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. While the literature on adaptation to climate change is rapidly expanding, little is known about the actual extent of implementation. We systematically screened >48,000 articles using machine learning methods and a global network of 126 researchers. Our synthesis of the resulting 1,682 articles presents a systematic and comprehensive global stocktake of implemented human adaptation to climate change. Documented adaptations were largely fragmented, local, and incremental, with limited evidence of transformational adaptation and negligible evidence of risk reduction outcomes. We identify eight priorities for global adaptation research: assess effectiveness of adaptation responses; enhance understanding of limits to adaptation ; enable individuals and civil society to adapt; include missing places, scholars, and scholarship; understand private sector responses; improve methods for synthesizing different forms of evidence; assess adaptation at different temperature thresholds; improve inclusion of timescale and dynamics of responses.

Main text

The Paris Agreement commits Parties to track climate adaptation progress.[1,2] In response, there have been consistent and increasingly urgent calls for robust, systematic, and transparent assessments of adaptation progress, including regular stocktake of insights from empirical research.[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 gaps, support prioritization of adaptation finance, and map evidence across regions and sectors.[3–5]

In the absence of systematic, global data on adaptation practices, adaptation actions documented in the academic literature provide a valuable complement to efforts to track adaptation on the ground (see Supplemental Materials 1 for background on adaptation tracking and global adaptation mapping). Other studies have assessed adaptation planning and policy at the regional,[6–14] national,[15–18] and sub-national[19–23] levels, using information from National Communications,[24–26] local climate change action plans,[22,23,27,28] adaptation project proposals,[29] and peer-reviewed literature.[20] Systematic approaches to synthesizing these and other types of adaptation evidence are emerging and are crucial for learning about what adaptation measures work, under what conditions, for whom, and why.[1,30–34] However, to date, there have been few syntheses of adaptation actions documented in the academic literature.[30–32] The literature on climate change adaptation is vast and fast-growing, and spread across disparate academic communities.[32,35–37] Relatively few of these papers document adaptation actions that have actually taken place, but separating out the studies that report on adaptation actions (rather than, e.g., vulnerability assessments or studies that model the potential for actions to address climate change or document the barriers preventing adaptation) is a monumental task. Moreover, it is impossible to document and capture all — or even a fraction of — adaptation-related activities occurring on-the-ground, and there are therefore no reliable estimates of what proportion of adaptation activities are documented or reflected in the academic literature (SM1). As a result, this knowledge base has remained under-utilized, despite the opportunities it presents to better understand adaptation activities to date and to inform future responses and research.

This paper presents a comprehensive, systematic, global review of the academic literature that documents implemented human adaptation actions in response to climate change. We focus on empirical studies reporting observed adaptation-related responses (hereafter referred to as 'responses'), reflecting our aim to capture adaptations with the potential to directly reduce climate risk, acknowledging that responses do not necessarily lead to reduced risk. In doing so, we focus on a specific subset of adaptation literature that reflects observed and implemented responses rather than processes of decision-making, adaptation governance, and planning.

As the volume of literature makes reliable synthesis via conventional assessment methods impossible, we draw on two recent approaches in information science: machine learning[38–40] and collaborative networks.[41–44] Machine learning techniques allow us to rapidly sort thousands of documents, capturing the breadth of adaptation literature to an extent that would not be feasible using manual methods.[32,36,37,39,40,45] 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 (see Methods). We developed a network of 126 global experts in adaptation research to collaboratively and systematically extract information and evidence from these articles, asking: What climate hazards are driving responses? Who is responding? What types of responses are documented? Is adaptation reducing climate change risk? Are adaptations transformational?

Stocktaking global adaptation responses

Academic studies report adaptation responses across all global regions, with the greatest number of papers reporting responses in Asia (35% of articles) and Africa (32%) (Figure 1, Table 1). 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 66% of all articles), and this was consistent across all regions except for Oceania and Europe, where health (both) and adaptation in urban areas (Europe) were more prominent (Figure 1). We found geographical gaps in evidence (i.e., far fewer papers) from South America, Central and North Africa, the Middle East, and Central Asia (Figure 1). Health risks of climate change were among the top three issues motivating responses across all regions. Poverty and livelihood-related responses were particularly common in Africa, Asia, and North America. In North America and Europe, there was relatively strong reporting of urban responses (Figure 1). Percentages reported throughout this section do not sum to 100%, unless otherwise noted, as articles could describe actions taken in multiple regions or sectors, by multiple actors, and in response to multiple hazards.

