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Rapid Umbrella Review: Effectiveness of climate change adaptation interventions in low- and middle-income countries

Final report

Agulhas Applied Knowledge

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Executive Summary

Background

Climate change adaptation is a critical global challenge, particularly for low- and middle-income countries (LMICs) that face disproportionate risks of food and water insecurity, extreme weather events, and associated social and economic shocks. Despite over $1 trillion in annual global climate finance, developing countries receive less than a tenth of estimated adaptation needs; in 2022, just $28 billion flowed to LMICs against an annual requirement of $215-387 billion. Recent global agreements, such as the Global Goal on Adaptation (COP28) and the 2024 Bonn Climate Conference, have established clear priorities (e.g., early warning systems, resilient food/water systems) and target increased funding, yet major implementation and knowledge gaps persist around the effectiveness, equity and sustainability of adaptation interventions on the ground.

This rapid umbrella review (RUR) was commissioned to address this evidence gap and inform the programming and priority-setting of the UK's Foreign, Commonwealth and Development Office (FCDO) as it prepares for the next phase of International Climate Finance (ICF). The review synthesises recent evidence across systematic reviews of adaptation interventions, providing an evidence base to guide investment decisions, support scale-up of promising approaches, and contribute to policy and practice in LMICs.

Scope

This RUR examines the effectiveness of climate change adaptation interventions in LMICs with a focus on outcomes aligned with ICF priorities, including capacity building, sectoral transformation, and poverty reduction. It explores 106 systematic reviews published since 2019. Specifically, it aims to answer:

- Which interventions are most effective in reducing exposure, reducing sensitivity, and increasing adaptive capacity?
- What are the key enablers and barriers for successful adaptation?
- Which social groups benefit, and under what conditions?
- What measurement approaches are used, and where are evidence gaps most acute?[1]

The review's principal audience is FCDO decision makers reprioritising ICF adaptation programming for 2026-2032. The RUR will also provide evidence on adaptation and poverty to inform FCDO's new Climate-Development "Best Buys" paper, being developed in the summer of 2025.

Methods

A rapid umbrella review methodology was used, adapting systematic review principles to streamline search, screening, and synthesis processes. Key steps included:

1. **Search strategy:** Two academic databases (Scopus, Web of Science) were systematically searched in November 2024, and grey literature from 17 institutional websites was also screened. Search terms related to adaptation outcomes, interventions, and LMIC geographies.
2. **Inclusion criteria:** Studies published since 2019, with ≥50% focus on LMICs, were screened using a population, intervention, comparison, outcome, and study design (PICOS) framework.

[1] See 'Scope and objectives' on page 3 of the main report for the full list of review questions.

Systematic reviews, meta-analyses, and evidence gap maps were included, while primary studies were excluded. To pass through screening, all studies had to include a focus on adaptation intervention outcomes.

3. **Screening:** From 3,348 initial records, 106 studies were included after title/abstract screening, full-text review, and quality appraisal.
4. **Analysis:** Qualitative synthesis and mapping approaches were used, categorising findings by adaptation benefit (reduced exposure, reduced sensitivity, increased adaptive capacity), intervention type, and contextual/contextual enablers. Quantitative data were used for descriptive purposes only.

Study limitations include the rapid timeframe in which the RUR was conducted, and notably the need to review a vast body of evidence within a short period, which limited the depth of synthesis that could be achieved. The study's scope was also restricted to research published from 2019 onwards. This limitation, while keeping the review manageable, may have excluded relevant, earlier studies. The choice of conducting an umbrella review also introduced certain limitations. While umbrella reviews offer a broad overview and are valuable for summarising large volumes of evidence, they do not include primary studies and operate at a higher level of abstraction. This makes it difficult to assess causation and can introduce greater heterogeneity, complicating the process of drawing consistent conclusions.

Findings

Landscape of studies

Most reviews had a global or multi-country focus. Kenya and India were the most frequently represented at the country level, followed by Ethiopia, China, Niger and Ghana. In contrast, many countries – 57 in total – were mentioned in fewer than five studies each.

Agricultural, technological, and social and behavioural interventions were most common across the literature. Infrastructure and finance-based interventions were less prevalent.

The outcome areas most frequently reported across the studies were increased adaptive capacity (79) and reduced sensitivity (78). Reduced exposure was less commonly reported (42). We also found lower levels of reporting on additional benefits, specifically reduced greenhouse gas (GHG) emissions (25) and reduced poverty (19).

Summary of findings by outcome type

Key findings on reduced exposure

Evidence on reduced exposure to climate hazards is strongest in certain contexts, most notably in coastal, flood-prone, and urban environments. The most consistently positive outcomes stem from nature-based solutions (NbS), built infrastructure, and planned mobility interventions.

In coastal areas, restoration and conservation of mangroves, coastal forests, and wetlands emerged as particularly effective in reducing the physical exposure of people, assets and livelihoods to storm surges, sea level rise, and tropical cyclones. For example, a systematic review from Bangladesh found that villages protected by healthy mangroves experienced about half the monetary loss from flood and wind damage during major cyclones compared to unprotected villages. Mangroves act as natural buffers, slowing storm surge and wave velocity by up to 92% and thereby significantly reducing both human and economic losses. However, the full realisation of these protective benefits requires substantial time for ecosystem

restoration, and short-term protective outcomes may be limited unless these measures are combined with other immediate hazard management actions.

In urban settings, NbS such as tree planting and the expansion of green spaces provide shade and absorb heat, directly lowering the exposure of people and infrastructure to urban heat stress. Although the reviews highlight limited quantitative evidence from urban contexts, qualitative findings indicate improved microclimates and reduced urban heat through the strategic integration of vegetation and shade-providing structures.

Migration and mobility strategies also play a significant role in exposure reduction. Well-planned, informed migration, integrating indigenous knowledge, helps populations escape the direct path of climate hazards, whether by moving seasonal grazing for livestock, relocating households, or shifting cultivation patterns to less hazard-prone regions. However, emergency or unplanned migration carries greater risks, including loss of social networks, reduced access to support services, health issues, and weakened origin communities due to lower labour availability.

In agricultural contexts, interventions such as agroforestry, the introduction of perennial vegetation, and conservation agriculture (e.g., mulching, cover cropping) serve to protect soils and crops from heat, wind, water run-off, and erosion. These practices physically buffer the land against climate extremes, thereby stabilising farm productivity in the face of hazards like drought and intense rainfall. Reviews also note that certain indigenous practices, for example, shifting cultivation and livestock mobility, help spread livelihood risks across landscapes and climatic zones, further minimising the likelihood of catastrophic exposure to single events.

Despite the breadth of interventions with potential to reduce exposure, most of the studies reviewed lack robust, quantifiable metrics of exposure reduction outside of the highlighted coastal and agricultural examples. Moreover, the durability of exposure reduction depends strongly on ecosystem health, restoration timescales, and the degree of integration with infrastructural or risk-management investments.

Key findings on reduced sensitivity

With so many studies focusing on climate-smart agriculture (CSA) and agroforestry, there is greater confidence that these approaches can help reduce sensitivity to climate risks. CSA encompasses a wide range of practices, from high-tech and sensor-driven precision approaches through to adjusting seed selection and planting techniques. Across this spectrum, improvements to farm yields and productivity are widespread. Loss reductions are also reported in terms of reduced crop failures, economic losses, soil erosion or food insecurity. However, the extent to which these benefits translate into concrete adaptation to climate risks or into reduced social vulnerability is less clear. Evidence on improvements in income and food security is often mixed or statistically insignificant.

For crop yields to translate into additional vulnerability-reducing benefits (i.e., adaptive capacity benefits), numerous other factors need to be in place, such as access to market, storage facilities, processing capacity, or affordable transport. Furthermore, adoption of these techniques hinges heavily on the education, training, and capital availability of target groups. Most concerningly, there is evidence to suggest that beyond a 2 or 2.5 degree average global temperature rise, these adaptation benefits will no longer hold. Sustainable outcomes are likely to rely on combinations of other interventions, for example, the provision of financial capital, building of social capital, and infrastructure improvements.

Livelihood and income diversification is documented as both a strategy and an explicit outcome of adaptation measures. Households may diversify income sources to reduce reliance on a specific crop or farming system, or they may participate in a training session or receive access to resources that then leads to diversification, which the literature treats as a positive outcome. Generally, diversification is of livelihoods or farming strategies such as crops or techniques. Intercropping, for example, or combinations of traditional with drought-tolerant seed types, can buffer variability while increasing yields.

There is also substantial evidence highlighting the role of indigenous knowledge in facilitating adaptation benefits. Like CSA, indigenous knowledge and practices are often associated with reduced sensitivity to climate risks but can be more accessible to highly vulnerable households and those without a history of education or access to training.

Planning and infrastructure interventions in urban settings are also associated with reduced sensitivity to risks. These include managing water flows during tidal surges and storms, and increasing thermal comfort through building design and technologies.

Key findings on adaptive capacity

Adaptive capacity hinges on the ability of affected people to make active decisions about how they respond to climate risks. Typically, outcomes related to adaptive capacity refer specifically to people or institutions, rather than crops or farming systems. The adaptive capacity of ecosystems was not addressed in our dataset.

Where adaptive capacity is discussed directly, it is sometimes presented as an outcome in itself, though it is rarely defined in detail. No strategic reviews quantified how much adaptive capacity changed because of an intervention, and few made concrete conclusions about the extent to which different interventions might influence adaptive capacity in any clearly defined sense. For example, studies frequently report increased income or food security following an intervention, but they do not indicate how much of these gains are used for absorptive or adaptive purposes, nor do they consider other possible contributors to adaptive capacity.

Features of adaptive capacity are nonetheless implicit in many of the outcomes described in the strategic reviews. Interventions that build knowledge and understanding of climate risks among vulnerable people – for example, through climate information services (CIS), digital decision support tools, or awareness-raising initiatives – clearly contribute to adaptive capacity. However, these benefits depend on how individuals use this information to make further decisions, so the immediate impact may not be concrete or easily measurable.

We classify increased income as an adaptive capacity benefit. Income contributes to an asset base that provides flexibility, such as savings that help people to respond to a range of risks. While many studies record income gains for individuals or households, they rarely specify the size of these increases, the baseline from which they are measured, or whether household costs are also rising. Increased incomes are often (but not always) reported alongside agricultural innovations or the adoption of new techniques. Social capital, such as networks and relationships that enable resource and information sharing, is another important adaptive asset, especially for poorer households. Social capital frequently appears as a key adaptation resource in the literature.

Interventions that seek to build knowledge and understanding of climate risks among vulnerable people all contribute to adaptive capacity without having an immediate concrete co-benefit. That is, they then

rely on user choices to realise an additional co-benefit. These might include climate information services, digital decision support tools, or awareness raising on the nature of climate risks in a region and the adaptation options available. However, the effectiveness of these interventions is limited by the way they are delivered. CIS must be accessible, comprehensible and actionable. CIS also need to be trusted, recognising that data and methodological limitations lead to errors in predictions. Training on adaptation techniques and methods is typically more available to wealthier and educated farmers, and consideration is needed on how these types of interventions are to benefit the most vulnerable people.

Emerging technologies offer new opportunities for sensitivity benefits that may lead to adaptive capacity co-benefits. For example, artificial intelligence and machine learning can support planning by collating, organising and presenting actionable data-driven insights – for municipalities or farming households. Mobile apps can also provide personalised advisory support for a range of farming challenges. But these technologies are severely hampered by a digital divide which excludes some from benefiting from these technologies and, particularly in Sub-Saharan Africa, infrastructure limitations that undermine the reliability and usability of technologies.

Gender and social inclusion

The reviews covered were relatively light on how adaptation influences different social groups and why. No reviews focused on this specifically, and gendered implications of adaptation are typically mentioned only in passing. Wealthier and more educated people can benefit more from adaptation interventions, supplementing their already larger asset and knowledge base. Without due care and attention, women can be overlooked in interventions across the agroforestry and CSA space.

Key enablers to effective adaptation interventions

Effective climate change adaptation relies on several key enablers:

- **Social capital:** Trust, reciprocity and strong community networks facilitate resource pooling, risk sharing, and collective action during climate shocks. Leveraging and strengthening social capital enhances resilience, adaptive capacity and the sustainability of adaptation efforts, especially when inclusion and equity are prioritised.
- **Participation and inclusion:** Involving local communities, particularly those most affected by climate risks, in all stages of adaptation interventions ensures relevance, acceptance and sustainability. Bottom-up and participatory approaches, in which communities and their representatives are given the opportunity to identify adaptation approaches and how they are implemented, are key. Such approaches draw on local and indigenous knowledge, foster ownership, and deliver more equitable and lasting benefits. The process of identifying, designing and delivering adaptation interventions makes a significant difference to their effectiveness.
- **Good governance:** Robust governance structures and decentralised decision making are essential for effective adaptation, and help to mitigate some of the effectiveness risks often associated with overly top-down intervention designs. Good governance aligns adaptation with broader development goals, ensures resource equity, and supports inclusive participation.
- **Financial mechanisms:** Access to finance through savings groups, microcredit and insurance enables individuals and communities to invest in adaptation, diversify livelihoods, and recover from climate shocks. Well-designed, inclusive financial mechanisms are foundational for scaling up and sustaining adaptation, particularly for the most vulnerable.

Findings on cost effectiveness

Evidence on the cost effectiveness of climate adaptation interventions is limited, with only nine studies providing explicit cost data. Findings should therefore be interpreted with caution due to the small sample size and variability across intervention types. Cost effectiveness varies widely by intervention type and context. Nature-based, community-driven and traditional practices tend to offer the best value, but all interventions require careful implementation, supportive policies, and access to finance to ensure long-term success and scalability.

Conclusions

This study finds that systematic reviews of adaptation focus heavily on agriculture, and generally report positive outcomes and adaptation benefits, although effectiveness varies by context and intervention type. Integrated, multi-faceted interventions that combine scientific and local knowledge are more effective and sustainable than single-strategy approaches.

Overall, the report finds that nature-based solutions (e.g., mangroves, agroforestry), built infrastructure (especially when combined with ecosystem approaches), and early warning systems are most effective at ***reducing exposure*** to climate hazards, while climate-smart agriculture, diversification of crops and livestock, and water-efficient irrigation systems can all help to ***reduce vulnerability*** to climate impacts. In terms of ***increasing adaptive capacity***, the study highlights knowledge sharing (climate information services), income diversification, financial inclusion, community-based adaptation, and participatory approaches as key approaches for enhancing the ability of communities to respond to climate risks. However, the benefits are contingent on appropriate, participatory processes in the design of interventions, and frequently on combinations of intervention working together.

While the adaptation interventions included in this study show evidence of effectiveness, ongoing research is needed to address continued knowledge gaps and ensure effective, equitable and sustainable responses to climate change. Further research could focus on long-term effectiveness, cost effectiveness, urban adaptation, integrating different knowledge systems, and better understanding maladaptation risks.

Table of Contents

Figures

Tables

Boxes

Abbreviations

AA	Autonomous Adaptation
AI	Artificial Intelligence
AWH	Atmospheric Water Harvesting
CE	Collective Efficacy
CI	Climate Information
CIS	Climate Information Services
CMDN	Coastal Mega-cities in Developing Nations
CREL	Community Resilient Ecosystem and Livelihoods
CSA	Climate-Smart Agriculture
CSAF	Climate-Smart Agroforestry
COP28	The 2023 Conference of the Parties of the United Nations Framework Convention on Climate Change
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
EWS	Early Warning Systems
FCDO	Foreign, Commonwealth and Development Office (UK)
FFS	Farmer Field Schools
GCF	Green Climate Fund
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information System
ICF	International Climate Finance
ICM	Integrated Coastal Management
ICT	Information and Communications Technology
IK	Indigenous Knowledge
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
LCZ	Local Climate Zone

LDCs	Least Developed Countries
LLM	Large Language Model
LMICs	Low- and Middle-Income Countries
NbS	Nature-based Solutions
NGO	Non-Governmental Organisation
NRM	Natural Resource Management
PES	Payments for Ecosystem Services
PICOS	Population, Intervention, Comparison, Outcome, and Study Design
PNAE	National School Feeding Programme of Brazil
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REDD+	Reducing Emissions from Deforestation and Forest Degradation
ROBIS	Risk of Bias in Systematic Reviews
RUR	Rapid Umbrella Review
SIDS	Small Island Developing States
SOC	Soil Organic Carbon
SR	Systematic Review
SSA	Sub-Saharan Africa
SWC	Soil and Water Conservation
ToR	Terms of Reference
UN	United Nations
URL	Uniform Resource Locator
VSL	Village Savings and Lending
WCS	Weather and Climate Services
WRM	Water Resource Management
WSN	Wireless Sensor Network

1 Background

The world is not currently on track to meet the goals set out in the 2015 Paris Agreement. The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Synthesis Report (AR6) underscores that human-induced global warming is already driving unprecedented changes to the Earth's climate, with widespread and intensifying impacts on both nature and people. Over one-third of the earth's population lives in areas that are highly vulnerable to climate change (IPCC, 2023). Many of the most adverse climate impacts are felt in low- and middle-income countries (LMICs) where people are already exposed to food and water insecurity, disasters and heat extremes. This is particularly the case for least developed countries (LDCs) and small island developing states (SIDS), where capacity to cope with climate change is lowest. Recent negotiations at the 62nd Sessions of the Subsidiary Bodies (SB62) in Bonn (June 2025) have reinforced the urgency of enhanced adaptation action and finance. Parties reiterated that adaptation must be at the heart of the global climate agenda, calling for more robust governance, transparency, and accountability mechanisms to ensure that adaptation commitments translate into tangible results on the ground (SB 62, 2025).

Driving progress on adaptation is more important than ever. The Global Goal on Adaptation framework agreed upon at COP28 sets clear thematic focus areas for all countries. These include establishing early warning systems by 2027 and risk assessment-informed national adaptation and monitoring and evaluation plans by 2030. It also emphasises water scarcity, resilient water and food production systems, and ecosystem restoration. Many LMICs will need international support in finance, technology transfer, and capacity building to make progress in these areas. At the 2024 Bonn Climate Change Conference, Subsidiary Bodies[2] recognised the importance of factors like leadership, institutional arrangements, policies, data and knowledge (including local or traditional knowledge), skills and education, public participation, and strengthened and inclusive governance (including the involvement of indigenous peoples and local communities) (UNFCCC, 2024).

