

This is the **submitted version** of the journal article:

Berrang-Ford, Lea; Peñuelas, Josep; Siders, A. R.; [et al.]. «A systematic global stocktake of evidence on human adaptation to climate change». Nature climate change, Vol. 11 (October 2021), p. 989-1000. DOI 10.1038/s41558-021-01170-y

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A systematic global stocktake of evidence on human adaptation to climate change

Analysis

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Abstract

Assessing global progress on human adaptation to climate change is an urgent priority. National and local governments and institutions worldwide look to learn about adaptation responses to climate risks, recognize successes, identify gaps *vis a vis* risks, guide national adaptation plans, and assess progress towards the global goal on adaptation. Yet there is little available synthesis of the rapidly expanding literature on adaptation, making it challenging for governments and practitioners to make evidence-based decisions. Responding to this urgent need, we launched a collaborative global network of 126 researchers to assess 48,316 scientific documents on adaptation. We present the first systematic, global stocktake of the academic literature on human adaptation to climate change, representing an unprecedented analysis of the breadth of adaptation research globally. We combine a novel typology for assessing empirical research documenting human adaptation with systematic review and machine learning approaches to identify and synthesize 1,682 articles. We find a growing literature reporting on human efforts to respond to climate change, but negligible evidence of risk reduction, the underlying aim of adaptation. Human responses to climate change were largely local and incremental, with limited evidence of rapid, extensive, or transformative change. The overall extent of global adaptation across regions and sectors is low. We offer seven priorities for global adaptation research moving forward, including: enhanced assessment of adaptation effectiveness and adequacy; increased attention to the role of individuals, civil society, and the private sector in adaptation; enhancing knowledge of adaptation responses in under-researched regions of the world; assessing and reporting adaptation benefits according to different warming levels; and exploring and articulating the time dynamics of adaptation responses.

Main text

The Paris Agreement highlights the need to track climate adaptation progress, including regular stocktake of insights from empirical research.^{1,2} In response, there have been consistent and increasingly urgent calls for robust, systematic, and transparent assessments of adaptation progress.^{1,3} Understanding if and how adaptation is taking place is critical for decision making. Assessments of adaptation progress can facilitate sharing of best practices, identify successes and gaps, and map evidence across regions and sectors³⁻⁵; such work has been referred to as ‘adaptation tracking.’

In the absence of systematic, global data on adaptation practices, adaptation actions documented in the academic literature provide a valuable (though imperfect) proxy for tracking adaptation on the ground. Existing literature includes assessments of adaptation planning and policy at the regional,⁶⁻¹⁴ national,¹⁵⁻¹⁸ and sub-national¹⁹⁻²³ levels, using for example National Communications,²⁴⁻²⁶ local climate change action plans,^{22,23,27,28} adaptation project proposals, and reported adaptations in the peer-reviewed literature²⁰⁻²². Systematic approaches to synthesizing this evidence are emerging and crucial for learning about what adaptation measures work to what extent, under what conditions, for whom, and why.^{1,32-36} However, to-date, there has been only limited synthesis of adaptation trends and insights from the scientific literature.^{32,29,30} The literature on climate change adaptation is vast and fast-growing, with over 10,000 new articles published annually since 2016, and spread across disparate academic communities.^{31,35,46-48} This under-utilized evidence base of tens of thousands of scientific articles related to climate change adaptation offers new opportunities to better understand activities to-date and inform future responses and research.

This paper presents the first systematic, global stocktake of the academic literature on human adaptation to climate change. We focus on empirical studies reporting observed adaptation-related *responses* (hereafter referred to as ‘responses’), reflecting our aim to capture solution-oriented evidence (responses, rather than vulnerability assessment or impact studies, for example), and recognizing that not all responses are actually adaptive. As it is not possible to reliably and feasibly synthesize broad insights across this literature using conventional assessment methods, we draw on two recent trends in information science: machine learning^{31,33,34} and collaborative network science.³⁵⁻³⁷ Machine learning techniques allow us to rapidly sort through thousands of documents, capturing the breadth of the literature to an extent that would not be feasible using manual methods.^{31,38-40} We used supervised machine learning to screen 48,816 articles published between 2013 and 2019 and identified 1,682 articles that met our inclusion criteria. We developed a network of 126 experts in adaptation research to collaboratively and systematically extract adaptation information from these articles, asking: what climate hazards are driving responses, who is responding, what types of responses are documented, how do responses intersect with the Sustainable Development Goals, what is the extent of the responses, and is there evidence that responses are reducing risk?

Findings

There is reporting on adaptation across all global regions, with the greatest number of papers reporting responses in Asia (35% of articles) and Africa (32% of articles) (Figure 1). Only a minority of publications focused on Central and South America (6%) or Small Island States (2%). Reporting in Africa and Asia is dominated by literature from Southern and Eastern Africa and South Asia, with

limited documentation from Central, Western or Northern Africa and from Northern, Central, or Western Asia. Responses were most frequently documented in the context of food and agriculture (close to two-thirds of all articles), and this was consistent across all regions except for Oceania and to a lesser extent Europe (Figure 1). Poverty and livelihood-related responses were prominent in Africa, Asia, and North America. Responses to the health impacts of climate change were among the top three hazards motivating responses across all regions, and were the primary sector reported in Oceania and Europe. In North America and Europe, there was relatively strong reporting of urban responses (Figure 1).

Placeholder for Figure 1

1. What climate hazards are being responded to?

Drought (54% of all articles), extreme precipitation and inland flooding (43%), and precipitation variability (44%) are the most frequently cited hazards that responses seek to address; along with specific hazards, many responses were motivated by observed or predicted general impacts of climate change (58% of articles) (Figure 1, h-m). Drought and precipitation variability are particularly important motivators of responses in Africa and Central and South America, for example through uptake of new forms of agriculture,^{41–43} food systems,^{44–47} and household-level water supply in cities.^{47,48} In Bolivia, Guatemala, and Kenya, for example, the threat of droughts and precipitation variability have spurred changes in food systems.^{49,50} Flooding and rising sea levels most commonly drive responses in Small Island States, compelling people to prepare inland and coastal flood management infrastructure, implement new building codes, and develop hazard maps and early warning systems.^{51–53} In cities worldwide, flooding and sea level rise are most frequently cited as key motivating hazards.^{18,54–56} For example, increasing flood risks are prompting European countries with large urban areas to diversify, coordinate, and align flood risk management strategies¹⁸. While not commonly identified as a major driver of responses, increased frequency and intensity of extreme heat (28% of articles) appears to play a role in motivating responses across most regions and sectors. Responses to loss of Arctic sea ice (2%) are infrequently documented and largely restricted to polar regions in North America.^{57,58}

2. Who is responding?

Responses occur at multiple levels of social organization from farmers and urban dwellers, to water, electric, and transportation utilities and managers, to international institutions.^{24,51,59–64} However, the vast majority of responses documented in the scientific literature are undertaken at the local level, and by households or individuals in particular (82% of all articles), in the absence of institutional or policy intervention (Figure 1, n-s). Household or individual-level responses are particularly dominant in the context of food, health, and poverty in Africa and Asia.^{49,65,66} Studies in Ghana and Uganda observe that farming households have responded to drought by diversifying and irrigating crops, planting drought-tolerant crops, and livelihood diversification strategies, including migration,^{65,66} while in Kenya, households are diversifying livelihoods through farming and ecotourism.⁴⁹

