges for applying pathways

Climate change is a 'wicked problem' characterised by the long-time scales, divergent values, and uncertainty across multiple domains of coupled human–environment systems (Moser *et al* 2012). The challenge, therefore, is not only DMDU, but in socially and even politically charged settings (Hill *et al* 2020, Cradock-Henry and Frame 2021, Ishtiaque *et al* 2021). This is reflected in the results of the thematic analysis, which identified six key challenges for applying APs: (1) complexity and uncertainty; (2) contested knowledge, equity, and decision-making; (3) assessing options; (4) tipping points and thresholds; (5) timing; and (6) monitoring and evaluation (table 7).

4.2.1. Complexity and uncertainty

As discussed earlier, APs have been applied in diverse contexts, and the main challenge for its application is how best to characterise complexity and uncertainty of both knowledge and information, as well as the social elements of the decision process. In articles on floods and water management, sea level rise, natural resource management, agriculture and forestry, for example, authors highlight the inherent complexity and uncertainty of the problems being considered, the unequal distribution of power in decision making, and conflicts over values. Case studies describe the difficulty in moving from stepwise changes to transformational changes, and the socio-political challenges associated with decisions that may lead to a redistribution of benefits and costs, or be affected by societal changes as is the case with managed retreat in coastal margins for example (Lawrence *et al* 2018). Further, using APs to manage diverse socio-ecological problems can be difficult because of the complexities associated with applying the 'theoretical and methodological demands to real world applications' (Skrimizea and Parra 2020). Pathways planning requires the coproduction of transdisciplinary knowledge using multiple stakeholders to collectively explore ideas. These diverse stakeholders may have different levels of power, competing values, and varying knowledge (Abel *et al* 2016). And while technical and scientific knowledge and choices may define the intervention point in the pathway, it is often the political, economic, and ethical choices that define what trade-offs and adaptations will be considered acceptable (Skrimizea and Parra 2020). Finally, there are conceptual and methodological challenges associated with identifying tipping points in pathways, and the systems needed for evaluation and monitoring (Cradock-Henry and Frame 2021).

While there are few examples of published APs for contested, complex natural resource management problems, (Bosomworth *et al* 2017) (Vizinho *et al* 2021)both highlight challenges for pathways planning in these sectors. In agroforestry for example, the climate vulnerability for several species and crops needs to be addressed but each will have a different pathway and often specific information may be unavailable to define critical tipping points (Vizinho *et al* 2021). In addition, because agroforestry systems are multifunctional, farmers may find decision making difficult due to the presence of too many options, leading to ambiguity. Furthermore, while the process of developing pathways can provide shared new insight into problems, there is only limited guidance available on how best to navigate the inevitable tensions likely to arise between stakeholders as potential adaptation options emerge (Bosomworth *et al* 2017).

For APs focused on floods and water management, Bloemen *et al* (2018), suggest there is a need to address timely detection of tipping points in systems with large natural variability and to better identify preparatory actions to enable transformational change. Furthermore, early warning triggers are needed in advance of adaptation tipping points when there is a significant lead time for implementation (Ramm *et al* 2018). Vizinho *et al* (2021) further explore this debate on incremental, transitional, or transformational adaption concluding that adaptation is closely connected to the AP method and framework being used. While the APs process allows for flexibility, the combination of methods used to create

Table 7. A summary of the challenges associated with applying the adaptation pathways process and the numbers of articles associated with each coded theme.

Challenges	No. of articles	References
Complexity and uncertainty	9	Abel *et al* (2016), Babovic and Mijic (2019b), Bloemen *et al* (2018), Bosomworth *et al* (2017), Ramm *et al* (2018), Rocle *et al* (2020), Skrimizea and Parra (2020), Vizinho *et al* (2021)
Contested knowledge, equity, and decision-making	8	Abel *et al* (2016), Bardsley *et al* (2018), Bloemen *et al* (2018), Bosomworth *et al* (2017), Hermans *et al* (2017), Skrimizea and Parra (2020), Thornton *et al* (2019), Wise *et al* (2014)
Assessing options	7	Aerts *et al* (2018), Babovic and Mijic (2019a), Babovic and Mijic (2019b), Bloemen *et al* (2018), Hall *et al* (2019), Kool *et al* (2020), Lawrence *et al* (2019)
Tipping points or thresholds	6	Abel *et al* (2016), Bloemen *et al* (2018), Haasnoot *et al* (2013), Hall *et al* (2019), Hermans *et al* (2017), Vizinho *et al* (2021)
Timing of adaptation actions	5	Abel *et al* (2016), Bosomworth *et al* (2017), Lawrence *et al* (2019), Ramm *et al* (2018), Totin *et al* (2021)
Monitoring and evaluation	3	Bloemen *et al* (2018), Hermans *et al* (2017), Kingsborough *et al* (2017)