However, the availability of adaptation finance and implementation of adaptation measures is not keeping up with the impacts of climate change, and the gap between needs and actions is increasing. At COP29 (Baku, 2024), parties reached a milestone agreement on a New Collective Quantified Goal (NCQG) for climate finance, setting a target of at least $1.3 trillion annually by 2035, with $300 billion specifically allocated for developing countries. The Baku Adaptation Roadmap and a high-level dialogue on adaptation were also launched to sustain political momentum and operationalise the Global Goal on Adaptation. Countries agreed to finalise a set of global adaptation indicators by 2025, to be integrated into national adaptation plans and biennial transparency reports. However, concerns remain over the sufficiency and accessibility of financial commitments, particularly for the most vulnerable countries (IISD, 2024; Adaptation Community, 2024). The UN Environment Programme's latest Adaptation Gap Report (2024) highlights that the adaptation financing gap is currently between $187 and $359 billion per year (UNEP, 2024). The recent SB62 sessions in Bonn have focused on operationalising commitments, with discussions centred on improving the governance, transparency and effectiveness of adaptation finance flows.

[2] Two Subsidiary Bodies, the Subsidiary Body for Scientific and Technological Advice and the Subsidiary Body for Implementation, assist the governing bodies of the UNFCCC on technical matters.

Despite the finance gap, adaptation interventions have proliferated and advanced in sophistication in recent years. Interventions routinely combine "hard" and "soft" measures, such as flood infrastructure with early warning systems or strategic local water infrastructures with government institutional strengthening. Locally led, nature and ecosystems-based interventions are recognised as essential for effective and sustainable delivery, particularly in reaching the most marginalised communities. Implementers are also increasingly aware of the need to ensure that intervention outcomes are "robust" in the face of uncertain and variable future climate and economic scenarios in each context (Wilby and Dessai, 2010). There is also increasing awareness of the limits to adaptation, and the point at which adaptation is no longer viable, as well as the need to consider losses and damages experienced by vulnerable people (IPCC, 2023).

However, robust knowledge on the relative effectiveness of different adaptation interventions is lacking. After lack of resources, lack of knowledge and awareness of adaptation measures among the public, stakeholders and policymakers is cited as the most significant barrier to actioning adaptation policies (Lee, Paavola and Dessai, 2022). Measuring and cross-comparisons of the effectiveness of adaptation interventions is made more difficult by the heterogeneity of adaptation programming. This diversity is matched by various understandings of "effectiveness" in the research and practice literature. For example, some research and evaluation studies focus on costs and benefits, typically in financial terms, while others focus on improved wellbeing, reduced vulnerability, increased adaptive capacity, or enhanced resilience of groups or systems (C. Singh et al., 2022). Assessments of the effectiveness of adaptation interventions therefore often reflect that different types of intervention seek to achieve different outcomes. Furthermore, adaptation interventions and their outcomes intersect with wider processes of change and business-as-usual development interventions, making it difficult to attribute results measured under any of the foregoing approaches to a specific intervention.

Various non-standardised methods and frameworks have been used to measure adaptation effectiveness. These include qualitative, quantitative and mixed methods approaches, with frameworks for effectiveness derived from contrasting economic, social or ecological schools of thought, and applied with varying degrees of rigour. There is little clarity on when and how these different approaches should be used. The Global Stocktake (GST) in 2023 highlighted the limitations in establishing clear, universal benchmarks for measuring the adequacy and effectiveness of adaptation, thereby allowing for comparable analysis. Beyond the question of how adaptation is measured, an even greater challenge is how this is then assessed at the aggregate level across interventions, particularly at the global level (Gao and Christiansen, 2023).

Closing the knowledge gap on effectiveness is vital for delivering on the Global Goal and ensuring both positive impacts for end-beneficiaries and value for money for the UK's International Climate Finance (ICF) and other international climate finance. Assessing both the financial and non-financial benefits and costs of adaptation measures – and comparing them across sectors and intervention types – is essential for decision makers to identify and fund contextually appropriate adaptation projects. Additionally, understanding the effectiveness of these measures requires examining the processes used to design, implement and evaluate adaptation interventions, as these processes determine who will be affected and how. Better data and knowledge on these issues can promote international leadership on adaptation and resilience and translate action by partners and funders into practical actions in LMICs. High-quality research, learning and knowledge dissemination are critical.

2 Scope and objectives of the review

This rapid umbrella review (RUR) explores the effectiveness of climate change adaptation interventions in low- and middle-income countries.

The principal objective of this RUR is to add to the evidence base that will inform decision making as the Foreign, Commonwealth and Development Office (FCDO) reviews its adaptation programming in Phase 4 of the UK's ICF, which will run from 2026/27 to 2031/32. Findings will provide an evidence base for adaptation spending and programming and, as far as the evidence allows, support FCDO's thinking on approaches to measure the impact of adaptation spending.

The RUR will also provide evidence on adaptation and poverty to inform the new Climate-Development "Best Buys" paper, to be developed in 2025. The research will look to gather evidence of poverty reduction as a result of adaptation interventions and (as far as possible) the conditions that enable this. The review will also be of value beyond FCDO by helping to address the knowledge gap on adaptation intervention effectiveness.

The study answers the following questions, developed in collaboration with FCDO's Environment and Climate Directorate, Adaptation and Resilience Team, and Research and Evidence Directorate:

Primary research question: How effective are climate change adaptation interventions implemented in low- and middle-income countries?

Sub-questions:

- Which interventions have been most effective in leading to a) reduced exposure, b) reduced sensitivity, and c) increased adaptive capacity?
- What enabling factors and/or barriers create or undermine the conditions for positive adaptation outcomes?
- Which social groups are currently benefiting most from adaptation interventions, and in which contexts are interventions benefiting the poorest and most vulnerable?
- What are the key underlying processes that explain how interventions create positive adaptation outcomes in different contexts?
- Are there aspects of adaptation interventions that are more likely to lead to maladaptive outcomes for some populations?
- Which interventions have the greatest potential for transformative outcomes for the poorest and most vulnerable?
- In what geographical regions is the evidence strongest for positive adaptation outcomes and their causes?
- What approaches and/or indicators are identified in the literature as being used to measure adaptation outcomes?

FCDO is especially interested in interventions that a) build capacity, planning and finance at national and international levels for advancing adaptation actions, and b) transform priority sectors and systems to prepare for and manage climate shocks. Therefore, a wide typology of adaptation interventions covering a range of sectors was included in the study.

3 Methods

The RUR adapts standard guidelines for a full systematic review but, given its rapid nature, it uses more targeted search, screening and quality appraisal strategies to ensure feasibility.

3.1 Search methods for the identification of reviews

The search was conducted in November 2024, and it focused on bibliographic databases and a targeted grey literature search. The following bibliographic databases were searched, and any duplications of literature across the databases were screened out:

- Scopus
- Web of Science

Academic databases were searched in English. *Annex 1* contains the detailed search terms for both databases.

Grey literature typically includes working papers, pre-prints, and discussion or conference papers where reviews of evidence are included. The following institutional and programme websites were searched:

- 3ie's Development Evidence Portal
- BRACED (Building Resilience and Adaptation to Climate Extremes and Disasters)
- Foreign, Commonwealth and Development Office Research Outputs
- Global Centre on Adaptation
- IDEAS Research Papers in Economics (RePEc)
- Inter-American Development Bank
- Mercy Corps
- Organisation for Economic Co-operation and Development
- Overseas Development Institute
- Resilience, Evaluation, Analysis and Learning
- Swedish International Development Agency Publications
- United Nations Development Programme
- United Nations Disaster Risk Reduction
- United Nations Environment Programme
- WeAdapt
- World Bank – Open Knowledge Repository
- World Health Organisation Repository

Grey literature that did not contain sufficient information to conduct a quality appraisal, such as briefs or presentations, was excluded.

3.2 Inclusion and exclusion criteria (PICOS)

A systematic approach was taken to identify and screen the landscape of available systematic reviews and rapid reviews.

We adopted clear screening protocols at the title/abstract and full-text screening phases to ensure that all relevant systematic reviews, meta-analyses and rapid reviews were included (i.e., all those that contain

evidence on the effectiveness of climate change adaptation interventions and/or how adaptation is measured).

We screened search results using an agreed population, intervention, comparison, outcome, and study design (PICOS) framework. In this study, comparison groups are not relevant as the included studies are all at the systematic review level.

Participants/population

Low- and middle-income countries as per World Bank classification (see *Annex 2*). Because some studies include evidence from more than one country, we only included studies where at least 50% of the included primary studies came from LMICs. Studies based on global data (i.e., multiple countries and contexts) can contain useful insights for adaptation in LMICs, and hence global studies were also screened and included if they met all inclusion criteria (including the 50% LMICs criteria).

Intervention(s)

A wide range of climate change adaptation interventions were considered. Interventions can be conceptualised as policies or activities that support the pillars towards greater climate resilience and successful adaptation, including building capacity, planning and finance, and transforming priority sectors and systems. Systematic reviews were included which are explicit about the links between a policy or intervention(s) and defined adaptation goals.

Furthermore, adaptation goals can adopt multiple typologies including reduced vulnerability, reduced disaster risk, increased adaptive capacity, and transformational adaptation, to name a few. Thus, a broad approach was taken that included a variety of interpretations – see *Annex 3* for our analytical framing of intervention types. The study also explored the potential co-benefits of adaptation interventions if found in the literature.

Studies that focused on the enabling conditions, barriers to adaptation, and approaches or strategies for planning and implementing adaptation were included, *provided they included data on intervention outcomes.*

Outcome(s)

We examined the effects of climate change adaptation interventions guided by Nalau's outcome framing (Nalau and Verrall, 2021):

- Increased adaptive capacity, which includes assessment of climate risks and vulnerability, design and implementation of adaptation plans, and policies and investments.
- To reduce exposure and sensitivity, including disaster risk reduction and disaster risk management, and resilient food, land and water use.

Study designs

Systematic reviews of adaptation policy and/or intervention effectiveness were included. Rapid reviews, meta-analyses and evidence gap maps were also included. We excluded studies that failed to adequately describe their methodology or that are (systematic) literature reviews. We adopted the definition of systematic reviews as set out by the Cochrane Collaboration:

> *"A systematic review attempts to collate all empirical evidence that fits pre-specified eligibility criteria in order to answer a specific research question. It uses explicit,*

> *systematic methods that are selected with a view to minimizing bias, thus providing more reliable findings from which conclusions can be drawn and decisions made"* (Higgins and Green, 2011).

Given the extensive nature of the evidence base, we adopted a timeframe considering studies from 2019 onwards. The rationale for this timeframe is rooted in the Terms of Reference (ToR), which suggested that the study "*…should build on recent mapping of the adaptation literature. In particular, the review should draw on the mapping of adaptation literature published by the Green Climate Fund in 2020*" (Doswald et al., 2020). Doswald et al., also referenced in the ToR, has been used as a starting point to implement our search strategy. An initial pilot search was conducted and subsequently updated in Scopus and Web of Science.

3.3 Data extraction (selection/screening, coding and management)

After completing the search process, we collated and removed duplicate records. We screened in two stages: trained reviewers assessed studies against the RUR's inclusion and exclusion criteria (see *Section 3.2* above); one screened titles and abstracts of studies identified by the search; a second independently reviewed 20% of the studies for inclusion to confirm the first reviewer's decisions. Full texts were obtained and screened when a decision could not be made based on title and abstract. Any disagreements were resolved by discussion, or by involving a third reviewer if a consensus could not be reached.

As this is a rapid review, a complete full-text screening process was integrated at the quality appraisal stage, providing reviewers with a second opportunity to exclude reviews that did not meet the PICOS. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram is presented in the findings section, summarising the study selection process.

We explored the use of large language models (LLMs) to assist in the screening of and data extraction from the large number of studies indicated during the pilot searches by highlighting content which may be relevant to the main research questions. However, given the recency of these technologies and the possibility of machine error, the results from using Google Sheets and ChatGPT were not sufficiently reliable or time-saving for LLMs to be adopted in the screening process.

Box 1: Piloting LLMs in the research process

The use of LLMs is novel for this type of research activity and was therefore explored through an iterative and team-driven process. During the inception phase, the team discussed the potential for using LLMs to assist at different stages of the research, including screening and extraction. Based on the current capabilities of LLMs and the format of the research data (i.e., the academic search results dataset in .csv), the team opted to trial the LLM at the title and abstract screening stage. A test of the LLM's capabilities – in comparison with manual screening by human analysts – was designed to establish a guideline and guardrail for whether the LLM could be used for the entire RUR dataset of search results.

The team decided not to precondition the application of the LLM, but instead to test a range of different screening prompts against a sample. This sample was defined as 5% of the full search database, which includes Web of Science, Scopus, and grey literature records. In total, the sample consisted of 169 randomly selected studies. A series of four prompts were defined to review each of the PI(C)OS criteria, directly aligned with the process of manual screening. All prompts ended with a

clause instructing GPT to make a recommendation to "include" or "exclude" each study, accompanied by a concise explanation of its decision. The team then reviewed the GPT results against the manual screening results to identify the percentage of agreement/disagreement against two error types:

- Type 1 error = human assigned "include" but GPT assigned "exclude"
- Type 2 error = human assigned "exclude" but GPT assigned "include"

No prompt met the threshold. Type 1 errors ranged between 5% and 53% of the sample while Type 2 errors ranged between 3 and 37% of the sample. The team manually reviewed a sample of the Type 1 and Type 2 errors to see if patterns could be discerned in what the AI tool was finding difficult, with a view to improving the efficiency and accuracy of the tool by improving the prompts. A second round of GPT screening was conducted using improved prompts. This reduced Type 1 errors but did not sufficiently reduce Type 2 errors. It was therefore decided that the GPT tool, in this iteration, was unlikely to provide sufficient rigour or time-saving benefits. GPT tools were therefore not used for data screening in this RUR.

Grey literature sources have been hand-searched for relevant literature and information.

Upon completion of the screening process, data were extracted from the included studies. The name of the organisation/institution, the URL link, the date the website was accessed (if relevant) and bibliometric data were logged in an Excel spreadsheet.

The team then used Google Forms to support data extraction across the studies in the composite database (i.e., from academic and website (grey literature) sources), allowing the data to autofill in Google Sheets and enabling the team to organise and code relevant findings under different themes.

Data from all included material was coded and extracted for the following areas:

- Context, i.e., type of participant, geographical context etc.
- Type of intervention(s)
- Enablers and barriers of the intervention(s)
- Type of review, design and methods used
- Outcome measurement
- Quality assessment
- Results and findings

See *Annex 5* for the data extraction template that was used.

3.4 Quality appraisal

In the protocol, we proposed to use the ROBIS tool developed by the University of Bristol (Whiting et al., 2016) to assess the quality of the included systematic reviews. However, due to the scope of the RUR and the complexities of the included studies facing us, in discussions with FCDO, an alternative quality appraisal tool was approved. The quality appraisal tool developed by Mader et al. was adapted for the purpose of this study (Mader and and Macdonald, 2022). The tool was initially developed to assess the quality of primary evidence; we modified it to make it fit for purpose for review-level evidence.

A representation of this tool is presented in *Annex 4*. The tool includes the following three domains:

1. ***Cogency:*** Does the study present a convincing causal argument? Is it causal? Is it theoretically grounded?
2. ***Transparency:*** How were the data collected? Were pre-specified eligibility criteria in place? How were the data analysed?
3. ***Credibility:*** Are the findings generalisable? Is the research process logical, traceable and clearly documented? Is there a clear description of how conclusions and interpretations were reached?

Each included study was assigned a grade for each of these domains; a study could be awarded a grade of up to 6 (i.e., 2 points per domain). If a study only partially met a dimension within one of these domains, then a point of 1 was assigned, or 0 if it failed to meet any of the dimensions within any of these domains. If a study scored 0 in any domain, it was excluded. Quality appraisal was conducted by individual reviewers, with a flagging system for a second reviewer to weigh and resolve doubts where scoring was uncertain. Low-quality studies were excluded from the synthesis.

3.5 Analysis and synthesis

Our approach to analysis and synthesis is largely qualitative, combining critical review (evaluating strengths and weaknesses of the evidence covered) and qualitative meta-analysis methods (aggregating findings across the evidence reviewed) to produce a synthesis of the findings (Timulak, 2009). Quantitative elements are only descriptive (e.g., using quantitative data to describe the status of an identified variable) and support the development of graphics and visuals.

The synthesis includes a **mapping** of the landscape to identify how different geographies, intervention types, outcome types and other factors intersect. It also serves to identify evidence clusters and gaps informing the subsequent in-depth synthesis.

3.6 Limitations

Timeframe: The rapid nature of this study was a major constraint given the depth and breadth of the evidence base. Despite streamlining the systematic review approach, many studies had to be combed through in a very short period. With more time, a more in-depth synthesis could be provided.

Period: The timeframe for included studies is another limitation. This study only explores the evidence base from 2019 onwards to keep the scope of the RUR manageable.

Study type: The study type also came with some limitations (see Mallett et al., 2012). While conducting an umbrella review allows for a comprehensive overview of the evidence and can be beneficial for synthesising large volumes of evidence on broad topics, the absence of primary studies and a higher level of abstraction can make it challenging to assess causation. The studies included are also mostly published peer-reviewed journal articles. While our review has attempted to include grey literature where possible, a focus on systematic reviews may overlook much valuable information contained in grey literature, particularly that coming from developing counties where there are barriers to publication in peer-reviewed journals. Heterogeneity can also be compounded in umbrella reviews, making it challenging to draw consistent conclusions.