Local governments are also prominent actors, particularly in large urban areas. In Ibadan (Nigeria), state governments established urban agriculture programs,⁶⁷ and city governments in Quito (Ecuador) and Lima (Peru) constructed large water reservoirs and water treatment plants to mitigate water shortages for urban populations.⁶⁸ Responses at the level of national governments also

receive substantial attention in Small Island States.⁶⁹ Caribbean governments, for example, have instituted education and capacity building programs.⁷⁰ In Central and South America and Small Island States, local civil society plays an important role, as in Bolivia where local community organizations support practices such as composting and climate smart agriculture.⁴⁹ Reporting of private sector engagement in responses is low across all regions⁶⁴ except for Australasia and Europe, where, for instance, tourism companies have initiated safeguards to protect the industry against glacier thinning and decline in snowfall.⁶⁸

3. What types of responses are being undertaken?

The vast majority of responses documented in the academic literature globally are behavioural in nature (75%), with many also technical/ infrastructural (63%) and institutional (42%) (Figure 2). Behavioural responses include actions such as: people making changes to their homes and land to protect them from floods, fires, and heat;⁶³ moving property out of hazard zones; and in some cases relocating or migrating from hazards.^{71,72} At the farm scale, behavioural responses include adoption of crops and livestock that are adapted to drought, pests, and encroaching salinity.^{73–77} Individuals shift to other economic and livelihood activities, abandoning fishing for farming,⁷⁸ or change food consumption practices to cope with environmental risks. In Africa and Asia, farmers commonly use drought-tolerant plant and animal species, water and soil management practices, and diversified income streams to spread risks and adjust to shifting climate conditions.^{76,79–84} Technical and infrastructural responses are also common, most notably in Europe and in cities, particularly in the water sector.^{85,86} Institutional responses such as instituting policies, programs, regulations, and procedures, and forming formal and informal organizations (e.g. social support groups), climate insurance services,⁸⁷ capacity-building, and financial assistance programs are reported most frequently in the food and health sectors and in cities. Institutional adaptations often support other responses, such as extension services designed to enable farmer uptake of drought tolerant crops,⁸⁸ or public education for flood risk preparedness.⁸⁹ Ecosystem- or nature-based responses (50% of all articles) such as natural regeneration of plant species,⁷³ intercropping, and mulching are used across all regions, most notably in Africa and Central and South America.^{90–92}

Placeholder for Figure 2

4. How do adaptation responses intersect with the SDGs?

We assessed the alignment of adaptation responses to exposure and vulnerability *vis a vis* the Sustainable Development Goals (SDGs), which set out pathways to reduce key social, environmental, and economic drivers of risk and vulnerability. Responses to heat risk, for example, might include increasing urban green space for urban cooling, or designing building codes to improve thermal comfort. Both approaches contribute to SDG 3 (health & wellbeing) and SDG 11 (sustainable cities & communities). The former approach (greenspace) is also closely aligned with SDG 15 (life on land), and the latter (building codes) with SDG 9 (infrastructure). For each article, we identified the SDGs most closely aligned with the response.

The primary SDG addressed was related to food security (SDG 2: Zero hunger) (Figure 3). This was followed by reductions in poverty (SDG 2), focus on sustainable consumption and production (SDG 12), livelihoods and work (SDG 8), sustainable cities (SDG 11), improved health (SDG 3), and clean water and sanitation (SDG 6). Few responses targeted education as a primary mechanism for risk reduction.

There is regional variation in the described pathways of vulnerability reduction (Figure 3). There is, for example, a prominent contribution to SDG 2 (zero hunger/ food security), primarily driven by a large proportion of literature on food and agricultural security coming from Asia and Africa. Food was the primary focus for adaptation responses reported in Asia and Africa, but also Central and South America, and Small Island States. In contrast, responses in Europe and North America predominantly focused on sustainable urban development and health. However, North America still retained a strong focus on reporting responses related to food and agriculture.

Economy-related drivers (SDG 12: Responsible production and consumption; SDG 8: Decent work and economic growth; 11: Sustainable cities and communities) were prominent in the global literature and across all regions. A small number of articles reported industry responses (e.g. insurance, tourism, commercial crop productivity, flood protection, water quality). Most economy-related responses were associated with small-scale livelihood diversification and agricultural production.

Placeholder for Figure 3

5. Is there evidence that adaptation responses are reducing climate change risk?

The extent to which responses contribute to reducing risk --the core aim of adaptation-- now and in the future is critical for understanding the benefits of adaptation as well as prioritising action. Evidence that responses reduce risk is often implied or assumed by the authors, and the extent of evidence varies by region, with most evidence in Asia and Africa (about 37% and 34% of occurrences, respectively), and less in North America (10%) and other regions (Europe, 7%; Central and South America, 5%; Australasia, 4%; and Small Island States, 2%) (Figure 4). Papers that do link response to risk reduction mostly refer to responses related to food (40%), poverty and livelihoods (23%), or health (15%). Evidence in other sectors is less prevalent (water and sanitation, 7%; cities and infrastructure, 6%; terrestrial and freshwater ecosystems, 5%; and ocean and coasts, 4%). Within regions, the distribution of evidence of risk reduction by sector varies: for example, a stronger urban focus in Europe and North America, and greater focus on food and poverty reduction in rural Africa and Asia.

The vast majority of papers lack detailed accounting of how and to what extent responses lower risk today and/or in the future under various warming and socioeconomic scenarios. Only 3-4% of the papers report that adaptation responses have been empirically assessed for associated reductions in risk outcomes. Few articles provide both a set of precise indicators and a full analysis of risk reduction levels. Only 30 articles presented evidence of risk reduction as a primary outcome of adaptation responses, for example in improved food security and health outcomes analyzed using indicators like increased agricultural yields and caloric in-take.⁹³ These studies applied either quantitative (15 articles) or qualitative (11) methods, and a minority (4) used a mixed methods approach. A further 9 articles reported improvements in adaptive capacity, but with no clear evidence of changes in risk outcomes.

There is indication that some opportunities for risk reduction may be counterproductive and/or constrained, especially over the longer-term. Maladaptation --responses that result in greater risks-- is mentioned in approximately one third of papers reporting on risk reduction, and eight out of ten mention constraints and limits to adaptation ranging from institutional constraints to ecosystem limits. Migration for example, is observed as an autonomous (spontaneous, reactive) response with

mixed evidence of risk reduction, especially in Asia, Africa, South and Central America and North America (37, 21, 7 and 6 papers, respectively), where labour migration is employed to diversify livelihoods. For communities with fewer resources, less experience with migration, and when the movement was not undertaken voluntarily, migration had maladaptive implications, especially to the sending community by reducing local labour and increasing demands on female heads of households.

6. What is the extent of responses?

We define adaptation extent using a typology of depth, scope, speed,⁹⁴ and overcoming present limits (Table 1). While not a measure of adequacy or effectiveness, adaptation extent reflects whether evidence is broadly indicative of a profile of low to high adaptation. Profiling the overall extent of adaptation across regions provides imperfect but valuable insight into how regions and sectors are broadly progressing on adaptation. Based on the evidence in our database, we evaluate each element in the typology as high, medium, or low, to deliver a combined assessment of the overall extent of responses for each global sector and region. An overall high extent of adaptation reflects widespread responses that are implemented at or very near their full potential across multiple dimensions of the typology. They demonstrate transformative adaptation at large scales or a high level of speed and an ability to overcome constraints. Conversely, an overall low extent of adaptation reflects adaptation that is largely localized, implemented slowly, involves small adjustments to business-as-usual, and is limited by several constraints. .