Placeholder for Table 1

Placeholder for Figure 1

Climate hazards driving adaptation responses

Many responses were motivated by observed or predicted general impacts of climate change (58% of articles)(Table 1). Of those that noted particular hazards as motivators, drought (54%), extreme precipitation and inland flooding (43%), and precipitation variability (44%) were most common (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,[42,46,47] food systems,[48–50] and household-level water supply in cities.[51,52] In Bolivia, Guatemala, and Kenya, for example, the threat of droughts and precipitation variability have spurred changes in food systems.[53,54] 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.[55–57] In cities worldwide, flooding and sea level rise are most frequently cited as key motivating hazards.[17,58–60] For example, increasing flood risks are prompting European countries with large urban areas to diversify, coordinate, and align flood risk management strategies.[17] While not commonly identified as a major driver of responses, extreme heat (28% of articles) appears to play a role in motivating responses across most regions and sectors.[19,61–63]

Level and actors responding to climate hazards

Responses occur at multiple levels of social organization from individual farmers and urban households, to water, electric, and transportation utilities and managers, to international institutions.[24,55,64–69] However, the vast majority of responses documented in the academic literature are undertaken at the local level, and by households or individuals in particular (82% of all articles) (Figure 1, n-s, Table 1) (see Supplemental Materials (SM1) for a reflection on how results in the academic literature may differ from other data sources). Household or individual-level responses are frequently reported in the context of food, health, and poverty in Africa and Asia.[53,70,71] For example, studies in Ghana and Uganda observe farming households responding to drought by diversifying and irrigating crops, planting drought-tolerant crops, and livelihood diversification strategies, including migration,[70,71] while in Kenya, households are diversifying livelihoods through farming and ecotourism.[53]

Local governments are also prominent actors (Table 1), particularly in large urban areas. In Ibadan (Nigeria), state governments established urban agriculture programs,[72] and city governments in Quito (Ecuador) and Lima (Peru) constructed large water reservoirs and water treatment plants to mitigate water shortages for urban populations.[73] Responses at the level of national governments also receive substantial attention.[74] Caribbean governments, for example, have instituted education and capacity building programs.[12] In Central and South America and Small Island States, a relatively large percent of papers describe actions by local civil society, as in Bolivia where local community organizations support practices such as composting and climate smart agriculture.[53] Reporting in the academic literature on private sector engagement in responses is low across all regions[69,75] except for Australasia and Europe, where, for instance, tourism companies have initiated safeguards to protect the industry against glacier thinning and decline in snowfall.[73]

Types of responses documented

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, Table 1). Behavioural responses include actions such as: people making changes to their homes and land to protect them from floods, fires, and heat;[68] in some cases relocating or migrating from hazards;[76,77] or adopting crops and livestock that are adapted to drought, pests, and encroaching salinity.[78–82] Individuals shift to other economic and livelihood activities, abandoning fishing for farming,[83] 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.[80,84–89] Technical and infrastructural responses are also common, most notably in Europe and in cities, particularly in the water sector.[90,91] Institutional responses such as creating policies, programs, regulations, and procedures and establishing formal and informal organizations — e.g., social support groups, climate insurance services,[92] 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[93] or public education for flood risk preparedness.[94] Ecosystem- or nature-based responses (50% of all articles) such as natural regeneration of plant species,[78] intercropping, and mulching are used across all regions, most notably in Africa and Central and South America.[95–97]

Placeholder for Figure 2

Evidence of climate risk reduction due to adaptation

Given that adaptation aims to reduce climate risks by reducing vulnerability and exposure to climate hazards, understanding the extent to which responses have contributed to risk reduction is critical to evaluate effectiveness and inform future action. Yet the vast majority of the papers we reviewed lacked detailed accounting of how and to what extent responses lower climate risk, with authors often assuming or implying risk reduction.