There is value to conducting umbrella reviews, however, primarily for the following for reasons (Polanin, Maynard and Dell, 2017):

1. They can contribute to the knowledge base, going beyond what systematic reviews and meta-analyses report and examining trends over time, and thus be particularly useful to policymakers, practitioners and researchers.
2. Where many systematic reviews on a given topic exist reporting discordant views, systematic reviews of reviews (also called umbrella reviews) can be particularly useful to make sense of these diverging conclusions by comparing and contrasting the results of multiple systematic reviews.
3. They have the potential to conduct network meta-analysis to allow comparisons of multiple treatment and control groups, assuming the underlying systematic reviews are sufficiently homogeneous.
4. They can point out when systematic reviews need updating again.

Finally, it is worth noting that umbrella reviews also have a role to play in translating knowledge into policy impact (Whitty, 2015).

That being said, there are not many umbrella reviews in the context of global development. It is therefore difficult to find much guidance in the literature, beyond what can be found in the medical arena, on how best to embark on such a review in this area of research. Consequently, there is significant scope to improve methods guidance as well as reporting standards in the context of umbrella reviews in global development.

4 Findings

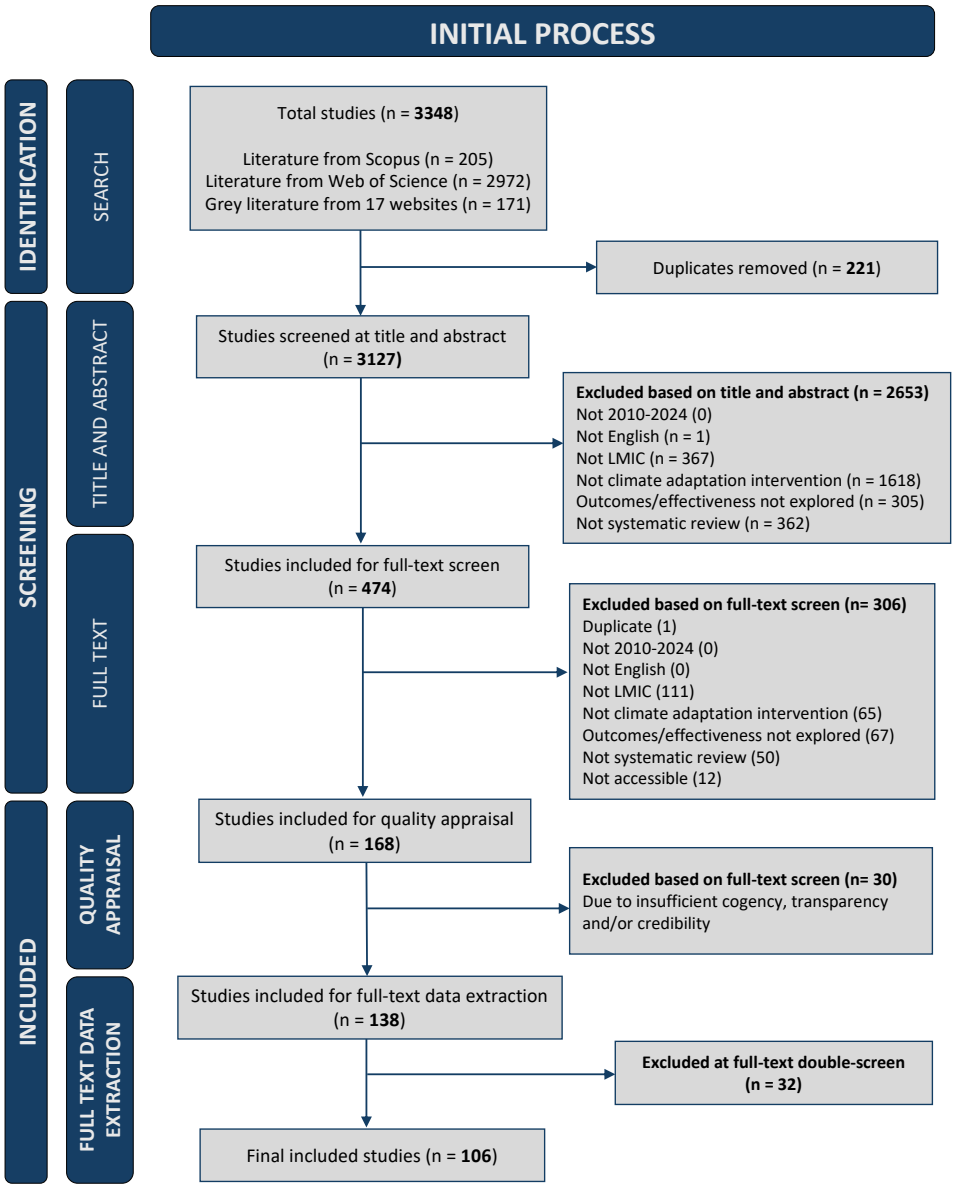
This section presents the study's results and findings. It starts by summarising the landscape of studies identified, highlighting the diversity of findings across different geographies, geography types, and intervention and outcome types. It then explores overall findings from the study, synthesising the evidence to answer the primary and secondary research questions. Findings have been grouped based on prominent intervention types and key themes that emerged from the literature.

4.1 Landscape analysis

106 studies were included in this review, from an initial return of 3,348 documents identified from the searches. Out of the 3,348 total documents, 221 duplicates were removed, with 3,127 studies going through to title and abstract screening. 2,653 studies were excluded at title and abstract level, with 474 studies going through to a light full-text screening. 306 studies were excluded at the full-text stage, with a further 30 excluded at quality appraisal and 32 excluded during data extraction, bringing the final number of included studies to 106. Of the included studies, 36 were categorised as high confidence (with a score of 5 or 6) and 70 were categorised as medium confidence (with a score of 3 or 4) as per the quality appraisal process.

A PRISMA flow diagram is used below in *Figure 1* to summarise study selection.

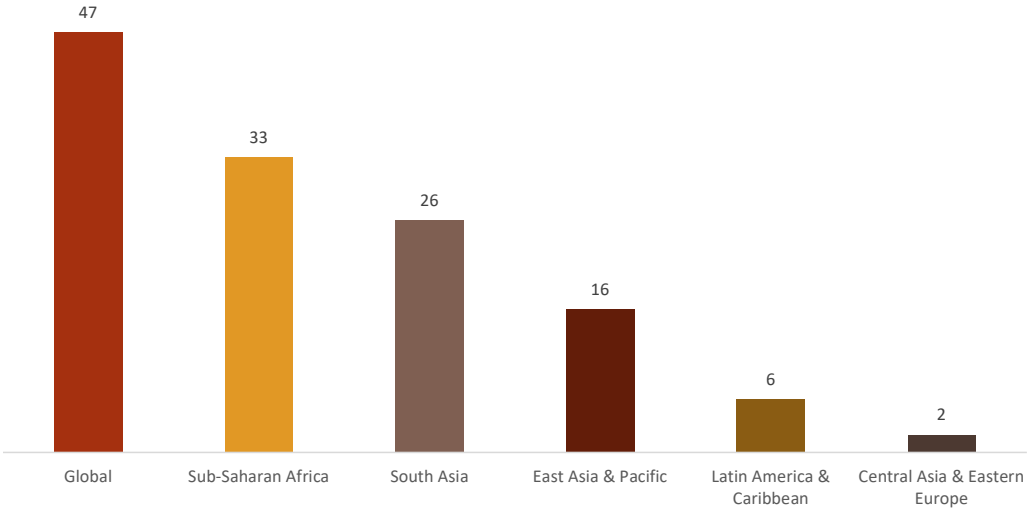
Figure 1: PRISMA diagram



Geography

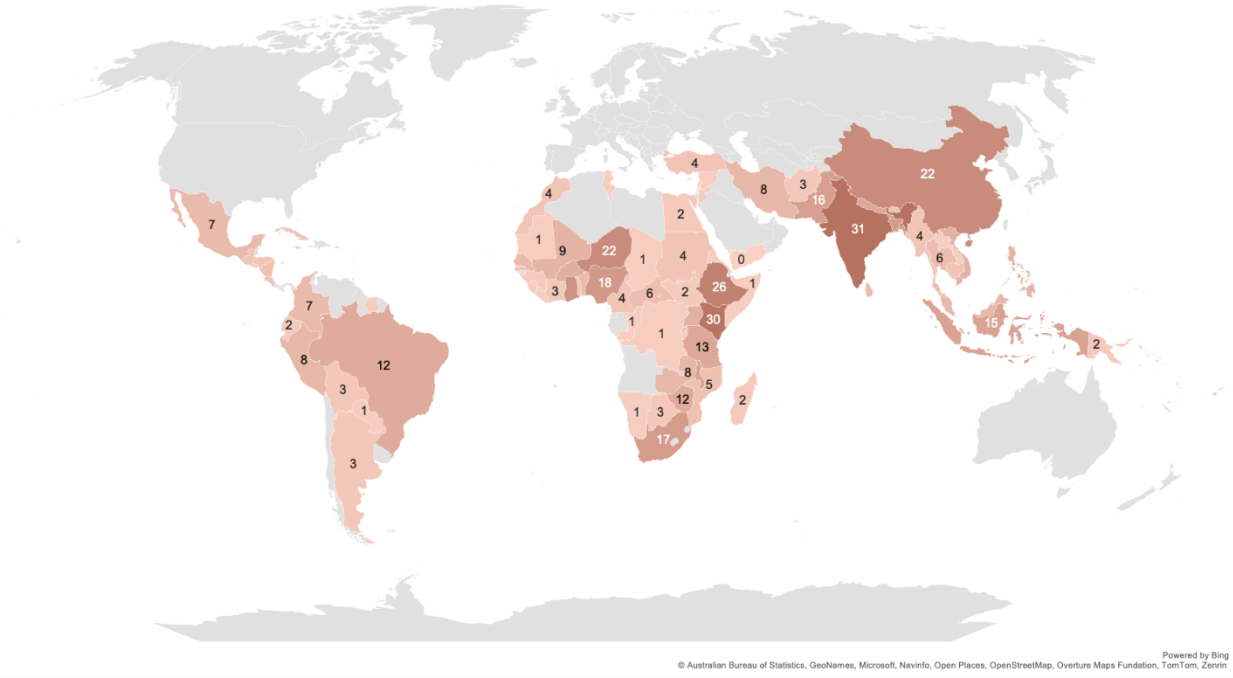
Most studies did not focus on any one region and were categorised as global studies. Global studies were only included where most results were deemed to come from LMICs to avoid a Global North bias in the study findings. Sub-Saharan Africa, South Asia, and East Asia and the Pacific were well represented in regionally focused studies. A far smaller number of studies focused on Latin America and the Caribbean, and Central Asia and East Europe.

Figure 2: Number of included studies by region



The countries most represented in the literature include India and Kenya (31 and 30 studies respectively), Ethiopia (26), China (22), Niger (22) and Ghana (20). Many countries were represented in a small number of studies, with 57 countries mentioned fewer than five times across the literature.

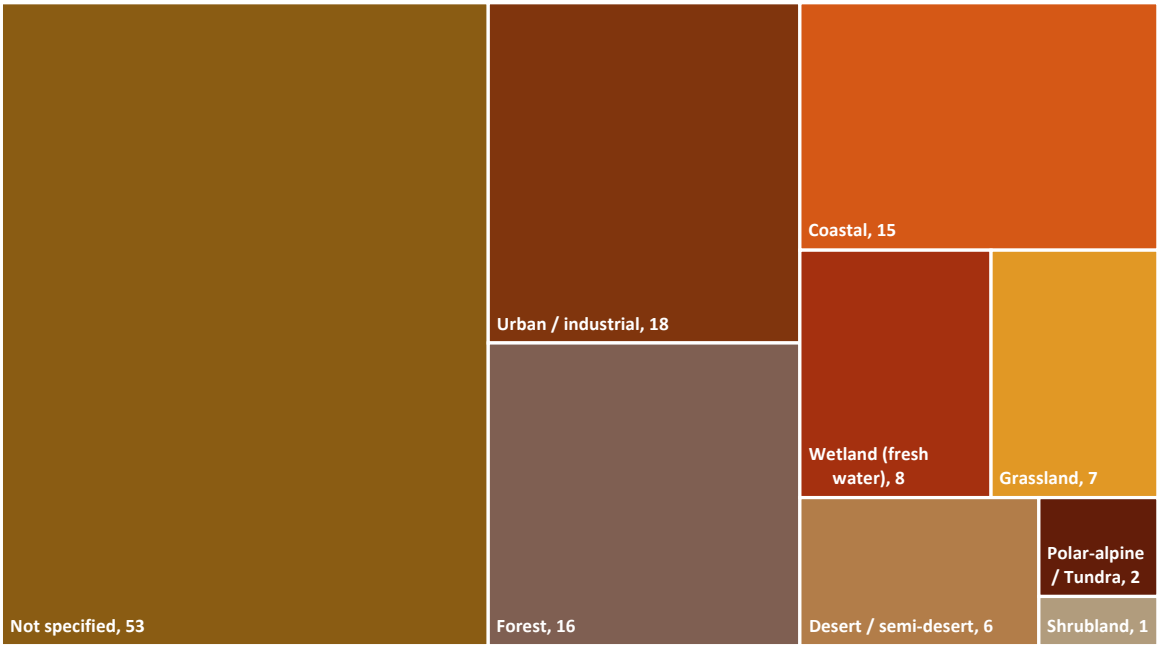
Figure 3: Number of included studies by country[3]



[3] The number of included countries is higher than the number of regions as most studies focused on more than one country.

Most studies (53) did not specify geography type. Where geography type was specified, the largest mentions were for urban/industrial (18), followed by forest (16) and coastal (15).

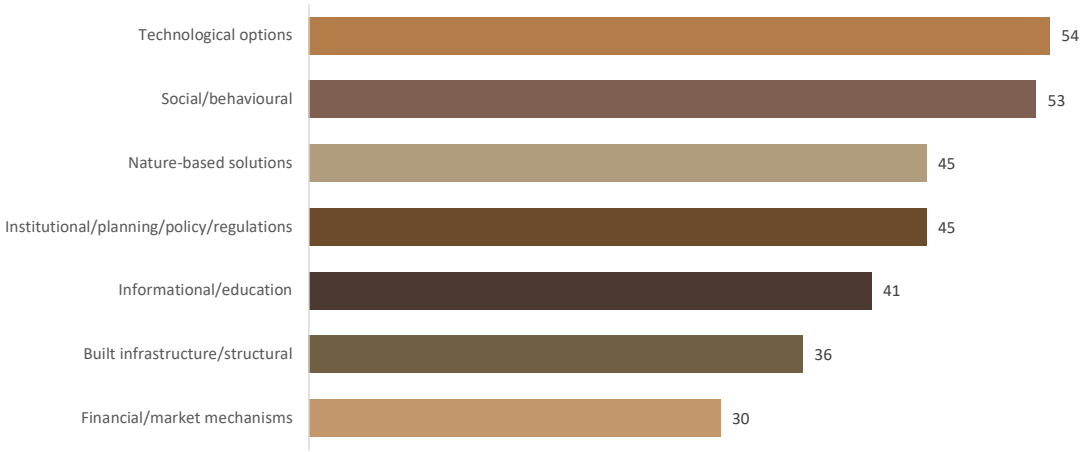
Figure 4: Number of studies by geography type



Intervention type

Findings are reasonably balanced against intervention type. Technological options (54 studies) and social/behavioural (53) interventions were most prevalent in the studies, while built infrastructure/structural (36) and financial markets/mechanisms (30) were the least represented.

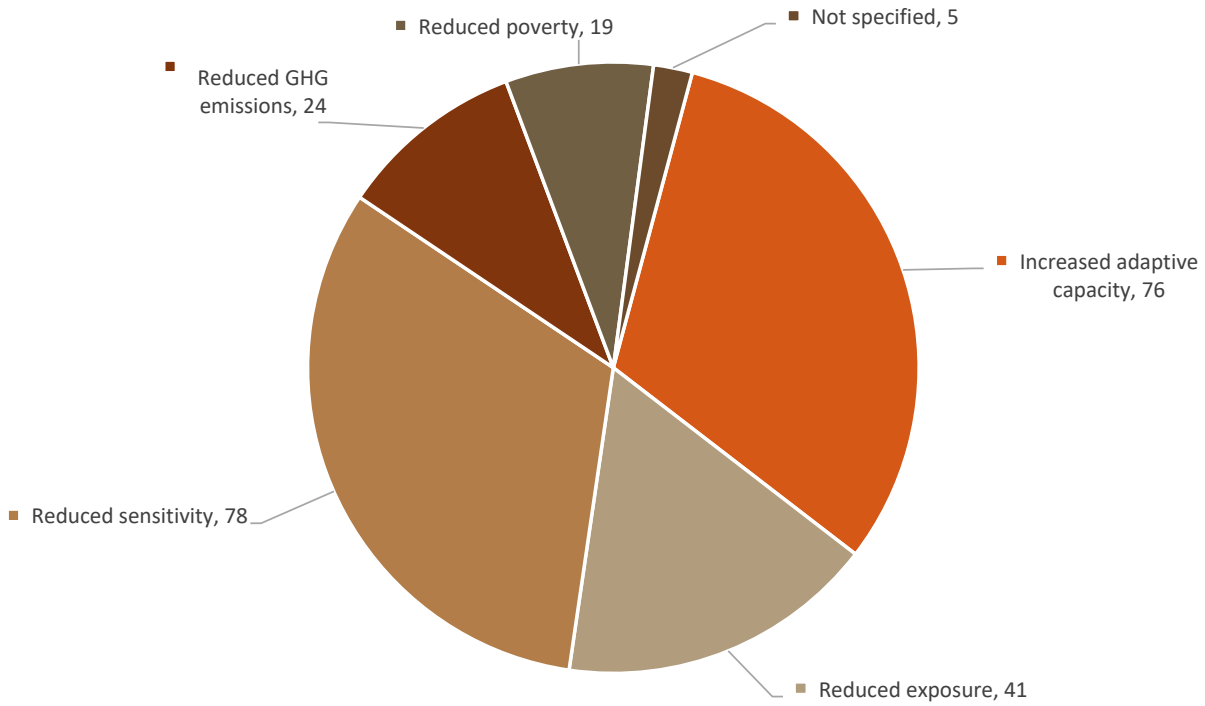
Figure 5: Number of identified intervention types



Outcome types

The outcome areas most frequently mentioned across the studies are reduced sensitivity (78) and increased adaptive capacity (76). Reduced exposure was mentioned in 41 studies. We found lower levels of reporting on co-benefits, specifically reduced GHG emissions (24) and reduced poverty (19).