Across all regions and sectors, the depth of responses is low, with few exceptions, involving minor adjustments to business-as-usual rather than system-wide transformation, and short-term responses to extreme weather events more than long-term change. Alterations in farming practices (e.g. irrigation, crop variety, timing) or infrastructural modifications (e.g. building elevation) fall into this category. Less commonly reported are high-depth responses, such as permanent relocation of a village or a large-scale, multi-stakeholder effort to create a resource governance system.^{95–97} Documented responses tend to be small in scope, focused on a single sector or a small geographic area. Autonomous responses by individuals to deal with heat, for example, tend to be small-scope.^{98,99} Conversely, a national plan to address numerous aspects of climate change is large-scope.¹⁰⁰ The speed of adaptation is often not documented explicitly but ranges from fast responses that occur in less than a year (e.g. using shade or fans in a heat wave, changing timing of a crop planting) to slow responses that require more than a decade of planning and execution. Some fast actions may occur quickly at an individual level but still be slow to spread to other individuals (e.g. uptake of a new irrigation technique by farmers). Numerous constraints that limit the ability of various actors to respond are noted, and there is little evidence of these constraints being overcome.

Our stocktake suggests that the overall profile of adaptation extent across most global regions and sectors is low (Figure 4). There is insufficient evidence to support categorizing the adaptation extent in any region or sector as high. Some examples of high adaptation exist,^{101,102} but are not sufficiently widespread to imply high overall extent across an entire region or sector. Evidence for medium extent was available for only a small number of regions and sectors. Overall, there is negligible documentation of responses that are simultaneously widespread, rapid, and that challenge norms and adaptation limits. Documented responses are taking place primarily through early stage planned actions and expanding autonomous actions. Our results suggest there are trade-offs between the scope and the speed of responses, perhaps due to the long planning timelines involved in coordinating or executing large-scale (e.g., regional or national) measures. The inverse relationship

observed between speed and scope -- large projects are rarely rapid, and rapid projects are typically small in scope -- may imply soft limits to changes that are both rapid and widespread.

Placeholder for Figure 4

7. Discussion

Ultimately, adaptation intends to reduce the adverse effects of climate change and in some cases to take advantage of new opportunities. Although our results find widespread evidence of adaptation-related responses, there is little evidence that responses are, in fact, reducing current and/or future climate risk. This knowledge gap is more broadly due to substantial and recognized difficulties involved in measuring the actual (when responding to observed risks) and potential (when responding to projected risks) effectiveness of a wide range of adaptation responses across sectors and geographies. Absence of evidence of risk reduction does not necessarily imply that no risk reduction is taking place. Rather, our results point out the stark inadequacy of the current evidence base available to assess the effectiveness of responses in terms of risk reduction.¹⁰³ Here we argue that the inability to confidently and systematically gauge effectiveness of responses critically limits the ability to report on and galvanize global adaptation.

Nevertheless, at a global level, our results reveal several interesting and important patterns, such as the prevalence of autonomous adaptation and behavioral responses. There are also some concerning gaps, such as a relative dearth of transformative adaptations in cases where current and projected risks are high, and the lack of evidence of risk reduction or overcoming well-known limits to adaptation. While this global stocktake is an important advancement, results also indicate a need for synthetic analyses at the regional and sectoral levels, given the observed high degree of inter-regional variation, and our focus on academic literature excludes other data sources, such as reports by government agencies; it was not feasible to include grey literature in this analysis due to heterogeneity in formatting and indexing. We identify seven key priorities for global adaptation assessment moving forward:

1. **Explicit assessment of adaptation effectiveness.** Few studies attempt to assess outcome measures.¹⁰⁴ Ultimately, and in most cases, adaptation success will result in avoided harm at some point in the future. This is intrinsically difficult to measure, but it is possible to assess change in risk factors, such as flood damage, local temperature, and crop yield. Introducing effective monitoring of these variables at the start of adaptation programs, ideally in a comparative way with control areas, would allow assessment of response effectiveness, and at least observed, current benefits. Dedicated funding, training, monitoring, and research streams are needed to overcome existing barriers to the development and implementation of frameworks for effectiveness assessments. There is significant potential to draw on existing tools such as theories-of-change, and from synthesizing insights from evaluations in the non-academic literature, to increase consideration of how responses are affecting transitions towards risk reduction and minimizing the risk of maladaptation.
2. **Enhance understanding of limits to adaptation and assessment of adequacy.** Investigation of adaptation limits remains underdeveloped within adaptation research, yet it is important to track if and how implemented adaptation is addressing or approaching limits, i.e. whether it is adequate in the face of climate change. Frameworks to assess adaptation adequacy

remain elusive, and this is unlikely to change within the timescales available for rapid climate action. It is clear, however, that the extent of adaptation globally is low, though this is highly variable, with substantial potential to extend the depth, scope, and speed of adaptations, and begin to overcome barriers and approach limits. A precautionary approach and (limited) available evidence would suggest that we assume our current response is inadequate. More research is needed to understand why complacency persists and why we are not learning how to overcome well-known barriers to adaptation. Assessment of adaptation extent is an imperfect but useful tool to gauge progress on adaptation across scales.

3. **Enabling individuals and civil society.** Much global adaptation discourse focuses on institutional adaptation and addressing governance barriers with a focus on formal institutions and state actors. While critical, this narrative can divert recognition and resources from the importance of autonomous adaptation by individuals and households, particularly in the Global South. People are responding to climate change already but it is often reactive and short-term. To enable long-term adaptation it is critical to recognise and test different incentive mechanisms that enable behavioural change towards adaptation, including insights from environmental psychology.¹⁰⁵ It is also important to assess collective action for adaptation (i.e. autonomously organized adaptation action among social groups) as it holds potential to facilitate transformative adaptation through social change.¹⁰⁶
4. **Including missing places.** Adaptation research is notably greater in Africa and Asia, consistent with global areas of greatest climate vulnerability. But important gaps remain, including Central and South America, Central Asia, Central and North Africa, and the Middle East where vulnerability is high but adaptation research is comparatively sparse.
5. **Understanding private sector responses.** There is relatively little academic literature assessing responses within the private sector. While this may be proprietary (not reported) or published elsewhere, integration of private sector experiences and insights with institutional and public responses will be critical to comprehensive assessment of adaptation.
6. **Adaptation at different temperature thresholds.** We were unable to assess the need for (or potential effectiveness of) differential levels of adaptation at a range of warming scenarios. Indeed, the adaptation literature remains largely temperature-agnostic and disconnected from mitigation and warming estimates. This disconnect is partly because mitigation and warming estimates do not translate hazard trends into environmental and societal impacts that are a prerequisite to understanding and discussing adaptation needs and responses. As a start, adaptation studies could consider how limits to adaptation or the effectiveness of a given range of measures will differ by degree and speed of warming.
7. **Timescale and dynamics of response.** Greater understanding is needed about the durability of documented adaptation responses. Such understanding would help inform policies at various scales about responses available now, those that need to be planned, and the synergies or trade-offs between various types of responses over time. Future adaptation research and assessments should consider explicitly integrating these questions including, how long does it take for the benefits of adaptation actions to accrue, and to whom? Are the documented benefits maintained over time as hazards, vulnerability and exposure continue to change or do different groups begin to “win” and “lose”? To what extent are benefits and risks flexible to changing hazards and societal shifts?