The results from coding indicated that 62% of papers (n=1044) provided implicit or explicit evidence that adaptation activities were reducing risk or vulnerability (Question 5.1), but only 58 (3.4%) papers indicate that risk reduction outcomes of adaptation responses were formally assessed following implementation (Question 4.1). We conducted a further analysis of this subset of papers that were reported to include formal assessment of risk reduction to examine the current state of empirical evidence on risk reduction (see Supplemental Materials, SM2, for further detail and methods). Among this subset, 30 papers (1.8% of all academic studies in our database) present primary evidence of risk reduction, for example improved food security and health outcomes measured through indicators such as increased agricultural yields and caloric in-take.[98] These studies applied either quantitative (15 articles) or qualitative (11) methods to assess risk reduction, and a minority (4) used mixed methods. A further 9 articles quantitatively assessed improvements in adaptive capacity, but with no clear evidence of changes in risk outcomes. The remaining papers assumed risk reduction outcomes based on secondary evidence or theories of change. Among possible explanations for the limited evaluative evidence in the literature are differences among coders in understandings of risk reduction, assumptions regarding outcomes based on related but non-climate change-specific literature, and the difficulty of conceptualizing risk and factors leading to risk reduction. Additionally, technical challenges related to risk reduction evaluation include the lead time until responses show outcomes in terms of risk reduction, the difficulty of attributing such outcomes to the studied responses, and the difficulty of measuring avoided impacts or risks.[3,99,100]

Notably, some adaptation responses may be counterproductive, with mixed outcomes for risk reduction, especially over the longer-term.[101] This is mentioned in approximately 33% of papers in our sample (Question 5.3). For example, there is some evidence that watershed management responses such as water harvesting may reduce water supply risk in the watershed where water harvesting happens, but may have negative outcomes downstream, for particular user groups, or at longer time scales.[102,103] Migration provides another example of a response to climatic and non-climatic hazards where there has been mixed evidence of risk reduction, especially in Asia (37 studies), Africa (21), South and Central America (7), and North America (6). In some cases, migration may have negative repercussions. For example, labour may be reduced in communities where individuals migrate from, with the result that female heads of households experience increased demands with less ability to share labor.[104–107]

Evidence of transformational adaptation

As the impacts of climate change become more severe, adaptation may need to be more transformational than incremental, with responses going beyond business-as-usual or incremental changes to activities that change the fundamental attributes of socio-ecological systems.[108–114] To assess evidence of transformational adaptation of documented responses, we draw on a typology developed by Termeer et al. (2016) outlining three dimensions of transformative governance: depth, scope, and speed.[108] Depth describes the novelty of an action, scope the geographic or sectoral breadth, and speed the time taken to implement. We add a fourth component that asks to what extent adaptation actions are approaching or overcoming the limits known to constrain adaptation. We operationalize this typology to assess evidence within our database of transformational adaptation for global regions and sectors (Table 2) (see also Supplemental Materials, SM3, for detailed methods, categories, and definitions). We categorized evidence of transformational adaptation for the four dimensions within our typology (depth, scope, speed, limits) as high, medium, or low (SM3 Table 1). Evidence of high transformational adaptation involves an overall regional or sectoral profile of novel adaptations at large scales or across numerous sectors, implemented quickly, that overcome or reduce constraints on adaptation. Conversely, evidence of low transformational adaptation describes an overall profile of adaptation that is largely localized, implemented slowly, involves small adjustments to business-as-usual, and is constrained by barriers to adaptation.

Across all regions and sectors, the depth of responses is low, with few exceptions, involving minor adjustments to business-as-usual rather than transformation, and short-term responses to extreme weather events more than long-term proactive 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.[115–117] Documented responses also 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.[61,118] Conversely, a national plan to address numerous aspects of climate change is large-scope.[119] Individual actions can be large-scope when adopted by numerous individuals or households across a relatively large geographic region or when actions affect numerous aspects of life rather than focusing on a single hazard. 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 (80% of studies describe constraints), and there is little evidence of these constraints being overcome.

The overall transformative potential of adaptations documented in the academic literature across most global regions and sectors is low (Figure 3). Some adaptations exhibit high depth, scope, and speed, and challenge limits,[120] but these are uncommon. In fact, results suggest there may be trade-offs between the scope of responses on one hand and the speed of implementation on the other,[107] perhaps due to the long timelines involved in coordinating or executing large-scale measures. Further research will be needed to explore the implication that soft limits impeded the ability to implement widespread change with the urgency required for adaptation.