Figure 6: Findings by outcome



4.2 Summary of findings by adaptation benefit type

This section introduces the three broad types of adaptation benefit used to classify outcomes from adaptation interventions. These are captured in *Table 1* below. The section also provides a high-level summary of key findings on outcomes from across the strategic reviews. Intervention-specific outcomes are explored in more depth in the subsequent sections.

Table 1: Classifying outcome type

Reducing exposure	**Exposure** refers to the contact that people, assets or ecosystems have with a climate risk or ongoing hazard. An intervention provides an exposure benefit if it lowers the frequency and/or magnitude of impacts on a person, population or system targeted by the project.
Reducing sensitivity	**Sensitivity** refers to the characteristics of a system that make it susceptible to harm from a climate risk. An intervention provides a sensitivity benefit if it reduces the impact of a climate-related event on a person, population or system – that is, the event still occurs with the same or greater frequency and magnitude, but the person, population or system is not as affected by the event as before the intervention
Increasing adaptive capacity	**Adaptive capacity** refers to the ability of people or systems to manage climate impacts or realise emerging opportunities. An intervention provides an adaptive capacity benefit if it increases the ability of a person, population or system to manage climate impacts or realise an opportunity emerging from climate change, including by transforming how and where they live. This can happen despite exposure and high sensitivity. Increased adaptive capacity can *enable* efforts to lower exposure and sensitivity.

(Source: Adapted from Carr and Nalau, 2023)

Drawing on recent work, these benefits align with the components of climate risk, the magnitude of which is shaped by the level of physical exposure to a particular hazard, and the subject's sensitivity and adaptive capacity to address the impacts (Carr and Nalau, 2023; IPCC, 2023). The nature of responses to the risk can also shape the character of risk, potentially increasing it.

These benefits are not mutually exclusive. Interventions may contribute to reducing exposure and increasing adaptive capacity at the same time, for example, or may contribute to a specific benefit category that leads to further changes in another benefit category. This is sometimes referred to as co-benefits. For example, technologies that reduce exposure to flooding on a farm can lead to reduced crop loss, stabilising or increasing incomes and, in turn, boosting adaptive capacity to invest in further exposure or sensitivity reductions. Alternatively, interventions that support dissemination of climate information services increase knowledge (and therefore adaptive capacity) of forthcoming risks, thus enabling households to proactively invest in strategies that reduce the sensitivity of their crop to those risks. The difference between the two examples is the nature of the intervention. Uptake of farming technologies targets the farm system, with an immediate exposure benefit which may then lead to adaptive capacity co-benefits. Climate information targets the farmer, who may then use that information in a variety of ways, including deciding to use new farming technologies and techniques. Our approach focuses on the intervention as the starting point for analysis of emergent benefits and co-benefits, looking for associations of particular outcome types with specific interventions as they emerge in the literature.

While these are common concepts, many studies did not use these specific benefit categories to describe changes resulting from interventions. When they did, it was often with little definition. Rather, they reproduced outcomes most used at the primary study level. Reviews also used different units of analysis. For example, some reviews focused on outcomes relating to the particular crop type or farm system, while others focused more on outcomes for farmer or household. Consequently, the team used the outcomes described in the systematic reviews and categorised them using the definitions above, in this case taking the farmer or household as the unit experiencing the benefit. The following section elaborates on the types of outcomes categorised under each adaptation benefit.

4.2.1 Key findings on reduced exposure

Several studies were explicit about how interventions reduced exposure to climate hazards. For example, Villamayor-Tomas et al. compared the efficacy of coastal interventions, stating that *"in the coastal sector, there were positive mean effects for NbS, built infrastructure, informational and institutional interventions. The mean effects were particularly high for institutional and built infrastructure interventions. NbS were more positive in reducing risk of climate exposure than in decreasing vulnerability"* (Villamayor-Tomas et al., 2024).

Specific outcomes relating to exposure varied depending on context. Studies in urban contexts discussed outcomes related to the exposure of houses, infrastructure and people to flooding, storm surges or extreme heat. For example, mangroves reduce the velocity of damaging waves, and tree canopies in parks reduce heat experienced by people in urban centres. Shade from buildings or trees, labour schedules that avoid the hottest part of the day, and some modifications to buildings can all reduce exposure to climate risks. In other cases (e.g., Mzimela and Moyo, 2023), studies referred only to "flood resilience" in relation to moving people to safety.

Few studies offered quantifiable exposure-related outcomes relevant to urban contexts, except one, exploring nature-based solutions (NbS) in Bangladesh (Smith et al., 2021):

> *"Villages protected by mangroves experienced about half the monetary loss from flood and wind damage to houses, property, crops, livestock and aquaculture stock during Cyclone Sidr (TK 69,726 or approximately £1,025 per household), compared to villages without such protection. A 100-meter-deep strip of healthy mangroves can reduce storm surge velocity for a storm of similar magnitude by up to 92%, significantly reducing embankment maintenance costs…"*

Papers detailing adaptations in agricultural settings focused more on the exposure of crops or farms to climate hazards. For example, some pointed out how vegetation cover is created through agroforestry or mulching that protects soil and crops from heat stress and erosion (Dobhal et al., 2024; Ghosh et al., 2024; Mehta et al., 2023; Thottadi and Singh, 2024). The exposure of crops is reduced, which implies that farm productivity is protected.

Migration has a clear exposure benefit, through changing the physical proximity of individuals to climate risks, including where people practice livelihood strategies – for example through labour migration (Legide, Feyissa and Karo, 2024). Exposure can also be reduced by shifting the location of food or income generation activities in ways that spread "risks across space and time" (Mbah, Ajaps and Molthan-Hill, 2021). For example, through shifting cultivation approaches, or crop rotation, or farming in new areas, farmers are less likely to be affected by climate hazards (Chettri, Datta and Behera, 2024). Planning and appropriate information can facilitate more effective reduction of exposure through mobility and migration – for example, by facilitating faster evacuation of vulnerable people from hazard-affected areas.

4.2.2 Key findings on reduced sensitivity

Given the prevalence of studies related to agriculture, it is not surprising that many studies detailed impacts on the yield or productivity of farm systems or specific crops. **We have classified outcomes relating to crop yield or farm productivity as suggestive of sensitivity benefits, on the assumption that an intervention which stabilises productivity or increases yield of a farm system does so while exposure**

to climate risk remains the same. However, for crop yields to then translate into additional vulnerability-reducing benefits (i.e., adaptive capacity benefits), numerous other factors need to be in place, such as access to market, storage facilities, processing capacity, or affordable transport. Climate-smart agriculture (CSA) techniques are frequently associated with stability of production (Mizik, 2021; Chettri, Datta and Behera, 2024; Etana et al., 2022). For example, one study, focusing on the link between agroforestry and income, notes the following (Castle et al., 2021):

> *"The result of the meta-analysis on income suggests that agroforestry interventions overall may lead to a small, positive impact on income, with moderately high heterogeneity in the results. In cases where improvement yields were reported, there were generally attendant improvements in income. In the cases where payments were provided to offset the potential loss in yields, incomes also generally improved, though there were mixed results for the certification programs and the tenure security permitting scheme" (p.2) ... "There is a very small, positive overall effect of agroforestry interventions on income. Increased or neutral income effects are associated with either increased yields providing additional income, or incentive payments offsetting the costs associated with decreased yields" (p.4).*

Another set of sensitivity-related outcome types were loss reductions. For example, reduced crop failures, reduced economic losses, reduced soil erosion, or reduced food insecurity. As above, these outcomes contribute to the continued functioning of a livelihood type while exposure to climate risks remain the same.

Diversification features commonly across the dataset, discussed in the literature as both an adaptation strategy and an outcome of adaptation interventions. Households may choose to diversify income sources to reduce reliance on a specific crop or farming system, or they may participate in a training session or receive access to resources that then leads to diversification, which the literature treats as a positive outcome. Generally, diversification is of livelihoods or farming strategies such as crops or techniques. Intercropping, for example, or combinations of traditional with drought-tolerant seed types, can buffer variability while increasing yields.

4.2.3 Key findings on adaptive capacity

Adaptive capacity hinges on the ability of affected people to make active decisions about their response to climate risks. Adaptive capacity outcomes therefore tend to relate specifically to people or institutions, rather than crops or farming systems. The adaptive capacity of ecosystems does not feature in our dataset. Where adaptive capacity is discussed directly, it is sometimes presented as an outcome, on its own, and occasionally given more definition. For example:

> *"Additionally, Chanza and Musakwa (2022), Berkes and Jolly (2001), Jessen et al. (2022), and Liehr et al. (2017) also reported the contribution of indigenous responses to adverse climate change, such as food insecurity. Using early-maturing crop types, integrating crops and livestock, and involving some of the members of their household in off-farm or non-farm activities all contributed to increasing adaptive capacity"* (Legide, Feyissa and Karo, 2024, p.405).

By contrast, Mehta et al. (2023) are more specific, pointing out that *"Several multi-national and Nepal-based interventions focus on enhancing adaptive capacity by improving resource management and community engagement"*.

No strategic reviews articulated a quantifiable extent of adaptive capacity change because of an intervention, and few made concrete conclusions about the extent to which different interventions might influence adaptive capacity in any clearly defined sense. Several frameworks have been developed to articulate and measure adaptive capacity. For example, the Local Adaptive Capacity framework articulates the types of resources people might need to draw on to facilitate adaptation – their asset base, institutions and entitlements, knowledge and information, innovation, flexible and forward-looking decision making, and governance (Jones et al., 2019). A widely recognised "3A's" framework (Bahadur et al., 2015) focuses on how capacities are used to "anticipate", "absorb", and "adapt" to climate hazards. For this latter framework, there is not always enough detail to make concrete statements about how interventions are driving a particular kind of capacity. Studies frequently report increased income or food security following an intervention, but we are not able to identify how much of these savings are used for absorptive or adaptive purposes.

Features of adaptive capacity defined by the framework are, however, implicit in many of the outcomes described in the systematic reviews. For example, interventions that seek to build knowledge and understanding of climate risks among vulnerable people all contribute to adaptive capacity without having an immediate concrete co-benefit. That is, they then rely on user choices to realise an additional co-benefit. These might include climate information services, digital decision support tools, or awareness raising on the nature of climate risks in a region and the adaptation options available.

We class increased income as an adaptive capacity benefit, as part of an asset base that offers flexibility through savings to respond to a range of risks. Income benefits to people or households are frequently recorded but very rarely is the scale of income benefit made clear, nor the baseline from which it is measured, nor the extent to which other household costs might be rising along with increases in income. Increased incomes are often recorded alongside various agricultural innovations or adoption of new techniques, but not always. Social capital is also considered an adaptive asset and is particularly important for poorer households. Social capital often features as a key adaptation resource that in turn facilitates resource and information sharing.

Adaptive capacity can also be shaped by the right and entitlements available to vulnerable people – for example, their ability to demand or access emergency government support, or access social protection. No systematic reviews sought to understand how policy change or interventions to improve institutional performance affected such right and entitlements. Many reviews discussed the value of participatory tools that include groups targeted by the intervention in highlighting the multifaceted socio-economic factors that drive vulnerability, particularly for CSA-related interventions. However, there is no evidence in the systematic reviews that CSA improves adaptive capacity by enhancing citizens right and entitlements to services. Rather, CSA might be hindered if vulnerable people do not have access to critical resources, particularly land. Conversely, it is more common for reviews to highlight the potential for adaptation measures to exacerbate social exclusion; for example, by restricting community access to forests (Hajjar, Engbring and Kornhauser, 2021).

In general, **adaptive capacity is only loosely defined** and this review has made some assumptions to organise adaptation interventions by their primary benefit.

4.2.4 Intermediate outcomes

Many systematic reviews draw on primary research that is concerned less with adaptation benefits and more with immediate or intermediate outcomes from an intervention. This is particularly the case in agricultural studies – which often focus on farm yield and productivity – but is also the case in other sectors. Examples of intermediate outcomes might include change in terms of impact on farming inputs or farming resources, particularly in relation to soil moisture, water retention, reduced runoff, vegetative density, soil fertility, soil organic matter, or the adoption of new techniques and technologies. In non-agricultural settings, they include "urban density", ventilation, or the use of new technologies. Since these do not lead to adaptation benefits directly, but are a necessary condition for them, we have classed these as "intermediate outcomes". Generally, the literature presents change in these outcomes on the assumption that they will then contribute to adaptation benefits. A summary of repeating outcomes detailed in studies, and our classification of them, is found in *Table 2*.

4.3 Key enablers to effective adaptation interventions

Most studies report on the factors enabling adaptation interventions. We have mapped these and clustered them into four main categories, noting that successful adaptation interventions often include the presence of strong governance and institutions, social capital, access to finance, and the participation and inclusion of affected populations in the intervention design. These are shown in *Figure 7* and explained in more detail below.

Figure 7: Commonly reported enablers across all intervention categories

Social capital: Manifested through trust, reciprocity, and community networks, social capital enables resource pooling and risk sharing during climate shocks. Social capital enables individuals and communities to access information, coordinate actions, and build resilience to climate risks. It is often a precondition for collective action, allowing communities to work together towards shared adaptation goals. Trust and reciprocity within communities underpin these collective efforts, making them more resilient and sustainable. Social capital is a critical enabler of effective climate change adaptation. It strengthens adaptive capacity, reduces sensitivity and exposure to climate risks, and helps buffer against poverty. Adaptation interventions are more likely to succeed and be sustained when they identify,

leverage and strengthen existing social capital, while also addressing inclusion and equity to ensure that the benefits reach the most vulnerable.

Participation and inclusion: The meaningful involvement of local people, especially those most affected by climate risks, in the design, implementation and monitoring of adaptation interventions are fundamental enablers of effective climate change adaptation. Interventions that are participatory and inclusive are more likely to be relevant, accepted and sustained, and to deliver benefits across exposure reduction, sensitivity reduction and increased adaptive capacity. Bottom-up interventions – those that include local communities in planning, decision making and delivery – are better able to draw on indigenous and context-specific knowledge. This helps to ensure that adaptation strategies are tailored to local realities, making them more effective and sustainable. Similarly, when people are included in adaptation processes, for example by including indigenous decision-making processes as part of bottom-up programming, they are more likely to have a sense of ownership over the resulting interventions. This sense of ownership increases the likelihood that interventions will be maintained and adapted over time, even after any external support ends.

Participation and inclusion are not just desirable but essential for effective climate change adaptation. They ensure that interventions are relevant, equitable and sustainable, and that the benefits of adaptation reach those most at risk.

> *"Participatory and collaborative approaches increase ownership of the adaptation, bring together scientific expertise and local knowledge, and are conducive to holistic and culturally appropriate measures that consider climatic and non-climatic vulnerabilities. They thus optimize community or stakeholder buy-in to adaptive interventions which gives them the best chance of being sustained"* (Klöck and Nunn, 2019, p.206).

The integration of traditional and indigenous knowledge through meaningful participatory approaches is also a common theme.

> *"Involving Indigenous communities in climate-related policy making is crucial to capitalise on IK in building adaptation and resilience to climate change. It requires an inclusive approach to decision-making, planning, and management of climate policies (Inaotombi and Mahanta, 2018; Mangada, 2021; Sakapaji, 2022; Tsosie, 2019; Vargas, 2019; Wekesa et al., 2015) and to shift the focus to a bottom-up approach (Inaotombi and Mahanta, 2018; Mangada, 2021; Mensah et al., 2020; Amare, 2018) and in engaging multiple stakeholders (Mangada, 2021; Amare, 2018). Hooli (2016, p.698) contend that it is "very difficult or even impossible" to find sustainable solutions to local socio-ecological challenges without the full participation of local stakeholders. Empowering governance institutions at the local level is necessary to benefit from IK. Governance capacity at all levels need to be empowered (Sakapaji, 2022; Hosen et al., 2020) by investing in human resources, providing access to finance, and improving knowledge management systems (Maliao et al., 2022; Filho et al., 2023) to build adaptation and climate resilience (Sakapaji, 2022). Studies in Africa have highlighted the crucial role of local institutions in supporting local adaptation strategies by providing weather forecasts, facilitating information exchange, and managing resource (Legide et al., 2024)"* (Dorji et al., 2024, p.1118).

Good governance: Governance refers to institutional structures, decision-making processes, and policy frameworks that shape how adaptation interventions are designed, implemented and sustained. WOS366 notes that good governance is necessary for successful adaptation interventions but is often lacking. Effective governance enables localised, context-sensitive adaptation by decentralising authority and resources. Robust governance can also align adaptation interventions with broader development goals. Brazil's National School Feeding Programme (PNAE), for example, linked smallholder farmers to stable markets, incentivising agroecological practices and reducing post-harvest losses. Good governance enables effective adaptation by fostering inclusive participation, resource equity, and policy coherence. By contrast, across adaptation intervention types, top-down processes have been associated with poor adaptation outcomes when not designed appropriately. This can result in decisions that favour one community over another, foster inequality, and reduce adaptation effectiveness (when adaptations are not suitably designed for the context or rejected altogether by intended users). Prioritising decentralised institutions, gender-responsive planning, and hybrid knowledge systems can address systemic vulnerabilities.

Financial mechanisms such as village savings and lending groups, microcredit, and insurance are a critical enabler for climate change adaptation interventions. They enable individuals and communities to access the resources, technologies and inputs needed for adaptation. For example, in Zimbabwe, collective savings and lending groups provided a crucial source of finance for those in need to generate income and invest in adaptation, acting as an essential safety net during climate shocks (Thottadi and Singh, 2024). Without such mechanisms, resource constraints (capital, inputs, technology) are a major barrier to adopting CSA and other adaptive practices (Guja and Bedeke, 2024; Thottadi and Singh, 2024). Insurance payouts and group-based savings also help smallholder farmers and vulnerable households to absorb and recover from climate-related shocks (such as droughts or floods) without resorting to negative coping strategies (e.g., liquidating productive assets). This financial buffering effect strengthens resilience and reduces the risk of falling into poverty (Guja and Bedeke, 2024).