The collaborative network approach used in this study suggests one way forward for large-scale synthesis efforts to overcome barriers of scale. Including a diverse set of collaborators, both junior and senior researchers, also ensures diversity in expertise, viewpoints, and geography to help

ground results. There is potential in the future to blend this approach with additional machine learning techniques to enable even larger comparisons or more fine-grained data extraction. Our study highlights that new approaches to evidence synthesis are increasingly necessary to take stock of where we are and inform interdisciplinary climate solutions.

Methods

Objectives & scope

We systematically assessed the global academic literature to characterize human adaptation-related responses to climate change, published between 2013 and 2019. We frame the review using standards for formulating research questions and searches in systematic reviews, using a PICO_{ST} approach: population (P), interest (I), context (Co), study design (S), and time (T).

The population (P) includes all global human or natural systems of importance to humans that are impacted by climate change. The activity of interest (I) is adaptation-related responses. Due to the lack of scientifically-robust literature assessing the potential effectiveness of responses, we use the term ‘adaptation-related responses’ rather than the more common ‘adaptations’ to avoid the implication that all responses (or adaptations) are actually adaptive (i.e. reduce vulnerability and/or risk); some responses labelled as ‘adaptations’ might in fact be maladaptive. To be included, responses must be initiated by humans. This includes human-assisted responses within natural systems, as well as responses taken by governments, the private sector, civil society, communities, households, and individuals, whether intentional/planned or unintentional/ autonomous. While unintentional/ autonomous responses are included, these are likely to be under-represented unless labelled as adaptation and documented as a response to climate change due to the infeasibility of capturing potential adaptive activities not identified as adaptations. We exclude responses in natural systems that are not human-assisted; these are sometimes referred to as evolutionary adaptations or autonomous natural systems adaptations. While important, autonomous adaptation in natural systems is distinct from adaptations initiated by humans; this review focuses on responses by humans to observed or projected climate change risk. We include any human responses to climate change impacts that are, or could, decrease vulnerability or exposure to climate-related hazards, as well as anticipatory measures in response to expected impacts.

This review focuses on adaptation only, and excludes mitigation (responses involving the reduction of greenhouse gas (GHG) concentrations). We consider adaptation responses across contexts (Co) globally, and focus only on adaptation activities that are directly intended to reduce risk, exposure, or vulnerability, even if later identified as maladaptation.

We focus on the scientific literature only, and exclude grey literature and other sources of Indigenous Knowledge and Local Knowledge (IKLK) and practitioner knowledge. We focus on empirical literature only, including qualitative or quantitative analysis and all study designs (S). To reflect publications since AR5 and prior to the AR6 publication cut-off, we focus on literature published in the time period (T) between 2013 and 2019.

This review responds to the mandate of the IPCC’s AR6 outline, which highlights the need to document and synthesize observed responses to climate change. Throughout this protocol, we draw on the foci, categorization, and priorities outlined in the IPCC AR6 WGII outline as a reflection of stakeholder framing for this review. To maximize potential impact of outputs, the timeline for this review has additionally been aligned with the publication schedule and publication cut-offs to inform the AR6 assessment process.

Summary of procedure

We follow guidelines for systematic evidence synthesis using the ROSES established reporting standards¹⁰⁷. Our methods are outlined in detail in a series of protocols available via the *Nature Protocol Exchange* (currently in pre-screening). A summary of documents screened and coded at different stages of the review is presented in Figure 5.

Placeholder for Figure 5

Database searches

Search strings were developed for each bibliographic database. The searches focus on documents combining two concepts: climate change, and adaptation or response. Documents retrieved from searches were uploaded to a customized platform for management and screening (Zenodo.<http://doi.org/10.5281/zenodo.4121525>). Search strings are detailed in the Supplemental Materials (SM1).

Screening of documents

The objective of screening was to assemble a database of papers published between 2013-2019 on actions undertaken by people in response to climate change or environmental conditions, events and processes that were attributed or theorized to be linked, at least in part, to climate change. Inclusion criteria for screening are summarized in Table 2.

Table 2: Summary of inclusion and exclusion criteria used for screening

	Inclusion criteria	Exclusion criteria
1	Climate change related	Not climate change related
2	Adaptation	Mitigation
3	Empirical OR review of empirical	Conceptual, theoretical, simulated
4	Human system responses OR human-assisted	Natural system responses not for human adaptation
5	Response-oriented, including factors in response	Vulnerability assessment OR impacts-focused
6	Recent or current (e.g. within past 10yrs)	Historic OR Prehistoric OR Projected
7	Tangible responses with potential to directly reduce risk	Planning, prioritizing, proposing responses OR Link to risk reduction tangential or unclear

Documents published between 2013 and 2019 were considered, including documents reporting on adaptations undertaken prior to 2013. Documents were not excluded from screening based on language as long as they were indexed in English. Documents were not excluded by geographical region, population, ecosystem, species, or sector. Documents not indexed in Web of Science, Scopus, or Medline as an article or review, were not included. The focus was on adaptation; documents focusing on mitigation responses (i.e. reducing greenhouse gas emissions) were excluded. Adaptation actions could take place at any level of social organization (individual, household, community, institution, government). Adaptation responses to perceived climate change impacts were eligible for inclusion. Documents synthesizing climate change impacts on populations, without explicit and primary emphasis on *adaptation responses* were also excluded except when climate *responses* were synonymous with climate *impacts* (e.g. human migration or species shifts). Documents whose contributions are primarily conceptual or theoretical were treated as non-empirical and therefore excluded. We focused on documents that reported on responses that constituted adaptation based on a strict definition of the term: behaviors that directly aimed to reduce risk or vulnerability. Documents presenting empirical syntheses of vulnerability or adaptive

capacity without primary or substantive focus on tangible adaptation responses (reactive or proactive) were excluded. Documents were considered eligible for inclusion if they explicitly documented adaptation actions that were theorized or conceptually linked to risk or vulnerability reduction. This excluded assessments of *potential* adaptation, *intentions/plans* to adapt, and discussion of adaptation constraints or barriers in the absence of documented actions that might reduce risk, exposure, or vulnerability.

Supervised machine learning

We used supervised machine learning techniques to filter and prioritize screening of documents that were most likely to meet inclusion criteria. This approach involves manually screening (human coding) a subset of documents to ‘teach’ an automated classifier which documents are relevant according to a set of pre-defined criteria, and then use this trained classifier to predict the ‘most likely to be relevant’ literature.

Initial manual screening: We first screened a random sample of documents retrieved via the search strings. This sample of documents was reviewed by multiple team members; the documents that were labelled differently by different team members were then discussed until consensus was reached, to reduce bias and ensure consistency between team members. This initial phase created the first of several training samples used to train the machine-learning algorithm to predict relevant documents.

Iterative screening and training of algorithm: This sample of manually screened documents was used to train a machine learning classifier to predict the relevance of remaining documents. Batches of documents with the highest predicted probability of relevance were then screened by hand, with iterative re-training of the classifier after each batch to continuously improve prediction.