Placeholder for Figure 3

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 documentation of adaptation-related responses in the academic literature, there is little evidence on whether responses are reducing climate risk. We identified only 1682 articles that met our inclusion criteria from >48,000, highlighting that only a small fraction of the broader adaptation literature (<5%) is reporting on implemented adaptation responses. There are also concerning gaps arising from our results, such as a relative scarcity of transformative adaptations in cases where current and projected risks are high, and a lack of evidence that well-documented limits to adaptation are being challenged or overcome. These knowledge gaps reflect the 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.

Absence of evidence of risk reduction in the academic literature documenting implemented adaptation actions does not necessarily imply that no risk reduction is taking place. Adaptation actions are documented beyond the academic literature as well (e.g., grey literature). It is possible there is more evidence of risk reduction in these other literatures, so evaluating that literature will be an important next step for global adaptation stock-taking. We conducted an internal expert elicitation exercise to assess confidence in the extent to which our results reflect real-world trends in evidence of transformational adaptation, highlighting reporting bias but broadly supporting a pattern of low overall evidence on transformational adaptation (see Supplemental Materials, SM3 Table 3, and SM4). The absence of empirical evidence on risk reduction that we identified in our database was not just a matter of delay between implementation and realization of risk reduction (though that is certainly relevant), but a lack of engagement with pathways of risk reduction more broadly. We do not map responses against projected risk from climate hazards. Assessing the extent to which responses are addressing key climate hazards will be critical in identifying areas of progress and gaps in risk reduction. Our analysis suggests that synthesizing different sources of information will be needed at regional and sectoral levels, given the observed high degree of inter-regional variation. Nevertheless, our results highlight the stark inadequacy of the current methods and evidence base available to assess the effectiveness of responses in terms of risk reduction.[120] Here we argue that the inability to confidently and systematically gauge effectiveness critically limits the ability to report on and galvanize adaptation globally. Critically assessing the effectiveness of adaptation actions and their potential or actual risk reduction may require different approaches to adaptation research, including longitudinal studies to assess performance over time, more interdisciplinary and transdisciplinary collaboration to assess multiple facets of performance, and greater incorporation of Indigenous knowledge and local knowledge to assess the effects of adaptation on communities and local ecosystems.

We identify additional evidence gaps pertaining to adaptation-related responses. Geographically, evidence is primarily documenting responses in North America, Europe, and parts of Africa (largely anglophone) and Asia (largely southeast). Gaps in evidence are particularly notable in vulnerable regions in South America, Central and North Africa, and Central Asia. There remains relatively little documentation in the peer-reviewed literature on responses within the private sector. More broadly, terminology within the adaptation literature we reviewed is largely disconnected from frequently used terms in the impacts literature; for example, discussion of *barriers* rather than *adaptation limits,* and negligible focus on the implications of different warming levels on adaptation needs or sufficiency. Persistent lack of integration of concepts, terminology, and methods between climate impacts, vulnerability, adaptation, and mitigation research constrains progress on assessing how adaptation responses will interact with mitigation responses to reduce climate risk.

Recent review papers have documented the rapid rise in scholarship on climate change adaptation in recent years.[32,121,122] Our paper complements this literature by focusing specifically on the documentation of implemented adaptations in the academic literature and beyond responses by institutions. A review of climate change vulnerability research, for example, found that only about 30% of papers covered multiple systems/sectors,[123] which is similar to our finding that research on adaptation responses tends to have a single-sector focus. Several review papers document the geographic distribution of authors in the field of climate change and adaptation, with concentrations in the USA, Canada, Europe, UK, and Australia.[121,122] This authorship distribution is not reflective of our mapping of the study areas of literature documenting adaptation responses, which is largest in Asia and Africa. A recent bibliometric review of adaptation literature revealed a growing number of studies on food security and agriculture in the 2016-2020 period,[122] which is reflected in the large number of papers on food-related adaptation responses documented here.

The collaborative network approach used in this study represents a 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. These methods complement emerging citizen science approaches, which show potential for documentation of adaptation responses not readily captured in published literature.[124–127] Our study highlights that new approaches to evidence synthesis are increasingly necessary to take stock of current conditions and to inform interdisciplinary climate solutions.