the adaption plan is important to enable progressive implementation and changes in the adaptation options to be discussed. A challenge or barrier for using the AP process for large scale urban drainage studies is the time taken to run the computational models (Babovic and Mijic 2019b). These authors suggest that more efficient models could be developed using existing software or the sample rate could be reduced to overcome this problem.

Finally, (Rocle *et al* 2020) notes that if the structural factors in the AP are framed too narrowly or conservatively then the range of possible futures may be restricted and difficult to evaluate. They recommend integrating the weight of interactions between past, present, and future social and ecological vulnerabilities when implementing AP as societies and values change and evolve over time. Often economic, administrative, and legal considerations are emphasised over participatory, community and exploratory APs (Rocle *et al* 2020).

4.2.2. Contested knowledge, equity, and decision-making

Social and political aspects of APs were coded under the theme 'contested knowledge, equity, and decision-making'. Eight articles in the collection highlight the need to address the political influences of decision-making, power relations, equity and diversity issues, and conflict (Bosomworth *et al* 2017, Hermans *et al* 2017, Bloemen *et al* 2018, Totin *et al* 2021). These challenges are especially pronounced when there are multiple actors or stakeholders as part of the decision-making process and where significant externalities hinder or support implementation (Hermans *et al* 2017). Bosomworth *et al* (2017) points to examples from APs in natural resource management which neglect to consider questions relating to 'the decision context'. Understanding contested values, they argue, can help reveal tensions around divisive issues, which if judiciously resolved can lead to enduring outcomes (Bosomworth *et al* 2017).

Abel *et al* (2016), reporting on APs when 'no one is in charge' highlight social cohesion and intergenerational equity as key drivers of adaptation actions. They report that these issues can affect current property rights and impacts on land and water allocations resulting in a need for compensation and possible law changes. Also, when developing transformative scenario plans, Totin *et al* (2021) found it difficult to recruit stakeholders with different cultural values, goals, and knowledge; particularly when the voices of migrants, women, and youths were less influential or powerful and the ways this was reflected in outcomes and recommendations. One way to mitigate some of these effects is through the suggestion of Wise *et al* (2014), who call for reconceptualising adaptation as pathways of change in response to changing social norms and societal values associated with climate change impacts. Focusing on these underlying issues would be challenging but require all sectors of society to reflect on their behaviours and practices.

Other challenges identified in this sub-theme include 'the development of governance arrangements that encourage and generate the co-production of knowledge and learning among diverse local stakeholders and researchers/scientists' (Skrimizea and Parra 2020: 759). For Skrimizea and Parra, in order to advance equitable water governance, APs need to provide a mechanism for involving greater public participation, and incorporate medium and long-term horizons and scientific research into local processes. While, in an Australian study of rural farmers by Bardsley *et al* (2018), found regions where farmers traditionally embraced openness, reflexivity and innovation were able to adapt more sustainably than rural regions with conservative farmer behaviours. Thornton *et al* (2019) then highlights the need for understanding the diverse local, cultural, and ecological contexts when synergising adaption processes and pathways to enhance likelihood of implementation.

4.2.3. Assessing options

Incomplete or partial understanding of the economic costs and benefits of any proposed AP, may be a significant barrier to implementation and decision making (Babovic and Mijic 2019b). However, while APs aim to inform decision makers about potential adaptation options, seven articles described the challenges of *assessing* those options, and the limits currently available tools for doing so. For example, the costs associated with potential strategies (Babovic and Mijic 2019a) may not be known, or there may be residual costs and additional risks associated with moving from one strategy to another within an AP or between two different pathways (Bloemen *et al* 2018, Hall *et al* 2019, Lawrence *et al* 2019).