Assessment of ‘borderline’ documents: This iterative process continued until the classifier stopped predicting new relevant documents, and most documents being identified were only borderline relevant.

Estimating proportion of relevant documents retrieved through machine-learning. We used a random sample of the remaining un-screened documents to estimate how many of these documents might still be relevant, and completed screening when estimates indicated that the returns of additional screening would be low.

Performance statistics generated by the machine learning classifier showed negligible potential to increase recall further, meaning that the remaining un-screened documents were likely to be: a) not relevant and would be excluded if screened manually, or b) if relevant, would be borderline or marginally relevant, or c) relevant but include limited reference to key climate adaptation vocabulary (Figure 3). We can be confident that we retrieved at least 80% of the relevant articles; the 20% of articles that are not included are likely to comprise primarily of articles that are borderline relevant. Our database thus includes a substantial portion of the scientific evidence base on observed adaptation responses globally.

Coding and data extraction

A total of 2032 articles were retrieved from the screening stage and deemed potentially eligible for data extraction. The bibliographic information for articles meeting inclusion criteria during screening were imported into the platform SysRev (sysrev.com). Given that initial screening was conducted on title and abstract only, an additional screening step was undertaken during this phase (data

extraction) to ensure documents contained sufficient full-text information to extract relevant data. Thus, data extraction included two initial screening questions:

- 1) *“Is the document relevant according to inclusion/exclusion criteria?”* To verify relevance of borderline inclusions.
- 2) *Is there sufficient information detailed in the full text (a minimum of half a page of content documenting an adaptation-related response).* This question was used to screen out documents referring to relevant adaptation responses in their title or abstract, but including no tangible detail or documentation within the article itself.

Bibliographic information for all documents classified as relevant to inclusion criteria during screening were imported into SysRev. Extraction was undertaken by small teams of researchers based on regional and sector expertise. We developed an on-line training manual for coders. The training included both contextual information on systematic review methodologies, as well as key details to guide data extraction, including a detailed codebook.

Data extraction was guided by an adaptation typology designed to characterize *who* is responding, *what* responses are being observed, what is the *extent* of the adaptation-related response, and are adaptation-related responses *reducing vulnerability and/or risk*? Coding of regional and sectoral foci within documents allowed stratified analyses for individual sectors or regions.

Questions included both closed/restricted answer questions and open-ended narrative answer questions. The former facilitate quantitative categorical analysis (e.g. descriptive statistics, summarizing studies in ordered tables) and mapping of adaptation (breadth), while the latter facilitate contextual understanding of adaptation and qualitative analysis. Data extraction questions were framed around key guiding questions: who is responding? What responses are documented? What hazards are driving responses? What is the extent of adaptation responses? Is there evidence that responses are reducing risk? A detailed codebook for data extraction is included in the Supplemental Materials (SM2).

Quality assurance of coding

To enable cross-article comparisons, we conducted a quality assessment for each coder to identify those who had missed entries or skipped significant questions within the SysRev data extraction platform. Details of the quality assurance procedure are available at: *Nature Protocol Exchange (DOI pending)*.

Reconciliation of double codes

To consolidate multiple responses into a single entry for each article, we used a script in R that followed a series of if/then statements. The full code and rationale are available on GitHub (doi.org/10.5281/zenodo.4010763). A final database was compiled with a single line entry for each article. All articles were assigned to IPCC regions based on the countries identified during coding. The final database contains 1682 articles and 70 columns (70 data points for each article).

Synthesis

Geographical mapping: We used ‘geoparsers’ to classify documents based on their geographic focus. Geoparsers refer to algorithms that can extract geographic place names from text, based on dictionary methods or pre-trained models. We employed a geoparsers to determine the country of affiliation for the first author of the paper, as well as to identify which countries or places within countries are mentioned in abstracts.

Descriptive summaries: We conducted basic descriptive statistics to estimate total number of articles based on key restricted-answer variables, including sector, region, hazard, actor, response type, and SDG. We created simple bar charts and descriptive infographics.

Adaptation extent: For each article included in this review, we coded the depth, scope, speed, and challenge to limits of the adaptation action documented. We developed a table to define each element, and to define high, medium, and low categories within each. We circulated this table to the GAMI leadership team and external reviewers to receive feedback and validate our definitions. A table detailing the definitions of high, medium, and low for each of the four elements is provided in the Supplemental Materials (SM3). A small team of coders first coded 25 articles, with results reviewed and discussed to identify discrepancies and ensure consistency across coding. The team then coded all 1682 articles in the dataset. Each article was assigned to its relevant region and sector. Many articles fall into more than one region or sector if they, for example, involve comparative work or adaptations that address multiple issues. Papers could also be assessed as “not applicable” or “unable to assess” if the article provided insufficient information on the element in question (e.g., speed) to provide a score. For each region*sector combination (n= 49), the team assessed the overall level (high, medium, low) for each component (depth, scope, speed, limits). These aggregation assessments were based on: 1) the number of papers in each level; 2) the number of papers that assessed that component for the sector-region combination; 3) consideration of agreement (variability) across papers; 4) consideration of the robustness of the evidence for each component. Assessment of confidence in evidence was guided by the GRADE-Cerqual approach to evaluating confidence in qualitative evidence, adapted to the language of the IPCC’s uncertainty guidance^{108,109}.

If fewer than 5 studies were available for a particular assessment (e.g., speed-Africa-health), either because there were too few papers in the region*sector, or because many of the papers did not provide enough information to assess a given component, then the ranking in the final table was given as “Insufficient information to assess”. If confidence in the evidence, based on agreement and robustness, was very low, no assessment was reported. Methods for confidence assessment are provided in the Supplemental Materials (SM3). Overall extent scores were based on aggregation of the four components (scope, depth, speed, limits) (see Supplemental Materials for details).

Acknowledgements

We kindly thank the following individuals for contributions to various stages of this initiative: Christopher Alarconr, Steven Arowolo, Roger Cremades, Emilie Cremin, Krishna Dave, Steve Davis, David Die, Sarah D'haen, Tyler Harrison, Dorothy Heinrich, F.I. Hoefsloot, Jimmy Kumar, Rinchen Lama, Ashwina Mahanti, Chesney McOmer, Aditi Mukjerji, Nnedimma Nnebe, Michelle North, Chidi Ofeogbu, Harsh Panchal, Janak Pathak, Spandan Pandey, Douglas Singini, Arjuna Srinidhi, Vedika Thimmaiah, Alice Yue, Kai Zhu.

Thanks to Thomas Leuchtefeld and the SysRev team for extensive technical and design support in partnering with this initiative.

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TABLES

Table 1: Scenarios of low, medium, and high adaptation extent for four dimensions (depth, scope, speed, and limits). Adaptation extent does not imply adequacy or effectiveness of responses (low adaptation extent may be sufficient for some climate risks, and high adaptation extent may be insufficient to offset climate risks). In the absence of clear conceptual approaches for systematically assessing adequacy and effectiveness, however, these scenarios provide a systematic framework for tracking adaptation progress and assessing the state of responses.