We identify eight key priorities for global adaptation research moving forward (Box 1). These recommendations are drawn from key insights emerging from our results, combined with our collective reflection on critical gaps in research and knowledge that constrain assessment and learning on progress towards adapting to climate risks globally.

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Methods

Methods protocols

Detailed protocols for this manuscript are published via the *Nature Protocol Exchange*, including: Part 1 - Introduction and overview of methods (DOI: 10.21203/rs.3.pex-1240/v1),[131] Part 2 - Screening Protocol (DOI: 10.21203/rs.3.pex-1241/v1),[132] and Part 3 - Coding protocol (DOI: 10.21203/rs.3.pex-1242/v1).[133] We additionally provide a backgrounder and reflective discussion of adaptation tracking and global mapping methodologies in SM1. Detailed methods are provided describing our assessment of evidence of risk reduction (SM2) and transformational adaptation (SM3), including confidence assessment, and an internal expert elicitation exercise (SM4). Full search strings are available in SM5, and our full codebook is provided in SM6.

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,[33,134] using a PICoST 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 'adaptation' 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.[135] 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 the paper reporting them labelled them as adaptation or they were documented as a response to climate change. The document search for this review included search terms such as adaptation, resilience or risk management (see SM5), potentially not capturing activities not clearly identified as a response to climate changes. We exclude responses in natural systems that are not human-assisted; these are sometimes referred to as evolutionary adaptations or autonomous natural systems adaptations.[136,137] 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. We included papers in any language that were indexed (title, abstract, keywords) in English.

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 academic literature only, including empirical articles or reviews, data papers, and letters, but excluding conference papers, book chapters, and other non-journal document types. We 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 (https://www.ipcc.ch/site/assets/uploads/2018/03/AR6_WGII_outlines_P46.pdf) as a reflection of stakeholder framing for this review. To maximize potential impact of outputs, the timeline for this review has been aligned with the publication schedule and publication cut-offs to inform the AR6 assessment process (https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/).

Summary of procedure

We follow guidelines for systematic evidence synthesis using the ROSES established reporting standards.[134] Our methods are outlined in detail in a series of protocols available via the *Nature Protocol Exchange* (currently pre-prints). A summary of documents screened and coded at different stages of the review is presented in Extended Data Figure 1.

Database searches

Search strings were developed for each bibliographic database. The searches focus on documents combining two concepts: climate change (climate* or global warming) AND adaptation responses (adapt* or resilien* or risk management or risk reduction). 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 (SM5).

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 Extended Data Figure 2.

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 were 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.[138] 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.[31–33,35,36,36,36,39,139] This approach involved a small screening team (n=4 people) 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 four screening 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. 'Predicted relevance' refers to the algorithmic likelihood that a particular article would be coded as 'relevant' based on the content of its title and abstract. 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. This meant that the screening team were able to prioritize manual screening of articles most likely to be relevant to our inclusion criteria.

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. We thus did not manually screen every article, but did screen the majority of articles we predicted (via machine learning and saturation of relevant articles during screening) to be relevant to our inclusion criteria.

Estimating proportion of relevant documents retrieved through machine-learning: We used a random sample of the remaining un-screened documents (which represent those which are rejected by our machine learning-assisted process) 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 (Extended Data Figure 1). 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 sectoral expertise. Each coder contributed to one or more teams based on their expertise. Recruitment of coding team members aimed to ensure geographical and sectoral expertise aligned with relevant volumes of literature. Teams ranged, for example, from 3 coders with experience on adaptation in Small Island States to 30 coders with expertise in food-related adaptation. Literature on food security in Africa, for example, was reviewed by a team of researchers with expertise in African adaptation and/or food security. We developed an on-line training manual for coders. The manual included both contextual information on systematic review methodologies, as well as key details to guide data extraction, including a detailed codebook. Non-English articles were coded by team members fluent in the language used (e.g. French, Spanish, Portuguese, Mandarin). Our geographically diverse research team meant that we had sufficient language competency to assess all articles meeting inclusion criteria.