Access to finance allows individuals and groups to diversify livelihoods (e.g., starting small businesses, adopting new crops, or engaging in off-farm employment), which is a proven strategy for reducing vulnerability to climate variability. Financial mechanisms support innovation by lowering the risks and costs associated with trying new adaptation approaches, especially for "first movers" in a community. Concessional finance and microcredit schemes are particularly important for piloting and scaling up innovative adaptation projects (Guja and Bedeke, 2024; Thottadi and Singh, 2024).

Financial mechanisms are a foundational enabler for effective climate change adaptation because they unlock resources, reduce risk, and create incentives for households, communities and institutions to invest in, adopt and sustain adaptation strategies. Their design and inclusivity are crucial for ensuring that adaptation is both effective and equitable, particularly for the most vulnerable. Where robust financial mechanisms exist, adaptation interventions are more likely to succeed and deliver lasting benefits.

4.4 Findings by intervention and approach

From the evidence collected on outcomes and intervention types across the systematic reviews included in this RUR, the review team has mapped out patterns to identify where certain intervention types are most often associated with outcome areas. We have attempted to summarise this mapping in ***Error! Reference source not found.*** below. This table shows, for the 106 studies included in our umbrella review, which outcomes in reduced sensitivity, reduced exposure, and increased adaptive capacity (as well as GHG emissions) are associated with which intervention area. We have also included, where this information was available, the enablers and barriers that affect the outcome area, as well as including any intermediate outcomes where reported. The table therefore identifies interventions that occur frequently across the dataset and presents the outcomes they co-occur with.

Causal linkages from intervention to specific outcomes are not described by this table, owing to multiple constraints. First, the literature is rarely clear on which aspect of an intervention led to an outcome or the mechanisms by which it might have done so; interventions are frequently presented as bundles of activity which are not easy to disaggregate to trace clear causal processes. Second, with all adaptation interventions, characteristics of local contexts shape the nature of the outcomes that follow from the intervention; due to the extreme diversity of populations presented across the literature and in our dataset, we are not able to draw clear counterfactuals between studies. Third, many systematic reviews are not clear on why they selected specific outcomes and why others are not mentioned in the text, leaving some methodological question marks.

For this review, we have included indigenous knowledge and social capital and collective action as intervention types. While these are often discussed as enabling factors that support climate change adaptation, the literature is clear that indigenous knowledge and social capital can also be considered as climate adaptation strategies.[4] Indigenous knowledge, for example, is considered both as a source of specific adaptation actions and as a valuable system to blend with scientific approaches for effective policy and intervention design. Social capital similarly plays a dual role – it enables adaptation by facilitating the flow of information, material support, and collective action, but several studies also report social capital being directly operationalised through interventions such as collective farming, community savings groups, and mutual aid systems. For these reasons, we have included indigenous knowledge and social capital as intervention types in this report, while also referencing them in the enablers section.

Box 2: Summary tables

Each section describes an intervention category and a set of activities associated with it. A table is included at the beginning of each section to provide an overview of the number of papers reviewed informing the detail in that section. The table is intended to support the quality of evidence assessment at the beginning of each chapter.

Where there is sufficient evidence, the table indicates how many systematic reviews (SRs) associated the intervention with outcomes classified by their adaptation benefit (reduced exposure, reduced sensitivity, adaptive capacity). Some intervention types, such as activities related to financial or market-based interventions, are widely mentioned but rarely discussed in detail. In these cases, the summary

[4] See, for example: UNFCCC (2024) *Progress, good practices and lessons learned, challenges and opportunities in the application of traditional knowledge, knowledge of Indigenous Peoples and local knowledge systems in adaptation,* link, and FAO (2021) *Compendium of community and indigenous strategies for climate change adaptation,* link.

table presents typical activities related to that intervention category, and the number of papers where they are mentioned.

Unless otherwise indicated, the tables should not be used to infer reliable causation from certain interventions to adaptation benefits. Nor does the table indicate the magnitude, scale or size of outcome associated with a particular activity or intervention. Typically, SRs were not detailed enough, nor sufficiently methodologically aligned, to make this type of statement.

The table is included for purposes of quality assessment of evidence. It does not indicate causation on outcomes from interventions or activities, nor does it indicate a high likelihood of certain adaptation benefits resulting from the intervention in most or all circumstances.

Table 2: Summary of outcomes by intervention type[5]

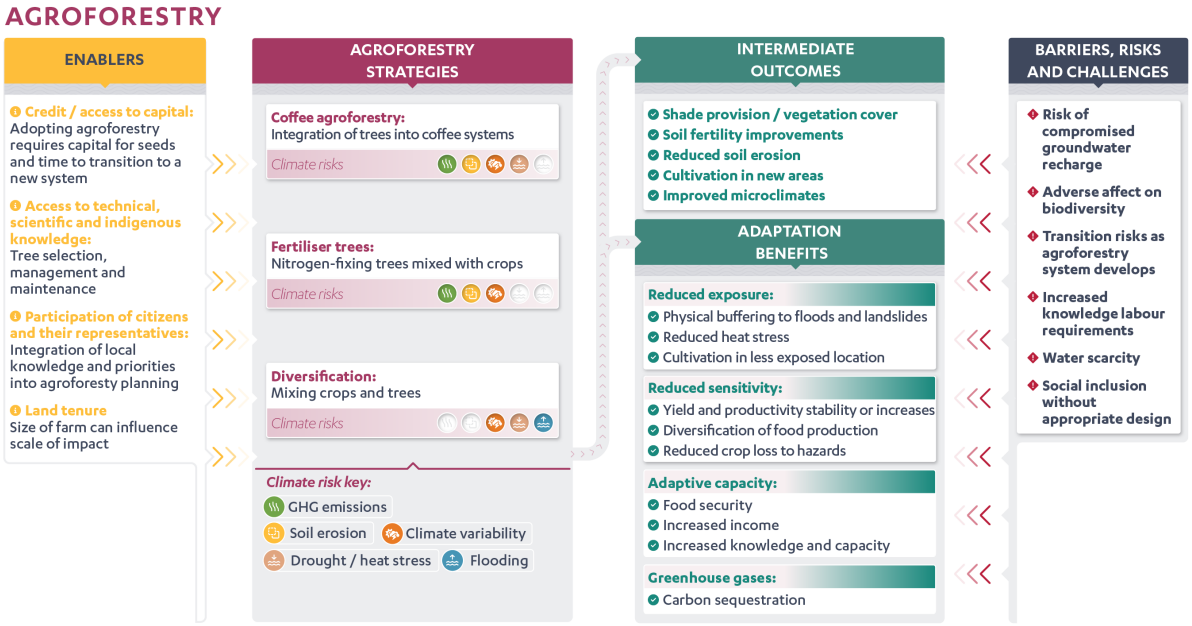
	REDUCED EXPOSURE	REDUCED SENSITIVITY	INCREASED ADAPTIVE CAPACITY	REDUCED POVERTY	REDUCED GHG EMISSIONS	HAZARDS ADDRESSED
AGROFORESTRY						
Coffee agroforestry	Reduced severity and impact of climate hazards	Increased yields	Increased income	Increased income	Carbon sequestration	*Climate hazards, hurricanes, seasonal variability drought, soil erosion and evapotranspiration*
Fertiliser trees	Reduced crop exposure to heat	Increased yields		Increased food crop value	Carbon sequestration	*Low agricultural output undermining adaptive capacity*
Prosopis tree-based agroforestry	Reduced crop exposure to heat, reduced severity of impact of climate hazards	Increased yields	Increased income, food security	Increased income, food security	Carbon sequestration	*Seasonal variability, drought, heat extremes, soil erosion, hurricanes, windstorms*
Diversification (tree intercropping)	Cultivation in less exposed location	Diversity of food production	Increased income	Improved dietary diversity and increased food intake		*Low agricultural output undermining adaptive capacity*
Payment for Ecosystem Services			Increased income		Reduced deforestation	
CLIMATE-SMART AGRICULTURE						
Soil management, crop management and planting techniques	Reduced exposure of crops to climate and to natural disasters (increased yields as a co-benefit)	Increased crop productivity and crop income, reduced climate sensitivity	Increased income Faster productive recovery	Increased income		*Soil degradation and erosion, heat extremes, natural disasters, floods*
Water harvesting		Reduced dry season stress, extended crop cycle, increased yields		Increased income	GHG emissions reduction	*Extended dry seasons, heat extremes, drought*
Organic farming		Reduced input costs, increased yields (over time)	Increased income, food security (limited to farmers able to afford transition)	Increased income (limited to farmers able to afford transition)	GHG emissions reduction	*Drought, flood, soil erosion, pests and disease*
Conservation agriculture		Increased yields, productivity, reduced crop failure, reduced labour costs	Increased income, food security	Food security	Soil organic carbon, carbon sequestration, reduced emissions	*Water stress, soil degradation*
Precision agriculture		Increased yields, increased productivity	Increased income, food security (limited to farmers able to adopt specific technologies)	Food security		*Water stress, crop pests, crop disease*
Diversification	Loss minimisation during drought	Reduced losses, increased productivity	Increased/diversified income, minimised losses, increased productivity	Increased income		*Drought, variability, fast and slow onset risk*
Crop technologies (alternative seeds)		Reduced sensitivity to crop failures		Increased income, food security		*Drought, flooding, saline intrusion*
Zero / minimum tillage	Increased yields due to reduced exposure	Reduced climate sensitivity			GHG emissions reduction	*Water runoff, soil degradation*
CSA training / extension services			Increased knowledge and capacity, increased adoption of new techniques			
DIGITAL TECHNOLOGIES						
Climate information and early warning systems	Reduced crop exposure to heat and flooding	Yield stability/increases, reduced losses	Increased income Knowledge, improved decision-making and capacity	Increased income		*Seasonal variability drought, heat extremes. Soil erosion, hurricanes, windstorms, climate disasters/ hazards*
Water scarcity management (irrigation, water harvesting)	Reduced water stress	Reduced labour costs, water conservation, thermal comfort	Increased income	Increased food crop value		*Drought, water stress, thermal discomfort*
Agriculture technologies (Internet of things, smartphone applications, GIS)		Reduced labour costs, yield stability / increases, reduced losses	Improved knowledge and decision-making			*Seasonal variability drought, heat extremes. Soil erosion, hurricanes, windstorms*
Urban sustainability (planning tools, building technologies)		Thermal comfort	Increased income Informed urban planning	Increased income		*Heat, flooding*

[5] The table identifies outcomes typically associated with particular interventions in the literature. It does not indicate causation or magnitude of effect and does not incorporate considerations of geography and context which are critical to effectiveness.

	REDUCED EXPOSURE	REDUCED SENSITIVITY	INCREASED ADAPTIVE CAPACITY	REDUCED POVERTY	REDUCED GHG EMISSIONS	HAZARDS ADDRESSED
COASTAL ADAPTATION						
Nature-based solutions	Reduced magnitude of storms, surges, waves, reduced erosion, avoided damage to infrastructure	Enhanced air quality, reduced crop losses	Increased income	Reduced poverty	Some GHG benefits due to mangrove planting	*Natural hazards, cyclones, storm surges, soil erosion*
Built infrastructure	Improved flood mitigation. Immediate storm surge relief					*Storm surges, flooding*
Coastal livelihoods infrastructure		Flood management around informal settlements				*Flooding, climate disasters / hazards*
Planning interventions			Increased public awareness of risks and participation in maintenance			*Water stress, flooding*
Behavioural adaptation (community-level adjustments)		Livelihoods diversification	Alternative income sources			*Seasonal variability, climate extremes*
GREEN INFRASTRUCTURE						
Sustainable buildings	Reduced resident exposure to high temperatures, reduced thermal discomfort			Improved wellbeing and improved understanding of sustainable approaches	Improved energy efficiency	*Exposure to high temperatures*
Green urban infrastructure (urban forests and tree planting, reflective roofing)	Reduced resident exposure to high temperatures, reduced pollution, decreased exposure to water-related risks	Reduced urban heat island effect, improved health outcomes, improved physical and mental wellbeing	Improved physical and mental wellbeing	Improved wellbeing and improved understanding of sustainable approaches	Improved energy efficiency, reduced energy demand	*Exposure to high temperatures, water stress*
Ecosystem management	Reduced thermal discomfort	Reduced sensitivity to heat and water-related climate risks	Reduced impact on livelihoods from climate risks	Improved income, food security		*Exposure to high temperatures, water stress*
CLIMATE INFORMATION AND EARLY WARNING SYSTEMS						
Early warning systems	Reduced exposure to climate risks, reduced exposure of key assets, planned (temporary) migration	Increased knowledge and understanding of climate risks of people or institutions, increased preparedness	Increased knowledge and understanding of climate risks of people or institutions, increased preparedness			*Seasonal weather variability, natural hazards / disasters*
Climate information systems	Reduced exposure to climate risks, reduced exposure of key assets, planned (temporary) migration	Increased knowledge and understanding of climate risks of people or institutions, increased preparedness	Increased knowledge and understanding of climate risks of people or institutions, increased preparedness			*Seasonal variability, long-term shifts in climate, long-term shifts in frequency and severity of natural disasters*
Indigenous knowledge forecasting	Planned (temporary) migration, shifting of assets		Increased knowledge and understanding of climate risks of people or institutions, increased preparedness			*Seasonal weather variability*
FINANCE AND MARKET-BASED ADAPTATION INTERVENTIONS						
Credit access	Facilitates reduced exposure of some assets to climate risk	More stable yields	Increased incomes, food security, smoothed liquidity flows and the potential to diversify livelihoods, investments in adaptation techniques and diversification	Increased income		*Climate hazards, reduced rainfall, pests and disease*
Insurance schemes		Improved risk management, asset protection	Improved risk management, income smoothing	Increased income		*Pests and disease, natural disasters, water stress*
Subsidies			Improved uptake of new technologies			*Long-term climate risks*

4.4.1 Agroforestry

Agroforestry features heavily in the studies, with positive outcomes in multiple countries and regions highlighted for reducing sensitivity and building adaptive capacity to multiple climate risks, including drought, flooding, windstorms, and consequential risks such as pests and diseases. A total of 21 systematic reviews focus on or include agroforestry: three explicitly focus on agroforestry and 18 overlap with climate-smart agriculture (CSA). Of these 18 reviews, agroforestry is mentioned to varying degrees: four studies have agroforestry as a main activity under CSA, seven make considerable references to agroforestry while it is not the main activity, and in the remaining seven there is some mention of agroforestry. In terms of geographical coverage, there are seven "global" studies, five studies focused on Sub-Saharan Africa (one of these is SSA/global), four focused on South Asia, two on East Asia and the Pacific, two multiregional, and one on Latin America and the Caribbean.



Confidence in agroforestry as an adaptation to climate risks

Agroforestry can be used to address typical farming risks including storms, drought and flooding. Agroforestry techniques offer protection against soil erosion, pests and diseases. Carbon sequestration is also a valuable potential benefit. Confidence in the robustness of the approach is limited by a widespread assumption that farm-level intermediate outcomes (soil moisture, reduced runoff, reduced soil erosion) will lead to productivity, food security and income benefits. These causal links are poorly articulated, and more research is needed to establish greater confidence in sustainable and long-term adaptation benefits. Most evidence comes from global studies that do not offer systematised regional evidence.

We have medium confidence in the effectiveness of agroforestry to reduce exposure to climate extremes, including flooding, landslides and heat stress. Water absorption, soil strengthening and the provision of shade to people and crops reduce the severity of hazards on people and assets. Agroforestry has been found in the literature to be effective at protecting crops from heat stress as well as flood risk, reducing the magnitude or severity of a range of risks to agriculture. We have medium confidence in the effectiveness of agroforestry to lead

to reduced sensitivity, with particular benefits to drought and flooding. Yield benefits in the face of changing temperatures are widespread, although mediated by farm size and appropriate use of agroforestry techniques. Wheat, millet, cow pea and other crops in particular benefit from windbreaks and shade, and moister microclimates. Reducing runoff and soil erosion appears to be a clear benefit, leading to decreased flood risk on farms. Drought-resistant trees would appear to have these benefits against a range of possible climate futures.

We have lower confidence in the adaptive capacity benefits offered to drought, flooding and higher temperatures. Agroforestry interventions can increase adaptive capacity by supporting income diversification opportunities. Unlike CSA, increased incomes often follow from agroforestry-based yield improvements, but effects are statistically limited, and there is little data on the scale of increase or corresponding changes in expenditure. Agroforestry does have food security benefits when fruit-producing trees are used. Coffee agroforestry emerges as a potential area for investment, but with a significant caveat that climate risks threaten the viability of much coffee-producing land. Agroforestry does have a barrier to entry, requiring appropriate knowledge, capital investment and time for trees to grow before they have any meaningful impact. However, it has more reliable benefits.

Quality of studies

Just over two-thirds of the studies are of medium quality, with six scoring as high quality. Most agroforestry studies in the review highlight impacts on sensitivity and/or adaptive capacity. Studies focused on exposure and/or GHG emissions are split evenly between medium and high quality (

Table 3). As studies tend to cover multiple, overlapping intervention areas and outcomes, there is some necessary double-counting. Most agroforestry studies were peer-reviewed publications, with only one technical report, which is a study that focuses on both agroforestry and CSA.

Table 3: Strength of evidence for agroforestry interventions

	No. medium-quality studies	No. high-quality studies	Total
Intervention	15	6	21
Exposure	4	4	8
Sensitivity	13	3	16
Adaptive capacity	13	5	18
Poverty	3	3	6
GHG emissions	6	3	9

Agroforestry in the literature

Agroforestry is described in the literature through a range (and combination) of interventions designed to promote the integration of trees into agricultural systems. Different types of agroforestry being implemented include improved fallow systems, incorporating trees in crop fields, silvo-pasture, coffee agroforestry (*Box 3*) and agrosilvopastoral systems (Castle et al., 2021), agri-silviculture systems in tropical hot-arid conditions (Dobhal et al., 2024), tree integration, intercropping, silvopastoral systems, mulching, hedges, ecological corridors (Carolina, Alejandra and Nadine, 2024). Specific crops discussed encompass pineapple (Mehta et al., 2023), wheat (Dobhal et al., 2024), and coffee cultivation (under shade trees) (Bracken, Burgess and Girkin, 2023; Dobhal et al., 2024; Castle et al., 2021).