Dimensions of adaptation extent	Extent of adaptation		
	Low	Medium	High
Overall	Adaptation is largely localized and consistent with small adjustments to business-as-usual. Coordination and mainstreaming are limited and fragmented.	Adaptation is expanding and increasingly coordinated, including wider implementation and multi-level coordination.	Adaptation is widespread and implemented at or very near its full potential across multiple dimensions.
Depth	Adaptations are largely expansions of existing practices, with minimal change in underlying values, assumptions, or norms.	Adaptations reflect a shift away from existing practices, norms, or structures to some extent.	Adaptations reflect entirely new practices involving deep structural reform, complete change in mindset, major shifts in perceptions or values, and changing institutional or behavioral norms.
Scope	Adaptations are largely localized and fragmented, with limited evidence of coordination or mainstreaming across sectors, jurisdictions, or levels of governance.	Adaptations is expanding and/or mainstreaming to include a wider region, multiple areas and sectors, or involvement of coordinated, multi-dimensional, multi-level adaptation.	Adaptations are widespread and substantial, including most possible sectors, levels of governance, and actors.
Speed	Adaptations are incremental, consistent with existing behavioral or institutional change.	Adaptations are increasingly exceeding business-as-usual behavioral or institutional change to reflect accelerated adaptive responses.	Adaptations are substantially exceeding business-as-usual incremental norms. Change is considered rapid in a given context.
Limits	Adaptations may approach but do not exceed or substantively challenge soft limits.	Adaptations may overcome some soft limits but do not challenge or approach hard limits.	Adaptations exceed many soft limits and approach or challenge hard limits.

FIGURES

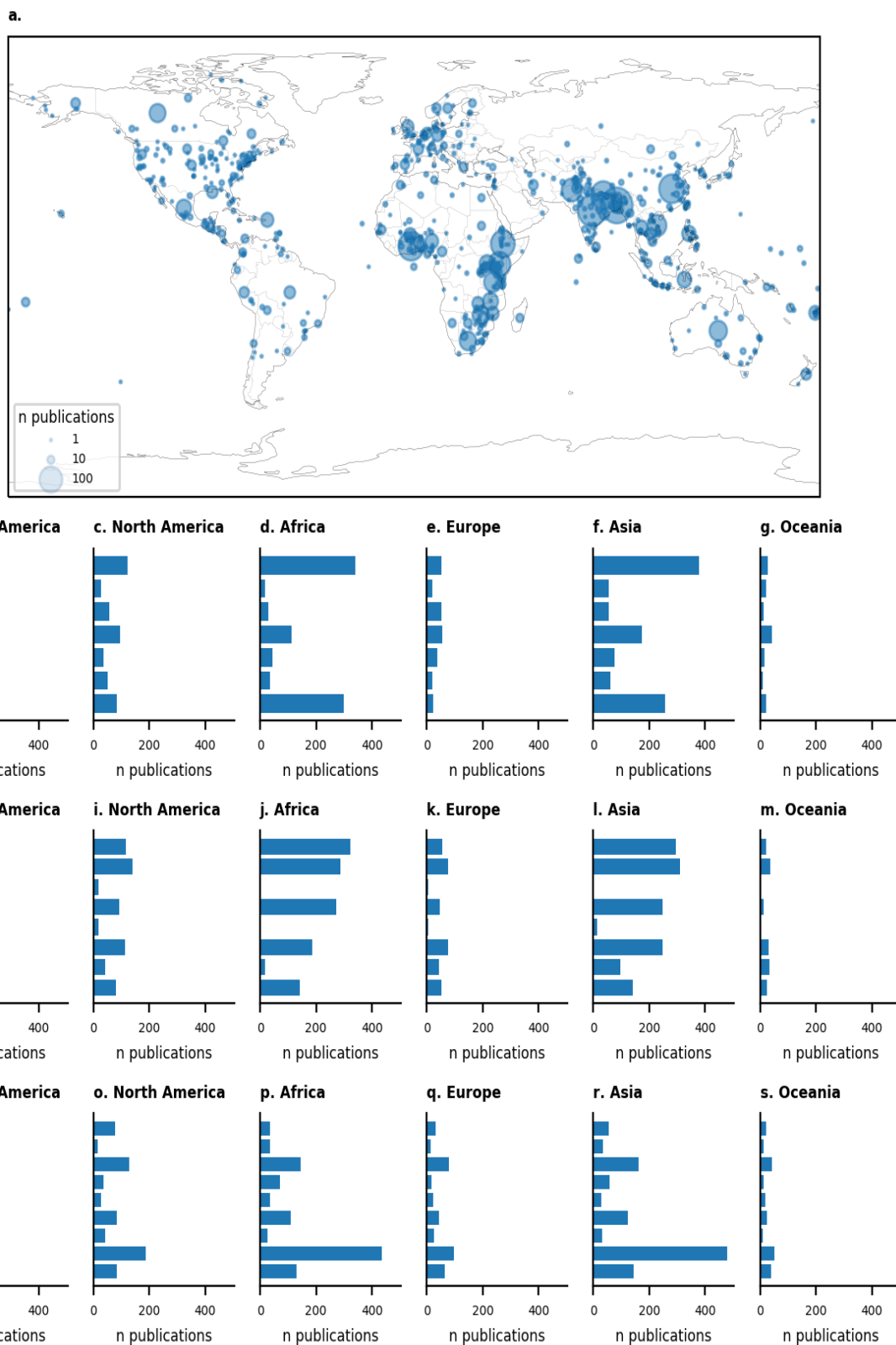


Figure 1: Geographical distribution of included studies (a), and descriptive summary of articles included in this review (b-s). Bar graphs show the total number of publications by global region for categories of sector (b-g), hazards (h-m), and actors (n-s).