Bloemen *et al* (2018: 1087) suggest that 'all schemes with a cost-benefit greater than one should be funded', and this cost-benefit ratio should be the determining factor for whether or not an AP is considered worthwhile. While sound in theory, however, Aerts *et al* (2018) note there are significant challenges to developing full cost-benefit analysis for APs. In coastal settings, for example, this cost-benefit analysis would need to include the cost of retreat and setbacks, administrative and planning costs associated with climate adaption, and an economic evaluation of environmental impacts (Aerts *et al* 2018). Furthermore, the least expensive pathway may not necessarily be the preferred option, therefore the benefits need to be expressed as the 'reduced risk over the lifetime of the adaptation measures' to improve the economic feasibility of the proposed pathways (Aerts *et al* 2018: 62). Assessing the costs and benefits of different pathway options would enable, for example, managed retreat expenditure to be staged over the lifetime of different strategies (Kool *et al* 2020). Even so, if there are constraints on obtaining investment finance for adaptation measures, this may not happen.

4.2.4. Characterising triggers and tipping points

Identifying triggers, signposts, tipping points or thresholds in AP is also challenging. Hermans *et al* (2017: 33) defines triggers as 'those values of signpost indicators, individually or in certain constellations, that suggest that critical assumptions may be violated, or at least need attention.' Two different types of difficulties—technical and political—were observed when specifying the signposts and triggers. First a high degree of technological knowledge may be needed to specify robust and reliable triggers and the processes required for these technical triggers will be different to the political ones. Second, decision makers may not want to pin down specific trigger values because of possible political implications and the difficulty in designing triggers that are acceptable to society.

Four of the six articles in this theme highlight trigger and tipping point challenges for flood and water management, sea level rise (Hall *et al* 2019) and forestry (Vizinho *et al* 2021) (table 7). In forest management there is the challenge of accommodating multiple species interactions and complex ecosystem functions when developing triggers and tipping points for APs (Vizinho *et al* 2021). To overcome this problem, Vizinho *et al* (2021) used visioning workshops or zonal planning tools to discuss forest type, species, crops, green corridors, water harvesting and animal grazing and only used AP as a resource in the second stage of planning. They still found the identification of thresholds and tipping points challenging because they can be reached by different drivers at different moments in time. In their case study, the AP aimed to reduce water scarcity, improve soil and fight pests and disease—important vulnerabilities on farms and measures chosen by stakeholders. They found it difficult to identify a tipping point under more frequent and intensive extreme events such as droughts.

In Haasnoot *et al* (2013) the adaptation tipping point or 'sell-by date' helps to identify the possible APs. However, in the flood and water management context the challenge is to know when to trigger the tipping point and how much lead time is needed to implement it when there is large natural variability relative to the magnitude of change (Haasnoot *et al* 2013, Bloemen *et al* 2018). In contrast, technical adaptation thresholds such as whether to open or permanently close sea water barriers can be modelled in detail (Hall *et al* 2019). Another challenge identified with controlling interconnected variables is that one threshold transgression might trigger a cascade of change (Abel *et al* 2016).

4.2.5. Timing adaptation actions

The timing of adaptation actions is closely linked to the triggers and tipping points in AP planning and there were five articles discussing this challenge (table 7). Identifying tipping points at the ecosystem scale is difficult and often contentious but made more difficult when trying to correlate any tipping point at a particular period of climate change such as 2030 or 2050 (Bosomworth *et al* 2017). Lawrence *et al* (2019) found the short-, medium- and long-term planning timeframes constraining because each action had a different adaption threshold and information on triggers was limited when switching between options or other pathways.

An additional challenge to using APs for flood management is the availability and length of time needed to collect relevant data (Ramm *et al* 2018), which may take decades. The authors suggest monitoring a variety of indicators to enhance detection of changes in coastal flood risk so that adaptation decisions can be triggered. Abel *et al* (2016) also discussed the problem of the lead time needed for new knowledge to be released, accepted, and integrated into management options e.g. fossil fuel and climate change data. They also described a further challenge

of long lags between decisions to build new infrastructure and its completion.

In a case study in Mali, Totin *et al* (2021) could not carry out the full AP process in the limited timespan available. They began the scenario exercise half-way through the project which took eight months to complete. The authors were not able to convene stakeholders and development partners (NGOs) to discuss the shared use of water-harvesting infrastructure before the project finished. So, designing and implementing APs takes time and should address major socio-institutional barriers to be practically implemented (Totin *et al* 2021).