Activities to support agroforestry include: provision of technical inputs, for example, tree germplasm; infrastructure, including terracing, solar dryers which protect coffee beans; farmer capacity strengthening; financial support; tenure security; and incentive systems such as payments for ecosystem services, certification schemes, credit advances, donations, grants, and creation of cooperatives (Carolina, Alejandra and Nadine, 2024; Castle et al., 2021).

Box 3: The role of coffee crops in supporting adaptation

Coffee crops are frequently mentioned in relation to agroforestry. Agroforestry interventions offer several benefits including providing shade, maintaining humidity, acting as windbreaks, and improving soil quality through increased water retention, organic matter, and fertility. These improvements lead to higher yields and help reduce the severity and impact of climate hazards, such as hurricanes, while also decreasing evapotranspiration. The latter is critical for countries like Mozambique where the effects of increasing temperatures threaten the viability of coffee production in the near future. A study in Cameroon found that trees on crop land and coffee-agroforestry influenced subjective resilience – people's self-reflection on their resilience to climate risks. However, limited diversity in tree species reduces nutrient cycling and biodiversity, and excessive shade can reduce yield. In Nicaragua, productivity outcomes of different coffee certification schemes were highly variable based on the requirements established by the certification programme, and these relate to selection bias: i.e., pre-existing differences among farmers under different certification schemes due to differences in programme requirements, as well as differences in the types of farmers who were targeted for the programmes.

> *"Tree diversity and carbon stock trade-offs with productivity were mediated by level of investment in labour and inputs, where farmers with higher tree diversity invested less, had lower productivity, but received a premium price. The certification schemes that required lower investment in labour and inputs tended to have lower productivity and those with higher investment in labour and inputs tended to have higher productivity"* (WOS2627, p.21).

Important enablers identified in the studies include access to information about climate-related threats as a key source of data for coffee smallholders to use in adaptation decision making, as well as access to financial resources, which encourages farmers to implement more sustainable practices. While sustainable practices can be more costly, they can lead to higher profits through premium prices.

Sources: (Dobhal et al., 2024; Castle et al., 2021; Bracken, Burgess and Girkin, 2023)

Systematic reviews describe agroforestry in terms of the intended benefits and as an effective adaptation strategy for climate change since it can help to improve soil health, increase biodiversity, and provide shade and wind protection for crops. It can also reduce soil erosion and improve water quality (Zenda and Rudolph, 2024; Bracken, Burgess and Girkin, 2023). Additionally, agroforestry can help to mitigate climate change by sequestering carbon. Bahadur et al. (2022) note that agroforestry may be a potential counterbalance to the impacts of agricultural intensification: increased runoff from intensive cultivation and decreased runoff from agroforestry or perennial cropping. Secondary benefits mentioned include additional food, fuel wood, and various ecosystem services (Abegaz et al., 2024).

Outcomes associated with agroforestry

Findings on agroforestry are more clearly related to adaptation outcomes in studies that focus on specific contexts and geographies. However, there is a tendency to assume that adaptation outcomes have been achieved as a natural consequence of "intermediate" outcomes, rather than measured explicitly. Overall, both positive and negative results of agroforestry interventions are captured across a range of studies and geographies providing some good and convincing examples in specific locations. These may be applicable to other, similar contexts.

For most systematic reviews, disentangling the outcomes attributable to agroforestry activities is not possible, as there is a tendency for interventions to be bundled together, typically under a CSA umbrella. For example, Villamayor-Tomas et al. (2024) (global SR: China, multi-country studies, India, Pakistan, Bangladesh, Ethiopia and Kenya) report that in the agriculture sector, all intervention types except for technological interventions had positive mean effects on reduced exposure to varying degrees. Latin American experience suggests that *"agroecological plots consistently have more topsoil, less erosion, more vegetation and lower economic losses than conventional plots*" (Carolina, Alejandra and Nadine, 2024, p.239).

Reduced exposure

A small number of studies, eight in total, provide evidence that agroforestry supports reduced exposure to climate risk or ongoing hazards. The studies are split evenly between high and medium quality. Agroforestry interventions in India and Pakistan emphasise reducing exposure by creating physical buffers against climate hazards (Mehta et al., 2023). In India, restoration of forests in Uttarakhand and Manas Tiger Reserve reduces exposure to climate extremes because the forests act as natural barriers against flooding and landslides. In Pakistan, forest conservation in 12 villages surrounding protected forests decreases exposure to desertification and heat stress by preserving vegetation cover. These initiatives protect both human settlements and agricultural lands from direct exposure to climate risks.

Also in South Asia, a review focusing on the effectiveness of NbS in Bangladesh for addressing climate change, natural hazards and other sustainable development goals reported that protecting and restoring terrestrial forests reduces soil erosion, nutrient loss and annual runoff (Smith et al., 2021). In addition, *"local tree species with deep tap roots could successfully stabilize steep slopes at risk of landslides although this is only suitable for slopes of less than 70 degrees"*. Agroforestry also potentially allows for adaptation in terms of reducing exposure of previously uncultivated land, as evidenced in Nepal. To cope with increasing temperatures, Himalayan farmers adopted altitudinal farming methods, including agroforestry, which have made previously neglected high hill areas suitable for cultivation (Chettri, Datta and Behera, 2024).

Reduced sensitivity and increased adaptive capacity

Sixteen studies provide evidence for reduced sensitivity due to agroforestry, 13 of medium quality and just three of high quality. Adaptive capacity is covered in 18 studies, 13 of medium quality and five of high quality.

Positive outcomes of agroforestry interventions in multiple countries and regions are highlighted in these studies for reducing sensitivity and building adaptive capacity to multiple climate risks, including drought, flooding, windstorms, and consequential risks such as pests and diseases. Agroforestry interventions reported improved soil health, increased yields (and incomes), improved water quality and

biodiversity – all contributing to sensitivity reduction and adaptation (for example, Snapp et al., 2021). Diversifying crops and trees grown on the farm brings several benefits, including increased income sources that continue to operate when cash crops are no longer an option (firewood, tree fruit, wood products), reduced pest and disease outbreaks, and improved food, security, provision of shade and alternative nutrients for livestock, and stability (Castle et al., 2021; Dagunga et al., 2023; Dobhal et al., 2024; and many others). One intervention standing out in East Africa is "home gardens" – locally kept household gardens including trees and crops. Studies note that these are "multifunctional", providing shade, income opportunities, subsistence, and asset creation (Muthuri et al., 2023).

Examples of the effectiveness of agroforestry are evidenced by improved yields, present in systematic reviews for a range of geographies and contexts. In Castle et al. (2021), the meta-analysis for impacts on yields indicated that agroforestry interventions may lead to a large, positive impact on yield (and increased incomes generally followed on from this), although there was high heterogeneity. For example, the impact of fertiliser tree adoption on food crop value (defined as the yield of all food crops per year multiplied by the farm gate price for each food crop that year) was found to have a significant, large and positive impact on crop value (35% increase) in Malawi. However, households with land holdings of fewer than two acres experience the greatest benefits from adopting fertiliser trees that fix nitrogen into the soil: *"Farmers with land ownership of less than one acre averaged an 82% increase in the food crops value from adopting fertilizer trees, and farmers with between one and two acres averaged a 66% increase in food crop value with fertilizer tree adoption"*. There were also positive yield impacts for soil fertility replenishment practices, including incorporating trees in agricultural fields, and improved fallow practices in fields where there are severe soil fertility issues.

Full benefits on crop yields may be unclear due to timeframe considerations. Farmers in Middle Nyando region (Kenya) tended to have increased yields with agroforestry practices from fruit production, although the timeframe of the study (four years since the programme began) meant that full benefits are potentially yet to be realised, and the results were not significant. The importance of timeframes is also seen in Carolina et al. (2024) – enough time needs to elapse for the full benefits of agroforestry to be realised. One study found that: *"Short-term tree species in agroforestry systems may increase crop yields by 200%; this leads to an increase in biomass, and crop residues may further be incorporated in the soil as mulch or utilized as feed for animals"* (Akinyi, Nganga and Girvetz, 2021, p.137).

When agroforestry systems provide tree shade in hot, arid conditions, there is a range of evidence that this improves climatic conditions. An example of this is where shade has supported windbreaks that have protected wheat crops, leading to increased yields in India (Dobhal et al., 2024). This demonstrates the important role of agroforestry in enhancing the ability of the wheat crop to withstand extreme temperatures. Also in India, Prosopis tree-based agroforestry – a type adapted to arid and semi-arid regions to provide shade and soil quality – has had positive impacts on a range of crops (cow pea, cluster bean, pearl millet, mustard, taramira, wheat and mung bean) due to the way it changes the microclimate in reducing soil and air temperature. Similar effects have also been seen in various studies in Africa. Examples include those where establishing drought-tolerant trees and crops has been shown to help alleviate high-temperature- and low-rainfall-induced drought conditions (such as in Niger – in Dobhal et al., 2024).

Agroforesty schemes are often also associated with payments for ecosystem services (PES), which incentivise forest protection or tree planting. **It is notable that the evidence for adaptive outcomes from PES schemes is both limited and reports mixed outcomes.** Effects of PES on incomes are reported as

either positive but small, or positive only for male-headed households – even then, this evidence is reported as low quality (Castle et al., 2021; Ategeka et al., 2024). Other evidence, reported as low quality, indicates decreases in deforestation resulting from PES in Sub-Saharan Africa (Snilsveit, 2019). As noted in the section below, these poorly evidenced benefits must be weighed against the concurrent risks and challenges of such schemes, relating to financial, transaction and maintenance costs, the time needed to see benefits, and the need to apply appropriate knowledge and techniques.

GHG emissions

Ten of the agroforestry-related reviews mention GHG emissions as a benefit of activities, six of medium quality and four of high quality. However, just two present quantitative estimates.

One review provides quantitative estimates of sequestration and other benefits resulting from agroforestry under CSA (Smith et al., 2021). Mixed evidence is provided in another review, with contrasting examples from Ethiopia, comparing farmlands with "climate-smart agroforestry" (CSAF) – described as a type of intensive agroforestry approach to agriculture, and Banyuwangi Regency, Indonesia, comparing cocoa monoculture and CSAF (cocoa-coconut) (Ntawuruhunga et al., 2023).

For Ethiopia, the study finds that the soil organic carbon (SOC) stock is not significantly higher under CSAF compared to farmland:

> *"The (SOC) stock under the chrono-sequence of 12–50 years of CSAF and farmland use varied from 28.2 to 98.9 Mg ha−1 or 12 to 43% of the stock under the natural forests. The SOC was less by 6.2 Mg ha−1 year−1 for CSAF12 and 0.9 Mg ha−1 year−1 for CSAF50 compared with natural forests. The corresponding values for farmlands were 6.6 and 1.3 Mg ha−1 year−1. The N values of all land uses were also less than that of natural forests. The SOC and N stocks tended to be less in farmlands than in traditional crop-tree integration systems. Results suggest that SOC stocks were not significantly higher with CSAF compared with farmlands, suggesting that the parkland systems as practiced are not sufficient to overcome other effects of cultivation"* (Ntawuruhunga et al., 2023, p.11).

While in Banyuwangi Regency, Indonesia, CSAF practices contributed more to reduced GHG emissions:

> *"The study aimed at evaluating the environmental performance of cocoa production from cocoa monoculture and cocoa-CSAF by life-cycle assessment based on ISO 14040 and 14,044, with adaptation for local impact indicators. The farms were purposively selected and data were collected in cocoa monoculture and cocoa-coconut CSAF. The analysis considered cocoa production at the farm level, from cradle to on-farm gate boundary, for 1 metric ton of cocoa pods. The results showed that cocoa-coconut CSAF had the least contribution to global impact categories of global warming, acidification, and eutrophication, accounting for 3.67E+01 kgCO2-eq, 4.31E-02 kgSO2-eq, and 2.25E-05 kgPO4-eq, respectively. Moreover, results showed that cocoa-coconut CSAF also had the highest organic carbon and soil organic matter conditions supporting the growth and activity of beneficial soil micro-beds"* (Ntawuruhunga et al., 2023, p.122).

Poverty reduction co-benefits

While positive impacts on yields and knock-on benefits in terms of increased incomes are noted in six studies (three of medium quality and three of high quality), there is not enough evidence to determine the direct poverty co-benefits of agroforestry interventions. Systematic reviews note that NbS can support income diversification opportunities and empower marginalised communities. Villamayor-Tomas et al. (2024) also find that *"NbS can have positive effects of crop diversification, water conservation and coastal habitat restoration on crop-yields, food security and poverty reduction, respectively*". Castle et al. (2021) found insufficient *"comparable evidence to quantitatively synthesize the impacts of agroforestry interventions on nutrition and food security outcomes, though the results indicated positive or neutral impacts on dietary diversity and food intake were likely"*.

Notable examples from individual contexts include a significant increase in both expenditure per capita and cash income per capita. Castle et al. (2021), for example, note a significant gain in income and expenditure resulting from a PES programme supporting the planting of trees on farms (along field boundaries or intercropped) for carbon sequestration in Mozambique. But *"for women-headed households and poor households, however, these gains were not observed. Women-headed households had a decrease in expenditure per capita and much lower magnitude increase in cash income per capita than the full population. Poor households had a small increase in expenditure per capita and in cash income per capita. These results for women-headed and poor households were much smaller than for the general population and not statistically significant from zero"* (Castle et al., 2021, p.23). A study in Western Kenya found positive statistically significant impacts on wealth among farmers who had their trees for four years, long enough for them to become productive and generate additional income.

Improved incomes generally follow on from yield improvements due to agroforestry practices, but direct income effects are statistically insignificant in relevant studies. For example, one study found: *"There is a very small, positive overall effect of agroforestry interventions on income. Increased or neutral income effects are associated with either increased yields providing additional income, or incentive payments offsetting the costs associated with decreased yields"* (Castle et al., 2021, p.4). The effect on incomes of measures to offset potential yield losses depends on the mechanisms used. *"In the cases where payments were provided to offset the potential loss in yields, incomes also generally improved, though there were mixed results for the certification programs and the tenure security permitting scheme"* (Castle et al., 2021, p.2).

Food security benefits are also highlighted as a positive outcome of agroforestry across several locations with varying degrees of evidence. In Nepal, sustainable agro-ecosystem management for smallholder farmers in Kavre District reduces sensitivity by enhancing food security and socio-economic wellbeing, making communities less vulnerable to climate shocks. In Bhutan, the holistic management of the Phobjikha Conservation Area and Puna Tsangchu Riparian Forest enhances biodiversity and water security, reducing the sensitivity of local populations to habitat degradation and food shortages (Mehta et al., 2023). In the case of Kenya, communities receiving agroforestry advice from an NGO increased the dietary diversity score by 1.22 and increased the number of food groups consumed by 2.291, out of 12 food groups analysed (Castle et al., 2021, p.24). In Zambia, improved fallows increased food security by increasing production of maize, leading to increased incomes from maize crops, although here the evidence base is thin.

Differential impacts across social groups

There is relatively scant mention of the differential impacts of agroforestry interventions on different types of social groups in the strategic reviews. In the Castle et al. review, which is specific to agroforestry, several studies explicitly considered variable impacts across different population sub-groups, including differential impacts on smallholders versus large-holders, on woman-headed households versus male-headed households, and on richer groups versus poorer groups. As expected, given the nature of the interventions, smallholder farmers typically experienced the most positive effect sizes due to agroforestry interventions. However, women and poorer groups experienced mixed outcomes relative to men and richer households (Castle et al., 2021, p.4).

Enabling factors

Key enablers of agroforestry uptake in the strategic reviews include:

- Access to finance: availability/lack of availability of specific resources and funding to drive uptake (Mehta et al.. 2023; Dobhal et al., 2024)
- Access to/incorporation of specific types of knowledge (i.e., technical, scientific, indigenous) (Mehta et al., 2023)
- Participation of citizens and/or their representatives (Mehta et al., 2023) and behavioural changes of targeted groups (Dobhal et al., 2024).

Barriers, limitations and maladaptation risks

Maladaptation: *"Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence."*

IPCC, 2022, AR6 Glossary

Several studies highlight potential maladaptation effects of agroforestry. One study highlights unintended consequences of tree planting, noting that landslide and soil erosion control in catchment areas through tree planting might compromise groundwater recharge (Mehta et al., 2023). Programmes involving the use of exotic species and monoculture for plantation can also adversely impact an area's biodiversity. Another study explores the opportunity cost of agroforestry interventions, noting that in rural Xinjiang, China, a reported negative effect is on incomes, since the additional time needed to manage the agroforestry systems has reduced off-farm income opportunities (Castle et al., 2021).

Systematic reviews identify several barriers that may prevent or deter farmers from adopting promoted agroforestry practices. The Castle et al. review, for example, highlights increased labour requirements, increased difficulty in farm management, lack of market access, and long waiting times for the accrual of benefits from planting trees, which may act as disincentives to agroforestry (Castle et al., 2021). Dobhal et al. (2024) also highlight the limited technical capacity of farmers as a barrier. Challenges to uptake also include land tenure security. Where land tenure is not secure, farmers may be reluctant to invest time and resources in agroforestry system management (Castle et al., 2021).

Overlooking women, extremely poor people and other socially marginalised groups in the design and implementation of agroforestry interventions can lead to exclusion from the benefits, or a disproportionate impact of negative effects (Castle et al., 2021).