Data extraction methods and codebook questions were developed in consultation with team members, informed by the literature on adaptation,[1,4,128] and guided by our key research questions: What climate hazards are driving responses? Who is responding? What types of responses are documented? Is adaptation reducing climate change risk? Are adaptations transformational? Data extraction methods and questions

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. A detailed codebook for data extraction is included in the Supplemental Materials (SM6). We classified responses based on global region and sector as per the IPCC AR6 outline. We categorized types of responses as behavioural/cultural, ecosystem-based, institutional, and technological-infrastructural. We additionally consider evidence of transformational adaptation based on dimensions of depth, scope, speed, and challenges to adaptation limits. A copy of the full codebook, including all variables and our operational definitions, is available in the Supplemental Materials (SM6). Coding of regional and sectoral foci within documents allowed stratified analyses for individual sectors or regions.

Quality assurance of coding

To enable cross-article comparisons, we conducted a quality assessment of 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: 10.21203/rs.3.pex-1242/v1).*

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 (see protocol on *Nature Protocol Exchange*, 10.21203/rs.3.pex-1242/v1). 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 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 the 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.

Evidence of transformational adaptation: For each article included in this review, we coded the depth, scope, speed, and challenge to limits of the adaptation response 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 advisory 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 SM3. A small team of coders (n=4) first coded 25 articles, reviewed their results, discussed discrepancies, and refined the category definitions to ensure consistency. For each element (depth, scope, speed, limits) coders also assessed the robustness of the evidence to support the designation as high, medium, or low. This robustness score was based on: 1) whether the article addressed the particular element explicitly or whether information had to be inferred, and 2) the quality of the evidence presented in the article (e.g., sample size, confidence in methods). 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). 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 and percent of papers that assessed each component for the sector*region combination; 2) relative agreement (variability) across papers within the sector*region (e.g., what percent described high depth adaptation); and 3) 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.[140,141]

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 too few papers provided 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, see in particular SM3 Table 3).

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Author contributions statement

The research was conceived, designed, and led by a Coordination Team, including: LBF, AL, ARS, APF, MC, NH, JaM, and KM. LBF led the overall project, MC led the machine learning, APF led the screening team, AL led the coding team, ARS led the synthesis team, and KM led the expert elicitation team. NH provided overall leadership and expertise in systematic review methods. Expertise in machine learning and data science was provided by JaM. The following individuals comprised the Advisory Team, which reviewed, revised, and refined the research design and protocols, aided codebook development and conceptualization of the research, supported team recruitment, and guided alignment of the work with IPCC timelines and methods: KJ, ET, KD, NS, DDe, DR, MvA, CT, AT, LCS, CS, MaN, MM, JaM, AKM, SL, TaL, SH, MH, EGi, MG, JDF, SE, ECP, KB, RB, and RBK. The Screening Team screened all documents for inclusion, and included: IVC, GaS, MiN, and APF. The Coding Team conducted all data extraction, and included: MaA, MARS, MW, DDo, TiL, CM, JIMS, GWP, PAA, IA, NC, WK, CG, VC, KJ, EGa, AS, GiS, ET, KD, NCH, CK, PK, BP, NPS, ET, DDe, DR, CZC, NU, ACS, VK, YS, LZ, ZZ, JX, PAW, IVC, NvM, LLTH, HT, STh, STe, KDS, MZS, RS, JS, EAS, LSSC, RRD, CR, PP, JaP, JoP, JPA, JBPM, SO, PNS, GNA, CAM, JoM, AM, GM, AMN, MLS, OL, SK, MJ, ETJ, LTMH, AH, RRH, GH, TH, AH, Egi, LG, AG, AFo, AFa, CE, ED, SC, TC, DC, KEB, IB, RBK, SLB, EB, SEA, IAR, CA, WA, TA, TZA. The Synthesis Team conducted and led synthesis of results: ARS, TiL, CM, NC, WK, CG, VIC, Ega, AS, GiS, ET, KD, NCH, CK, PK, BP, NPS, ET, DDe, DR. The expert elicitation team comprised: KM AND JN. LBF led manuscript writing. All team members contributed to manuscript development and revisions, and approved the final manuscript.

Competing interests statement

The authors declare no competing interests.