4.2.6. Monitoring and evaluation

Three articles highlighted challenges in monitoring or measuring AP plans. Bloemen *et al* (2018: 1096) found significant challenges in monitoring changes in the frequency of storms, droughts and heat waves because of the lack of observations in extreme events. For example,

> *"In the case of climate change-induced changes in peaks of river discharge, research combining monitoring data with model calculations shows that the natural variability in river discharge is so high that even when rapid (but not extreme) climate change is assumed, it can take 3–4 decades before the climate change signal can actually be distilled in a statistically sound way from monitoring data of river discharge".*

According to Kingsborough *et al* (2017) developing APs for heat risk management are extremely difficult due to statutory requirements and defining tolerance levels and trigger values that are informative, measurable and relevant to a wide range of stakeholders.

As AP approaches have a long-term focus, Hermans *et al* (2017) suggest improved systems for monitoring and evaluation are needed to contribute to the collaborative learning process, and to allow for changes in goals and societal values over time. Specifying signposts (indicators) and triggers allow policy to be connected to longer-term AP and for associated variables and indicators to be monitored when critical assumptions are violated or need attention.

5. Discussion

APs embrace uncertainty by providing decision-focused approaches that incorporate flexibility and opportunity for learning in complex and ambiguous conditions (Sparkes *et al* 2023). Researchers have applied APs in different domains, including disaster risk reduction and climate adaptation planning. As the use of pathways has expanded, practitioners have diversified methodologies, reorienting and adjusting approaches for different decision contexts. Our thematic analysis included coding the 49 articles in the collection for lessons, insights, and experiences associated with the development and application of APs. We identified six sub-themes: aiding decision making, negotiating shared values, importance of community input, decision making under deep uncertainty, planning interventions over time, and APs' limitations.

Several of the published case studies note the value of APs as a tool for decision making (Scussolini *et al* 2017, Bloeman *et al* 2018, Roy *et al* 2021). For example, Bloeman *et al* (2018) and Ranger *et al* (2013) argued that APs were effective tools for reaching decisions in a context of deep uncertainty, with Roy *et al* (2021) and Scussolini *et al* (2017) both praising pathways for informing both short- and long-term decision making. Others argued that APs help decision makers untangle how strategic variables—such as political changes, weather events, or changes in policy instruments—determine the range of options available at different scales and at different times (Rocle *et al* 2020). These strategic variables were noted by some researchers as 'preconditions' that affect the successful application of pathways. Bardsley *et al* (2018) identified that particular community values—such as cultures of innovation, tolerance, and belief in climate change—impact the success of an APs approach.

The ways in which APs enabled or helped provide a focus for community engagement and a space for deliberating shared values were also discussed in several articles. For example, Totin *et al* (2021) argued that including a diversity of relevant stakeholders in the development of APs helped these stakeholders better understand interconnections between issues. Other authors (e.g. Barnett *et al* 2014, Bloemen *et al* 2018) also praised APs for helping build community consensus regarding complex environmental issues. Although our review identified different participatory methods to ensure community engagement, recent research highlighted other options to structure normative pathways as a participatory research process with local stakeholders. For example, by using iterative discussions through a Delphi-based methodology to explicitly consider institutional and multi-actor dimensions in the formulation of future adaptive strategies (Gomes *et al* 2023).

A related insight was the importance of community input in establishing APs (Ramm *et al* 2018, Lawrence *et al* 2019, Cradock-Henry *et al* 2020, Kool *et al* 2020). For those who sought community input, it was typically viewed as critical to the process, with researchers noting it would be difficult to know how everyday lives would be affected by the different pathways without it (Ranger *et al* 2013, Ramm *et al* 2018). Different approaches were used to gain community input on different scenarios and pathways. For example, in Rocle *et al* (2020) the

authors use a narrative approach to constructing APs, arguing this enabled the establishment of multi-stakeholder partnerships, as well as debate over adaptation constraints beyond legal or financial factors. Other researchers argued how engagement with local indigenous people, and traditional ecological knowledge, resulted in the identification of more effective adaptation decisions (Singhu and Chudasama 2021). These examples align with reinforcing social learning as a process centred around multi-stakeholder collaboration, which goes beyond consultation or deliberation to enrich learning by observing others and promoting cognitive feedback from stakeholders' interactions (Ricart and Kirk 2022).