Implications for practice

Agroforestry is widely recognised as an effective climate adaptation strategy in diverse contexts, with evidence from multiple countries and regions showing positive outcomes for reducing sensitivity and building adaptive capacity to climate risks. Realising these benefits, however, requires overcoming adoption barriers, ensuring inclusive design, and supporting enabling conditions for sustained impact. Practical considerations include the following:

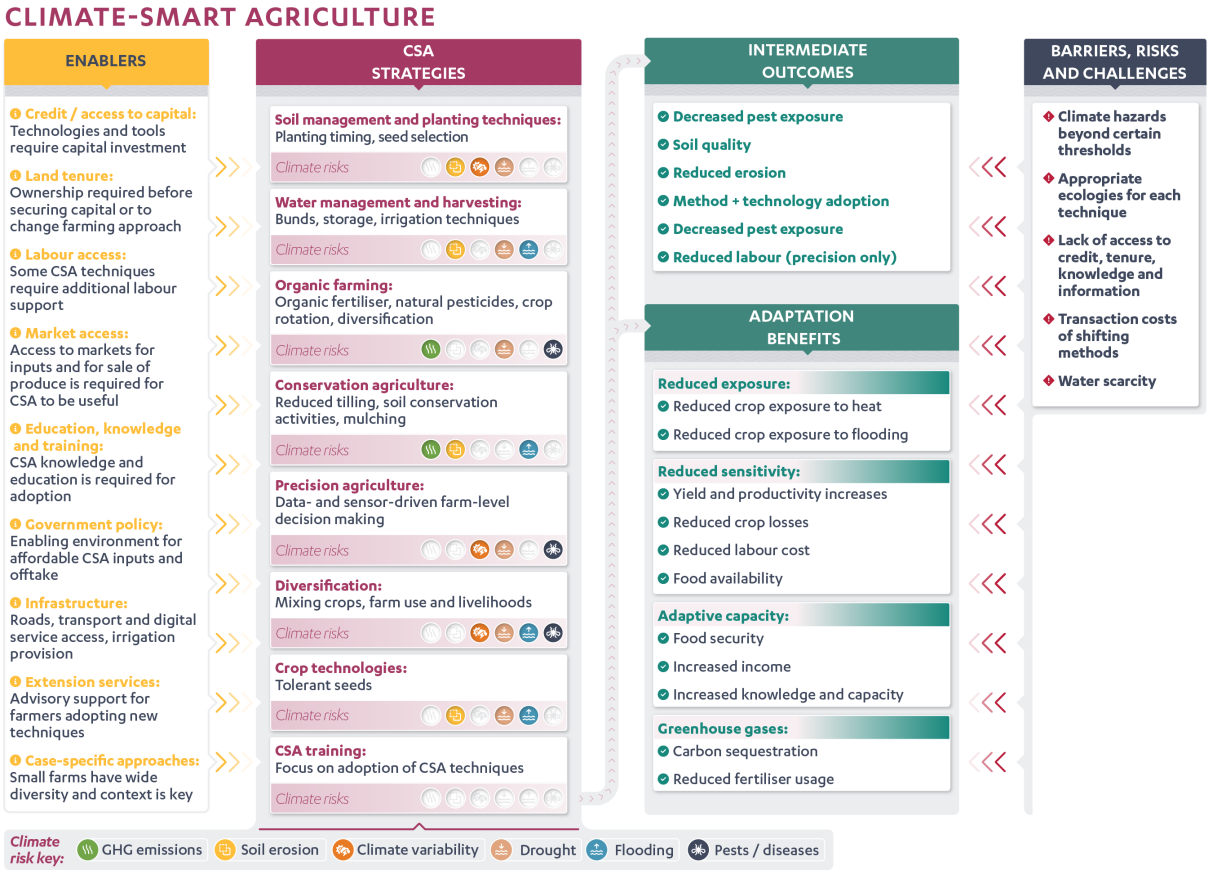
- **Support enabling environments:** Strengthen land tenure security, provide financial incentives, and invest in farmer training and extension services.
- **Prioritise inclusive and participatory approaches:** Ensure that interventions are designed to reach and benefit women, smallholders and marginalised groups. Interventions can be designed for this through participatory approaches that integrate communities into the planning and implementation process.
- **Monitor and evaluate outcomes:** Track both intermediate and final adaptation outcomes, including yield, income, food security and social equity, to inform adaptive management and understand how agroforestry leads to adaptation benefits.
- **Design for context:** Tailor agroforestry interventions to local ecological, social and market conditions, and avoid one-size-fits-all approaches. Participatory planning approaches can help to articulate local specificities.
- **Plan for the long term:** Recognise that full benefits may take several years to materialise and communicate this clearly to participants.

4.4.2 Climate-smart agriculture

Fifty-two studies discuss Climate-Smart Agriculture (CSA), 18 of which also include agroforestry. They cover a wide range of geographies and regions. CSA aims to increase agricultural productivity, facilitate adaptation to climate variability and reduce the experienced impacts of climate change.[6] Overlapping with agroforestry (and sharing some of the same techniques), CSA covers a wide range of approaches and strategies. Crop management practices and technologies are dominant strategies, including crop diversification, incorporating drought-tolerant varieties and early maturing crops, and changing planting dates. Studies looked at both the effectiveness of efforts to encourage adoption of CSA – enablers to its use – and the effectiveness of CSA in reducing climate risk. Activities are often implemented in a "bundle" and fall within the "domains" captured below in

Box 4.

[6] https://www.gov.uk/government/publications/climate-smart-agriculture-a-thematic-review



Confidence in climate-smart agriculture as an adaptation to climate risks

Typically, the types of climate risk faced by smallholders include greater variability of rainfall and growing seasons, increasing temperature extremes, more frequent droughts and floods, soil degradation and reduced water availability, and increasing incidence of crop pests and diseases. Some regional variations include greater incidence of flooding and saline intrusion in coastal areas and islands, and glacial melt in mountainous regions. Many reviewed papers make a significant assumption that targeting farm productivity will address climate hazards through reduced vulnerability (i.e., by addressing low income, unproductive farms, low knowledge).

We have high confidence that many CSA techniques, particularly those that enhance soil moisture retention and soil health, such as conservation agriculture, mulching, and integrated soil fertility management, reduce the sensitivity of smallholders to a range of climate risks, particularly to drought and water scarcity. Yield stability or increases despite variability are widely reported, often through low-cost measures (e.g., adjusting planting times, or the use of mulching). Modified crops to resist droughts, flooding or pests can be more effective, but have a higher cost outlay. Similarly, irrigation is widely effective for maintaining productivity for those with means, with evidence of positive economic returns and reduced poverty levels. As elsewhere, a combination of strategies such as irrigation and water management with other forms of CSA and crop management or technologies is particularly effective at reducing sensitivity to drought. Flood resilience measures often require coordination with

others (for example, through terraces, bunds, soil management) or some level of investment in rainwater harvesting or drainage. These sensitivity-focused measures enable poorer smallholders to "absorb" climate risks, and little more.

We have low confidence in the ability of CSA techniques and interventions to create the adaptive capacity co-benefits needed to reduce vulnerability, particularly for lower-income households. Evidence for conversion of productivity into income or food security is limited. Where higher incomes do emerge, they are not offered with any context of changing expenditure, household power relations, labour, land or inflationary costs. Food security benefits are recorded, but with no qualification of scale, magnitude or durability. Further, low-income households have less ability to invest in potentially transformative adaptations. Conversely, higher-income households are more able to access and utilise knowledge, invest in technologies and products, and apply them effectively. There is evidence that many contexts have limited potential for CSA as adaptation – past a certain level of warming, CSA will not be sufficient to facilitate continued agriculture.

The literature is very clear that access to knowledge of climate-smart techniques, extension support, and the integration of local or indigenous knowledge into any new techniques is a requirement for adoption and scaling of CSA approaches. Confidence in efficacy for adaptation would further rise if CSA is implemented in concert with other interventions and with a focus on enabling factors – in particular, integration of local and indigenous knowledge systems.

Box 4: List of climate-smart agriculture strategies identified in the review

- Pest-tolerant and climate-resilient seed technologies/varieties (early maturing varieties, drought-resistant, stress-resistant, flood-resistant, improved legumes, small grains, winter ploughing, drought-tolerant maize, and new seed varieties)
- Crop management (including crop breeding, sowing and harvest time management and crop rotation)
- Integrated pest management (IPM)
- Conservation agriculture (reduced or no-till farming, cover cropping, and residue retention to improve soil health, enhance water infiltration, and increase carbon sequestration)
- Agroforestry
- Improved water management, irrigation and rainwater harvesting, precision irrigation
- Fertiliser management (e.g., reduce GHGs)
- Soil health and land management (e.g., cover cropping, zero-till farming, and the use of organic matter to enhance soil structure, soil fertility (compost, earthworm humus, cover crops, manure, fallows, biopreparations), and carbon storage. Organic farming; biodiversity management (intercropping, crop rotation, conservation of native species and seeds)
- Post-harvest management (storage, processing and transportation)
- Technology adoption (e.g., precision agriculture, remote sensing, data analytics)
- Livestock management (improved livestock feeding, rotational grazing, manure management)
- Knowledge dissemination (training/FFS, extension services, information about CSA practices)
- Financial incentives (subsidies, credit, and insurance programmes)

Quality of studies

Of the 52 studies mentioning CSA, 18 (just over one-third) are rated as high quality, with 34 of medium quality. Studies tended to cover multiple intervention areas falling under the CSA umbrella as well as reporting on multiple types of adaptation outcome, so the figures in *Table 4* reflect these overlaps, with a degree of double-counting. Most studies were peer-reviewed publications, with only three technical reports included in the evidence base for CSA.

Table 4: Strength of evidence for CSA interventions

	No. medium-quality studies	No. high-quality studies	Total
Intervention	34	18	52
Exposure	9	7	17
Sensitivity	25	14	39
Adaptive capacity	23	14	37
Poverty	8	9	17
GHG emissions	12	7	19

Twenty of the 53 studies are global in focus, with additional studies having regional focus on Sub-Saharan Africa (18), South Asia (10), East Asia and Pacific (5), and just one study covering each of Latin America and the Caribbean, and Middle East and North Africa. Again, there is some overlap and therefore some limited double-counting. Many of the studies do not offer findings with much regional specificity, reiterating the value of context-based approaches.

Effectiveness of CSA

CSA can be an effective adaptation approach that has positive effects on outcomes such as food security. But success depends heavily on interventions implemented in concert and may be eroded in the face of shocks and stressors. There is wide-ranging evidence for improved soil quality and fertility outcomes, including through interventions to curb erosion, that increase yields, support incomes and result in fewer economic losses (Carolina, Alejandra and Nadine, 2024; Wekeza, Sibanda and Nhundu, 2022; Guja and Bedeke, 2024). This is discussed in detail in the following subsections.

CSA is typically more effective when multiple interventions are implemented as a package to support and complement each other (Thottadi and Singh, 2024; Chettri, Datta and Behera, 2024). An example of lack of integration of soil and water conservation (SWC) interventions leading to lacklustre programme performance is highlighted in Abegaz et al. (2024):

> *"…until 2015, under the integrated watershed management program, over 1.7 million ha of land were treated under area closure, and on over 2 million ha of land, physical and biological soil conservation measures were applied in different parts of Ethiopia (FAO, 2016). Although the adoption status of this practice is rated as high, many studies claimed that SWC did not adequately address the decline of soil fertility and agricultural productivity (Fikirie et al., 2018; Mulualem and Yebo, 2015) and the achievements were far below expectations, because many of the SWC components have not been well integrated with other soil fertility management practices (Lemma et al., 2015)".*

The resilience of CSA adaptation activities in the context of evolving climate conditions, extreme weather events, and the potential for new agricultural challenges is questionable (Magesa et al., 2023; Rahman et al., 2024). Some studies suggest that at extreme temperatures, adaptation strategies reach their limit, with examples from several countries in semi-arid East Africa. *"Williams et al., 2021; Trisos et al., 2022 indicated that about 83% of adaptation strategies assessed in Africa, including those used by farmers, showed medium potential for risk reduction. Trisos et al. (2022) further indicated that adaptation strategies, such as adjusting planting times, may reach their adaptation limit above 1.5◦C and 2.5◦C global warming"* (Magesa et al., 2023, p.52).

There is evidence that extreme climate events erode benefits, suggesting that in contexts where people are vulnerable due to their reliance on the environment for their livelihoods, CSA alone is not enough to protect wellbeing and ensure resilience. Magesa et al. (2023) provide examples from studies in several African countries, including Madagascar, Zimbabwe and Ghana. They note that: *"stress-tolerant crops have increased resistance to climatic extremes in the region and play an essential role during harsh climatic conditions (Nagargade et al., 2017). These varieties are expected to increase productivity during the low rainfall season or high salinity levels. However, their viability is uncertain when extreme events, such as droughts, persist for a long time."*

There is evidence that crop production technologies work better with corresponding water management and irrigation technology interventions, as drought consistently undermines effectiveness. Adaptations within agriculture focused on crop production and management techniques and technologies alone are likely insufficient in the face of extreme climate risk. More transformative approaches are needed. This further supports the need to implement a complementary suite of CSA interventions that include capacity building, access to credit, extension services, storage, markets, and improved rural infrastructure. Magesa et al. (2023), for example, note: *"The adaptation interventions detailed in this study might not be effective during times of more extreme climate changes in the coming decades. Hence, more transformative changes, such as building more infrastructures for irrigation, promoting crop insurance, using improved varieties, and increasing opportunities for livelihood diversification, should be considered in addition to the existing adaptation strategies."*

Reduced exposure

In all, 16 of the studies covering CSA reported evidence for reduced exposure, nine of medium quality and seven of high quality.

Overall, we found positive evidence for reduced exposure (Mbah, Ajaps and Molthan-Hill, 2021; Thottadi and Singh, 2024; Wekeza, Sibanda and Nhundu, 2022; Guja and Bedeke, 2024; Akinyi, Nganga and Girvetz, 2021). Reduced exposure to crop risk (e.g., leading to greater biodiversity, increased yields, crop revenues etc.) is achieved through adopting soil and water conservation measures, including organic farming (minimum tillage, organic fertilisers, natural pesticides, crop rotation and green manure). Additionally, studies emphasise joint adoption of strategies to increase benefits. There is also evidence of increased yields due to reduced exposure – adjusting planting days (Guja and Bedeke (2024) provide evidence from China) and timing for maximum soil moisture content. Constructing soil/stone/vegetation bunds in Ethiopia has also been shown to increase soil moisture, reduce runoff and enable greater productivity.

Diversification of farm activities emerges as an important factor in reducing both exposure and sensitivity and, in some cases, is already a well-established risk management strategy. For example, pastoralists in Sub-Saharan Africa diversify species types in their herds alongside a host of other strategies

to minimise losses due to recurring drought, but also to maximise productivity during periods of sufficient rainfall (Legide, Feyissa and Karo, 2024). Another review also notes that: *"further, mobility of livestock was increased (a conventional technique of transhumant herders and nomadic) in several regions of Africa to match animal production demands with shifting rangeland supplies, which substantially enhanced the adaptability of livestock systems to climate change",* specifically drought (R. Singh, Maiti and Garai, 2023, p.1043). Diversification is also seen in crop management:

> *"Agroecological management practices, like planting diverse crop varieties and (intervention) of farms led to the intermediate outcome of reduced crop damage from natural disasters, which ultimately reduced their exposure and sensitivity to natural disaster events. Compared to monoculture farms, agroecologically managed farms have the potential for a faster productive recovery (80–90% within 40 days following the hurricane) (Rosset et al., 2011). For example, in Sotonusco, Chiapas, Philpott et al. (2008) reported less damage to more diverse coffee systems during hurricane events compared to less diverse coffee systems. Similarly, in Cuba, diversified farms showed 50% lower losses as opposed to 90–100% extensive losses in monocultures. In order to lessen the perceived risk brought on by the increasing floods and landslide incidents, many farmers grow trees and refrain from cutting them"* (Dobhal et al., 2024, p.12).

Reduced sensitivity

Evidence for reduced sensitivity (absorptive capacity) exists in 40 systematic reviews, 14 of high quality and 25 rated as medium quality, and across multiple CSA activities. For instance, through maintaining and increasing soil quality and productivity (e.g., organic farming), and following on from decreased exposure to pests, diseases, land degradation, pollution, drought, and poor soil (Khumalo, Sibanda and Mdoda, 2024). One systematic review found reduced sensitivity results from reduced poverty: *"CSA reduces sensitivity particularly via reduced poverty. 69% of studies highlighted the positive impact of CSA on poverty, followed by 45% of screened studies pointing to reduced hunger… The most common practices, climate resilient seeds and zero/minimum tillage, allow farmers to cope with intensified droughts, heat waves, erratic rainfall. Climate-resilient seeds may even increase yields under adverse conditions. Zero tillage helps conserve soil moisture... reduce water runoff"* (Naveen et al., 2024).

Conservation agriculture and agroecology (mulching, cover cropping, crop rotation) increase soil moisture retention and nutrient cycling, making crops less sensitive to drought and poor soil. Crop diversification and enhancement (folio, Bambara groundnut, crop rotation) reduce sensitivity to crop failures and ensure food availability during hunger periods. Diversification, as described above, also has direct sensitivity benefits. Combining agricultural systems and practices (mixed farming, urban and peri-urban pastoralism) ensures food security if one crop/livestock system fails. Mizik (2021) describes a strong positive connection between irrigation farming and agricultural income: *"This impact comes from at least two sources: higher and more stable production, and the opportunity of off-season production"* (p.10). *"Shahzad and Abdulai… found that CSA practices significantly reduce food insecurity... According to Pilarova et al.'s results, additional incomes (remittances) and soil productivity are the major levers of CSA adoption"* (p.11).

Integrated soil fertility management, when carried out effectively, has been found to boost soil health, increase crop productivity and crop income, and reduce climate sensitivity in Ethiopia. However,

whether increased crop productivity translates to increased household incomes overall, considering expenditure, may well depend on the particular ecological context in which the methods are applied.

> *"Many studies recommended it as the best-bet and most feasible option which could provide a more holistic, lower cost, and sustainable climate-smart solution considering the complex socioeconomic and biophysical characteristics of the country (Agegnehu and Tilahun Amede, 2017); Guteta and Abegaz, 2016a,b; Mulualem and Yebo, 2015; Vanlauwe et al., 2010). However, many studies have claimed that adoption of this practice in various parts of Ethiopia was limited because of lack of proper implementation and wider dissemination"* (Abegaz et al., 2024, p.10).