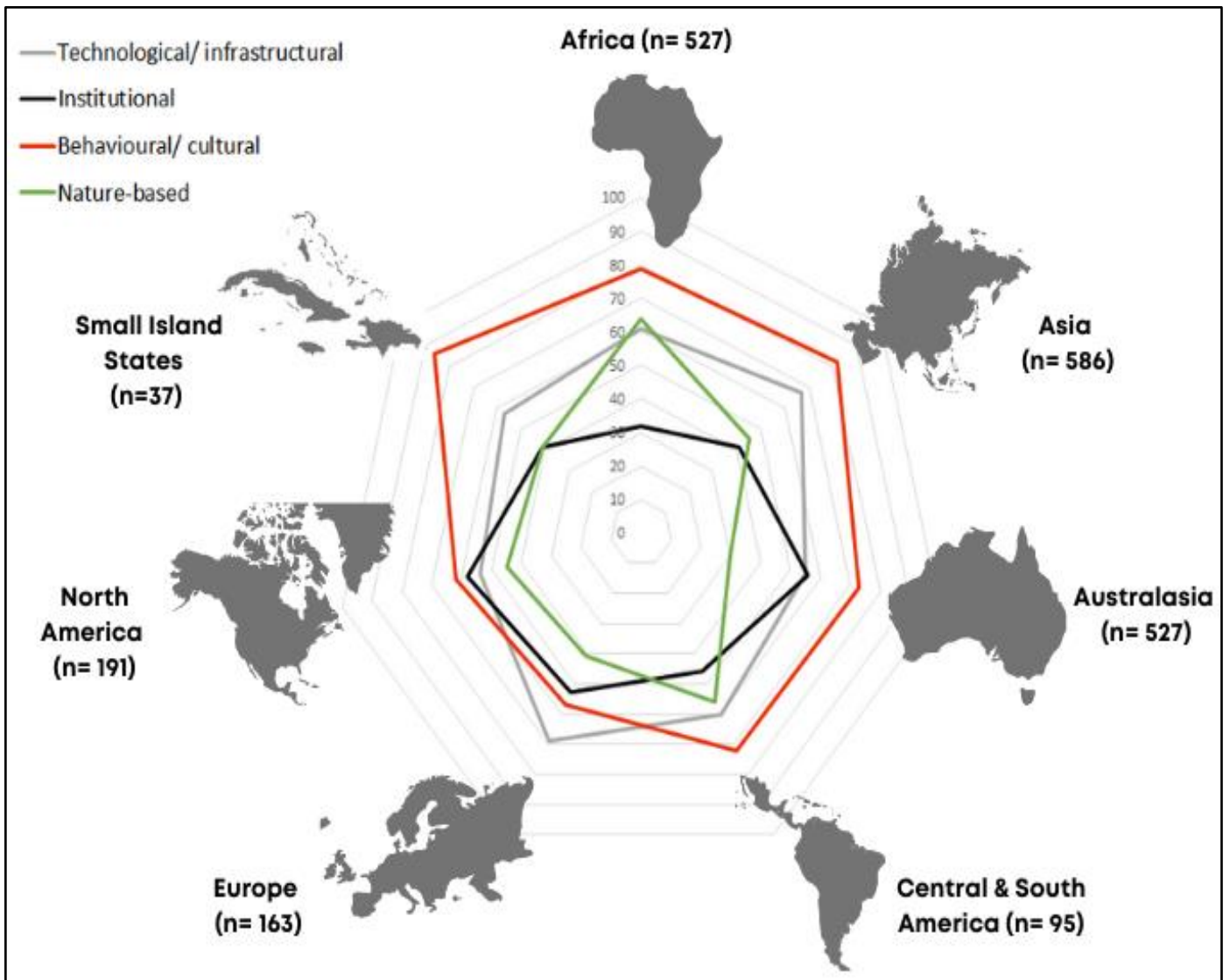


Figure 2: Types of adaptation responses, by global region. Radar axes reflect the percentage of articles mentioning each type of adaptation response over the total number of articles for that region. Adaptation types are not exclusive; articles frequently reported multiple actors engaged in adaptation, for example the development of thermal comfort design to reduce heat in buildings, including civil engineers (private sector), local government subsidies (government), and environmental NGOs (civil society).

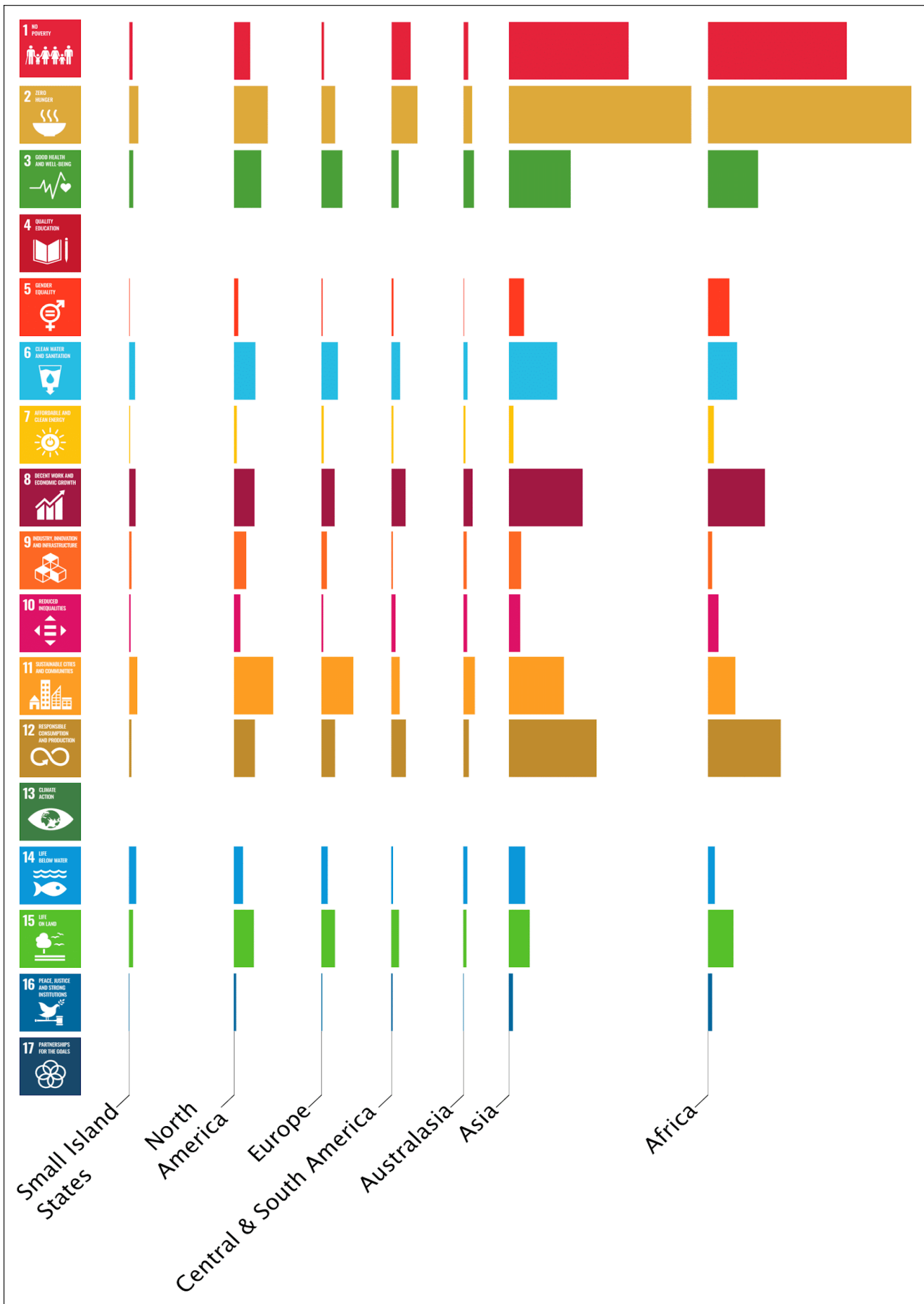


Figure 3: Sustainable Development Goals (SDGs) reported as vulnerability drivers in the scientific literature. These are based on the key pathways targeted by adaptation to reduce vulnerability or exposure. Broader co-benefits of

adaptations for other SDGs are not shown here. Colours reflect different SDGs. Bars reflect total number of publications reporting.