The efficacy of APs as a technique for decision making under deep uncertainty allowed some participants to confront uncertainty in a way that left them more confident with managing and dealing with these uncertainties (Carstens *et al* 2019). Sadr *et al* (2020) argued that APs processes can held avoid maladaptive decision making under conditions of uncertainty. In contexts such as sea-level rise, where impacts might take decades to accrue, researchers acknowledge this creates significant uncertainty around identifying adaptation tipping points (Ramm *et al* 2018). These long timeframes also create uncertainty regarding social factors like future land use decisions (Babovic and Mijic 2019b).

The ability for APs to enable planning over different time scales was another lesson identified during our review. As Haasnoot *et al* (2013) argued, a strength of APs' approaches is that they encourage planners and decision makers to consider adaptation over time, to think about actions that need to be taken now to keep future options open, and to consider what decisions and actions might be easily postponed. APs are therefore fundamentally a tool to understand the space–time elements of adaptation planning. They also help local communities conceive of this day-by-day element, such as in Lawrence *et al* (2019). Other researchers also commented on the ability of APs to reconcile multiple decision timescales to better plan for short-, medium, and long-term adaptation (Kingsborough *et al* 2016, Bloeman *et al* 2018, Radhakrishnan *et al* 2019, Roy *et al* 2021).

APs planning is not without its critics, however. Although most of the researchers shared complementary lessons about the use of APs, there were some reflections on the limitations of pathways planning. The list below highlights the limitations of using APs during the SLR:

- Cost and benefits of different APs not accounted for (Babovic and Mijic 2019a);
- A failure to recognise that not all investment decisions are easily phased over time, especially investment decisions that are long-lived investments but are required now (e.g. dams and airports) (Barnett *et al* 2014);
- Stakeholder and community consultation can introduce subjectivity into the development of APs (Bhave *et al* 2018);
- Development of APs can exacerbate tensions between stakeholders with divergent interests and objectives (Bhave *et al* 2018);
- Development of APs often requires a high level of engagement over a long period of time, and engagement from community members or technical experts can be hard to sustain over this process (Carstens *et al* 2019);
- The implementation, monitoring, and evaluation of APs is not funded (Cradock-Henry *et al* 2020);
- The technical barriers to adaptation in different industries will be contingent on a multiplicity of factors beyond climate (Cradock-Henry *et al* 2020);
- Presenting only one APs, rather than multiple pathways, constrains exploration of present and future adaptation thresholds (Lawrence *et al* 2019); and finally,
- In some contexts, effectively engaging stakeholders and the community might be more difficult, resulting in a process that only engages a small vocal minority of citizens (Totin *et al* 2021).

These limitations are not however, insurmountable, and can provide an opportunity to further enhance the value of the approach, particularly at the local level (Cradock-Henry and Frame 2021).

6. Conclusions

As the impacts and implications of climate change become increasingly clear, there has been a growing need for tools and processes to support decision making in the face of uncertainty. From scenario-based analyses that consider a range of plausible futures, to robust decision making—which iterates potential choices, and their related consequences to determine optimal solutions—the field of adaptation practice, has developed rapidly in recent years. Results of this review show that APs are an effective tool for engaging with a wide range of place- and problem-based issues. APs planning has evolved from an initial focus on technological and engineered based approaches, to become increasingly diverse, participatory, and collaborative. While APs have a proven track record, especially for floods and coastal hazards management, there are now several examples, as well as guidance drawn from case studies, for using APs to address climate adaptation outcomes, within the broader context of interacting and compounding stressors. Findings provide new insights into the origins of APs, and the scholars driving best practice. These results can help inform future research design, and provide methodologies to better engage with stakeholders' social, political, and economic concerns.

The reviewed studies have provided insight into the practical application and development of pathways, but further research, and methodological refinement is required. As some recent critiques of APs have noted, there has been only limited attention paid to the socio-cultural and political dimensions that influence the operationalising of proposed adaptation options within an APs process. New work therefore is needed on participatory ways to interrogate stakeholders' interactions, power dynamics, and political and regulatory dimensions within APs to ensure that stakeholders can lead and implement adaptation measures including compounding stressors arising from social and economic contexts while based on space–time narratives and cognitive drivers of the local communities. In conclusion, these challenges notwithstanding, the ongoing evolution of APs highlights its ability to be adapted for use in different settings, for bespoke interpretation, and for how they can contribute to climate-resilient futures.

Data availability statement

No new data were created or analysed in this study.

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