Data availability

Our *a priori* methodological protocol is registered (06-12-2019) and available via the OSF website:[142] https://osf.io/ps6xj

We have prepared a series of detailed methods to accompany this paper via the *Nature Protocol Exchange, including: Part 1 - Introduction and overview of methods (DOI: 10.21203/rs.3.pex-1240/v1),[131] Part 2 - Screening Protocol (DOI: 10.21203/rs.3.pex-1241/v1),[132] and Part 3 - Coding protocol (DOI: 10.21203/rs.3.pex-1242/v1).[133]*

The data presented in this manuscript included survey extraction of information on adaptation from peer-reviewed articles.

Code availability

References to relevant coding are listed in the methods section of this manuscript, and include:

Machine learning platform:[143] http://doi.org/10.5281/zenodo.4121525

Reconciliation of codes:[144] doi.org/10.5281/zenodo.4010763

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TABLES

Table 1: Distribution of article by categories of hazard, actor, sector, and type of response

Indicator	Category	Number of articles[1]	Share of database[2]
Hazards			
	Sea level rise	253	15%
	Extreme precipitation and inland flooding	726	43%
	Increased frequency and intensity of extreme heat	475	28%
	Precipitation variability	744	44%
	Drought	897	53%
	Rising ocean temperature and ocean acidification	51	3%
	Loss of Arctic sea ice	28	2%
	General climate impacts	973	58%
	Other	495	29%
Actors			
	International or multinational governance institutions	129	8%
	Government (national)	608	36%
	Government (sub-national)	251	15%
	Government (local)	603	36%
	Private sector (corporations)	149	9%
	Private sector (SME)	159	9%
	Civil society (international, multinational, national)	216	13%
	Civil society (sub-national or local)	435	26%
	Individuals or households	1374	82%
	Other	226	13%
Sectors			
	Terrestrial & freshwater ecosystems	208	12%
	Ocean & coastal ecosystems	166	10%
	Water and sanitation	240	14%
	Food, fibre, and other ecosystem products	1019	61%
	Cities, settlements, and key infrastructure	249	15%
	Health, well-being, and communities	510	30%
	Poverty, livelihoods, and sustainable development	731	43%
Type of response			
	Behavioural/cultural	1259	75%
	Ecosystem-based	840	50%
	Institutional	707	42%
	Technological/infrastructure	1048	62%

[1] Categories are not mutually exclusive and sum to more than 1,682

[2] Categories are not mutually exclusive and sum to more than 100%

Table 2: Scenarios of low, medium, and high transformational adaptation across four dimensions. Transformational adaptation does not imply adequacy or effectiveness of responses (a low level of transformational adaptation may be sufficient for some climate risks, and a high level of transformational adaptation may be insufficient to offset other climate risks). Dimensions (depth, scope, speed, and limits) adapted from Termeer et al. 2017.[107]

	Evidence of transformational adaptation		
Dimensions of transformational adaptation	**Low**	**Medium**	**High**
Overall	Adaptation is largely sporadic and consists of 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 affect wider geographic areas, multiple areas and sectors, or are mainstreamed and coordinated across multiple dimensions.	Adaptations are widespread and substantial, including most possible sectors, levels of governance, and actors.
Speed	Adaptations are implemented slowly.	Adaptations are implemented quickly.	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.

FIGURE CAPTIONS (MAIN FIGURES)

Figure 1: The geographic and sectoral distribution of the 1,682 articles included in the analysis. 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). Bubbles in (a) reflect number of publications based on the location mentioned in the study; bubbles shown in the centre of countries reflect articles with national focus or unspecified beyond the national level.

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 responses that involved multiple types of adaptation, for example installation of urban green roofs for cooling (nature-based, technological) or government-supported planting of drought-resistant seeds among subsistence farmers (behavioural, institutional).

Figure 3: Evidence of transformational adaptation by sector and region. The overall profile across global sectors and regions indicates that evidence of transformational adaptation is low. We found no sector or region with evidence of high overall transformational adaptation, and few with evidence of medium levels of transformational adaptation. Evidence across some sectors and regions was insufficient for assessment. Transformational adaptation does not imply adequacy of adaptations to reduce risk, which is currently not methodologically feasible or available in the literature. Transformational adaptation here is based on assessment of the scope, speed, depth, and challenges to adaptation limits of responses reported in the academic literature. Methodology provided in the Supplemental Materials (SM2).

Box 1: Moving forward: 8 key priorities for global adaptation research