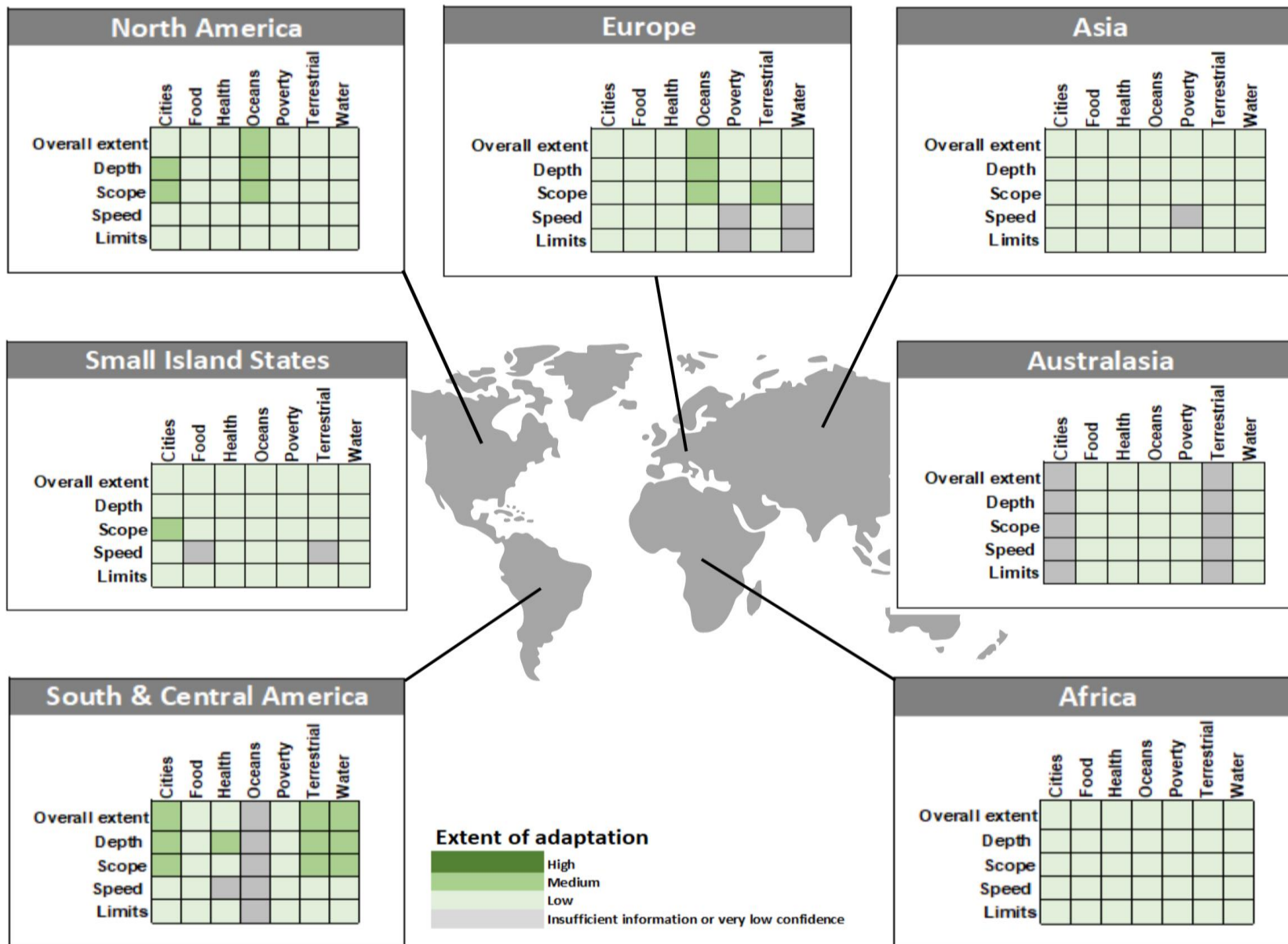


Figure 4: Evidence of extent of adaptation by sector and region. Extent does not imply adequacy of adaptations to reduce risk, which is currently not methodologically feasible or available in the literature. Extent assesses the scope, speed, depth, and challenges to adaptation limits of responses reported in the scientific literature. Methodology provided in the Supplemental Materials (SM3).

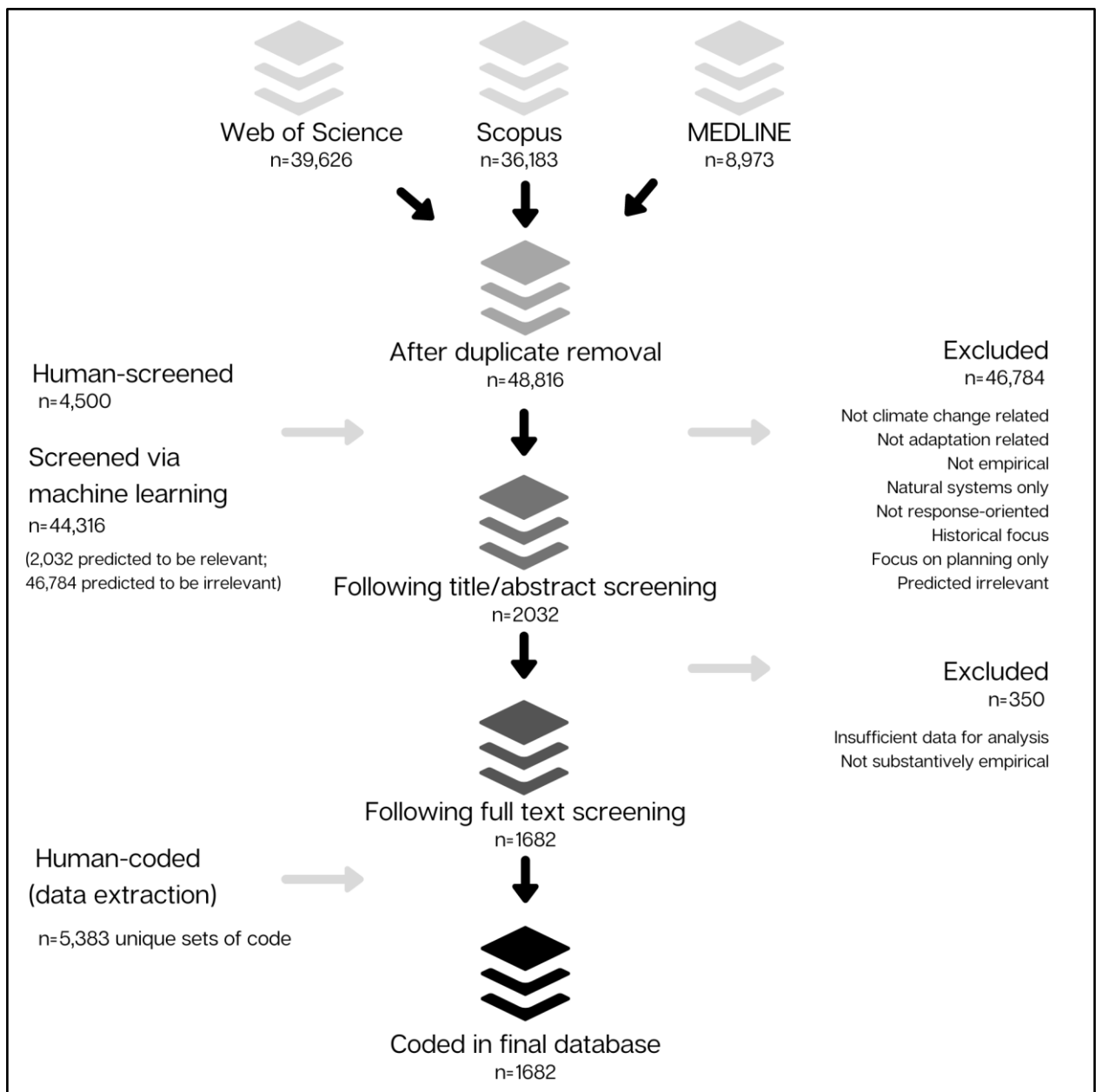


Figure 5: Flowchart of GAMI article review