Another specific approach, appropriate to marshy areas that flood often, is the use of floating beds, as demonstrated in India. Floating beds improve water quality by absorbing excess nutrients and pollutants, and biodiversity conservation. They also act as a natural filtration system, reducing risk of eutrophication and other water-related environmental problems. This practice reduces soil erosion as floating beds stabilise soil and prevent it from being washed away in heavy rains (Ghosh et al., 2024).

Increased adaptive capacity

Adaptive capacity was the most evidenced set of outcomes in the sample of CSA-focused studies, with a total of 38 studies – 24 of medium quality and 14 of high quality. There is evidence from across all regions and different types of geography.

Interventions that boost adaptive capacity through CSA include shifts in crop production technologies and farm management practices, for example to drought-tolerant varieties, livestock management techniques, and diversified farm and off-farm activities (Chami et al., 2022; Akinyi, Nganga and Girvetz, 2021, and others).

Adaptation outcomes relate often, but not always, to increased yields and subsequent income and employment benefits. For example, there is evidence for positive income and employment returns of CSAF systems (e.g., Western Uttar Pradesh, India; CSAF in cacao in Bolivia). In the Bolivian cacao case, yields were lower compared to monocultures but the return on labour across the years was roughly twice as high in CSAF systems (organic) compared to monocultures (conventional farming) (Ntawuruhunga et al., 2023).

There is emphasis across the literature on the influence of agroecological context on the success of interventions and, in turn, outcomes. Evidence points to combining interventions to support and complement each other to effect adaptation. For example, in the case of durum wheat in Tunisia, Chami et al. (2022) describe promising results in two contrasting climatic locations (semi-arid and sub-humid conditions) where different soil and crop management practices were integrated. They highlight particular success in a *"dry and marginal environment with crop-livestock interaction which positively impacts soil quality parameters, increasing soil moisture & hydraulic conductivity"*. Further evidence for improving outcomes by combining interventions/adaptive strategies is identified in Ogunyiola et al. (2022):

> *"Six studies showed the positive impact of using multiple strategies. Di Falco and Veronesi (2013) found that the combination of any two of the three strategies (i.e. changing crop varieties, water strategies [irrigation, water harvesting, water conservation], and soil conservation) significantly increased net revenues of farm households compared with using only one strategy."*

Poverty co-benefits

Seventeen of the sampled studies provided evidence for poverty co-benefits of CSA, split between those of medium and high quality.

There is evidence from Sub-Sharan Africa and South Asia of poverty reduction co-benefits resulting from CSA. For example, in Naveen et al. (2024), CSA practices increase crop yield and income, thereby decreasing poverty and increasing food security. This is, according to the authors, the most critical outcome of CSA since South Asia makes up two-fifths of the world's income-poor and malnourished. In Mizik (2021), Shahzad and Abdulai similarly found that CSA practices had helped to significantly reduce food insecurity and poverty in Pakistan. Further positive findings were also highlighted in Etana et al. (2022):

> *"In Pakistan, compared with those who did not adapt, households using one, two, and three adaptation strategies had 7-8%, 8-9%, and 12-14% higher food security levels, respectively (Ali and Erenstein, 2017). The poverty levels of these households consistently decreased by 2-3%, 3-5%, and 6-8%, respectively. In Malawi (Asfaw et al., 2016), the combined use of adaptation strategies (i.e. improved seed and tree planting, improved seed and inorganic fertilizer, legume intercropping, and inorganic fertilizer) increased maize productivity."*

Water-efficient irrigation systems are also linked to poverty reduction. In a Green Climate Fund (GCF) systematic review with global coverage, three studies reported the impact of water-efficient irrigation systems on poverty. The review found *"that water-efficient irrigation systems do have a minimizing and statistically significant effect on poverty levels",* although these results should be interpreted with caution given the small number of studies drawn on (Ategeka et al., 2024, p.42).

Other studies focus on improved yields and incomes as key benefits to participating farmers in CSA, although the link to poverty reduction is not explicit. Khumalo et al. (2024), for example, identify multiple potential impacts/routes towards income security arising from CSA in Sub-Saharan Africa. In the same region, Wekeza et al. (2022) also flag potential for improved wellbeing through the increased labour force requirement of organic farming, which is expected to lead to increased incomes. Findings from Ghosh et al. (2024) (South Asia), while not directly poverty-focused, also find that floating-bed agriculture can be economically beneficial to local communities by offering livelihood opportunities for many people living in areas with limited land resources or poor soil quality.

Interventions focused on home gardens can increase food security and household income. Smith et al. (2021) examine 154 interventions, of which 42 explicitly targeted poverty reduction: *"only 12 of these provided clear evidence that poverty had been reduced as a result of the intervention".* These findings include home garden interventions in Bangladesh:

> *"Homegardens are widespread and play a vital role in food security in Bangladesh. One study found that applying a year-round rotating system of different vegetables and fruit trees, chosen through a participatory approach using local traditional and indigenous knowledge, could more than double annual production, improve nutrition, increase household income, alleviate poverty and provide employment and empowerment for female family members."*

The same study also highlighted the Community Resilient Ecosystem and Livelihoods (CREL) project in Bangladesh: *"…the CREL project provided training and support for enterprise development to 60,000 households (...) 38,500 were estimated to have enhanced their incomes by a total of over US$5 million. Over 8,000 poor women (73% of livelihood beneficiaries) were empowered through financial training, helping them to improve access to services and credit, increase asset ownership and play a greater role in decision-making."*

Box 5: The Mbili-Mbili intercropping system in Kenya

Dagunga et al. (2023) looked at three spatial intercropping systems in Western Kenya to determine their effectiveness in increasing the yield and incomes of households. The Mbili-Mbili intercropping system is a specific method of spatial crop configuration where two rows of maize are planted alongside two rows of different legumes, with each legume species occupying one of the two rows. This contrasts with the Mbili system, which involves two rows of maize and two rows of a single legume species, and conventional intercropping practices.

> *"Study results showed that the Mbili intercropping system significantly outperformed the hill and conventional intercropping systems in all study sites except one. … A survey of farmers' experience with the Mbili-Mbili intercropping system revealed that approximately 79% of farmers reported an increase in maize grain yield in Mbili-Mbili than their usual systems. Farmers' observation on increased maize grain yield in Mbili-Mbili was thus consistent with results from researcher trials where yields increased by between 50% and 60% over the farmer practices. The potential of different intercropping options to increase yield is an indicator of household food security"* (Dagunga et al., 2023).

GHG emissions

Eighteen studies mentioned potential for GHG emissions reduction from CSA, twelve of medium quality and six of high quality. CSA provides opportunities across a range of interventions for carbon sequestration and reduced emissions; however, relatively few reviews gave figures for GHG emissions achieved through improved practices.

CSA supports reduced GHG emissions through practices such as enhanced soil carbon sequestration, zero or minimum tillage, direct rice seeding, mulching, and soil monitoring, with reportedly *"the potential to reduce at least 10-15% GHGs more than a conventional system"*. For example, the adoption of zero tillage in rice-wheat systems resulted in a reduced global warming potential by approximately $33-40 compared to conventional tillage, which emitted 7653 kg CO2 eq./ha/year (Naveen et al., 2024). No-tillage can significantly reduce GHG emissions to enhance soil organic carbon by 7.79%.

Evidence from two studies suggests that organic farming reduces GHG emissions. For example, in their systematic review of studies commenting on organic farming in Southern Africa, Wekeza et al. (2022) report that *"Skinner et al. show that GHG emissions are much lower (about 40%) on organic farms than conventional ones"*. Snapp et al. (2021) find that evidence mostly comes from the Global North on reduced GHG emissions from organic farming and ecological management of nutrients due to mitigation of nitrous oxide: *"There was limited data on GHG emissions for the tropics and almost no evidence regarding resilience to extreme weather events. One study that monitored farm plots in Nicaragua under*

conventional and participatory, sustainable management found that the later was associated with resilience after Hurricane Mitch."

Two reviews report evidence of decreased GHG emissions (both potential and actual) because of climate-smart livestock practices. Examples include improved animal feed or switching breeds to reduce enteric methane emissions (R. Singh, Maiti and Garai, 2023; Khumalo, Sibanda and Mdoda, 2024). Climate-smart manure management systems, involving *"separation of solid and liquid manure (centrifuge or filtering process) has a greenhouse gas mitigation potential of more than 30 percent (Montes et al., 2013)"* (R. Singh, Maiti and Garai, 2023, p.1044).

Evidence for reduced GHG from water management (irrigation and water-saving technology) was reported as mixed – with just one review providing data (J. Chen, Zhong and Sun, 2022):

> *"Compared to no-irrigated systems, Zheng et al. (2019) found that the total yield-scaled GHG emissions during the maize life cycle decreased by 22% to approximately 28% in irrigated agriculture."*
>
> *"Daccache et al. (2014) demonstrated that GHG emissions rose by 270% when rain-fed production shifted to irrigated production in the same region."*
>
> *"In North China Plain, the groundwater levels there have declined severely and GHG emissions from irrigation increased by 42% from 1996 to 2013" (Qiu et al., 2018).*
>
> *"Zou et al. (2012) claimed that water-saving irrigation may be a better way to cope with climate change and can reduce about 11.56 Mt GHG emissions per year in China. However, Daccache et al. (2014) found that compared to surface irrigation (gravity-fed open channels), sprinkler and drip irrigation may increase GHG emissions by about 135%. For water-saving irrigation in paddy fields, alternating wetting and drying irrigation was proven to reduce GHG emissions and enhance water use efficiency (Xu et al., 2015; Wang et al., 2020)."* (p.81192)

Differential impacts across social groups

Smallholder farmers were identified most in the literature as participants and direct beneficiaries of CSA programmes. One review notes that *"economic returns from crop diversification were highest among the poorest farmers. Similar results were found in this study, with crop diversification being the most used strategy by farmers in many African countries. Lipper et al. (2018) also found that poorer farmers in Sub-Saharan Africa highly employed crop diversification and labour diversification" (Magesa et al, 2023, p.9).*

The same study, however, also identified barriers to poorer households. *"Diversifying to off-farm activities requires a different level of investment to offer higher returns (FAO, 2017). Furthermore, they demand higher investment in terms of social, human, and financial capital to start up, making poor households less likely to be involved in high-return sectors, and diversification may not substantially help smallholder farmers get out of poverty (Gautam and Andersen, 2016; FAO, 2017)."*

Benefits to women farmers were identified in some studies. *"By leveraging ICT tools, women's capacity to access new knowledge is enhanced, and their awareness of the utility of information in addressing climate risks is heightened. This, in turn, motivates female farmers to adopt practices such as pesticide management, crop protection strategies, effective harvesting and storage methods, pest management,*

and post-harvest techniques. Adopting these practices reduces input costs, elevates productivity, increases income, and ultimately empowers women (Gata et al., 2020; Mittal, 2016)" (Thottadi and Singh 2024).

Enablers

Enabling factors for the uptake and successful scaling of CSA are similar to those for conventional agriculture – notably access to markets, finance, and land and non-land assets – but with additional notable emphasis on knowledge, farmer organisation, and institutional support. These are captured in Snapp et al. (2021), which summarises key factors:

> *"Scaling agroecology was most distinctive in its reliance on co-creation of knowledge with farmers to develop site-specific technical options, farmer organising and reliance on inclusive social movements. Market drivers differentiated agroecological production through public policy support for smallholder production (e.g., purchasing arrangements), local or regional food market development or certification, for example of organic or fair-trade goods. Government policy supported reformulation or shifts away from agro-industrial models (Mier y Terán et al., 2018) … In addition, enforced regulatory frameworks, payments for environmental services, and credit or payments conditional on environmental outcomes were important incentives associated with environmental outcomes for sustainable agriculture, in addition to market or technical interventions."*

Education is important in adopting CSA practices and in adaptation. Naveen et al. (2024) suggest that education is the predominant significant positive determinant of CSA practice update. This is also highlighted in Sikandar et al. (2023), while Saddique et al. (2022) state: *"Thirty-five papers have shown the importance of education in adaptation. Educated farmers have more information of advanced agriculture technologies and improved varieties compared to farmers with little or no education."*

Knowledge transfer, including access to and incorporation of specific types of knowledge, is a prominent factor in achieving higher CSA adoption, as is the ease with which farmers are able to adopt practices with little training and minimal behaviour change (Shaffril et al., 2020; Onyeneke et al., 2019; Mizik, 2021; J. Chen, Zhong and Sun, 2022; Chami et al., 2022; Slayi et al., 2024). Related to this is the importance of indigenous knowledge and knowledge sharing (discussed in *Section 4.3.4* below): *"Indigenous knowledge about plant health, as well as the pest and disease incidence, is required by the farmers to adopt appropriate adaptation measures"* (Onyeneke et al., 2019, p.983). Community engagement and knowledge networks are important factors in uptake of practices for adaptation, especially when grounded in local knowledge and smallholder experiences of change (Bracken, Burgess and Girkin, 2023; Chami et al., 2022; Slayi et al., 2024). This can be positively reinforced by collective action and organisational membership, for example in urban areas for marginalised groups like women and youth (Khumalo, Sibanda and Mdoda, 2024, p.17). Access to extension services also influences choice of adaptation strategy, and access to weather forecast information is positively and significantly related to adopting different CSA practices (Saddique et al., 2022, p.11).

Farmer field schools (FFS), training programmes, and the presence of extension services to support knowledge dissemination play a crucial role in promoting the adoption of new techniques (Saran et al., 2024; Sikandar et al., 2022; Prasad and Singh, 2024; Li et al., 2024; Muita et al., 2024). FFS provide ongoing education for farmers about new techniques and can be tailored to align with government programmes and policies. Saran et al. also found that women typically benefited more from FFS than men, although

the magnitude of this gender difference varies across contexts, and given the often small and heterogenous sample sizes in the literature would warrant further study to confirm. Extension services provide similar contributions to CSA adoption, but access can be limited in remote areas (Saddique et al., 2022). The same paper reported that extension officers were *"biased towards influential and wealthier farmers"*.

Government support through policies helps to maximise the benefits of CSA, while minimising trade-offs. One study reviewed in Etana et al. (2022) highlights how, in Botswana, divergence between government priorities and farmer preferences aggravated unequal power dynamics. Another example from Brazil suggests that government programmes like school feeding that create demand for diversified food products incentivise agroecological practices such as crop diversification. This, in turn, benefits households, in terms of both improving dietary diversity and improved resilience (Dagunga et al., 2023).

Access to finance, including through generation of off-farm income, supports CSA uptake (Smith et al., 2021; Saddique et al., 2022; Onyeneke et al., 2019). Off-farm diversification is identified as an important adaptive strategy that also allows further investment in CSA, especially advanced technology-related measures, as does diversification through value chains. Access to credit also supports diversification, in turn sustaining and improving incomes, as it provides the means to purchase improved crop varieties (heat-, drought-, pest- and disease-resistant), as well as supporting access to land (e.g., Northern Nigeria).

Productive assets, especially land and access to labour including family labour, are also critical enablers (Smith et al., 2021; Saddique et al., 2022; Etana et al., 2022; Nshakira-Rukundo et al., 2023). For example, larger family sizes are linked with greater uptake of CSA, as larger households are *"more likely to adapt labour-consuming adaptation strategies"* (Saddique et al., 2022). In one study, size of landholdings is noted as important: *"Larger landholding size has a positive and significant influence on the probability of adaptation strategies such as changing crop types, crop varieties, irrigation methods, and shifting from crops to livestock. These farmers can invest in high-cost measures and tend to respond earlier to certain climate hazards"* (Saddique et al., 2022). Studies included in Etana et al. (2022) find that access to water is a fundamental driver:

> *"Waha et al. (2018) showed that the beneficial impact of diversifying farming systems was positive only in areas obtaining 500–1000mm annual rainfall as well as rainfall variability of 17-22%."*
>
> *"…tillage practices improved economic return in Cameroon when there was an increase in precipitation (Molua, 2002), the effectiveness of irrigation was dependent on water availability in Brazil (Burney et al., 2014; Da Cunha, Coelho and Feres, 2015)."*

Location and, in turn, market access, especially commercial centres, were identified as vital in helping to reduce transactions costs, with farmers located close to market centres more likely to participate in, and benefit from, off-farm employment (Etana et al., 2022).

Barriers, limitations and maladaptation risks

Financial constraints

Financial barriers represent one of the most significant challenges to CSA adoption globally. Smallholder farmers frequently lack the financial resources needed to implement climate-smart practices, which require some initial capital outlay for new seeds, soil and crop management tools, or localised irrigation.

Loans can be withheld or unattractive due to farmers' lack of collateral, illiteracy, and high interest rates. Microloans are also associated with debt and unacceptably high repayments, as are local moneylenders (Goswami et al., 2023; Goodwin et al., 2022).

> *"Shahzad and Abdulai surveyed 540 farm households on the impacts of CSA adoption in Pakistan. To have an unbiased sample, they randomly selected villages from the three agroecological zones, and fifteen farmers from each of them. According to their results, being informed/trained and having access to credits are the strongest indicators of potential CSA adoption"* (Mizik, 2021).

Land tenure and security

Land tenure, or the lack of it, undermines and inhibits adoption of CSA approaches, particularly for women (Mizik, 2021). In Ethiopia, land scarcity is also a problem. One review, which looked at 10 countries, many of them LDCs, points out that *"Land tenure security directly correlates with the recovery of agricultural production costs and the corresponding prospective return. Clear and stable land rights ensure the recoverability of costs and the reliability of durable agriculture benefits, reinforcing farmers' confidence to invest in agricultural practices. Therefore, land tenure security could significantly support farmers' CSA practice adoption"* (Li, Ma and Zhu, 2024, p.13).

Reviews pick out different experiences relating to holding size. One review focusing on interventions across South Asia points out that smallholder farmers do not have enough land space for agricultural management practices, and the financial gain from the increased yield may be insufficient to invest in innovative practices. The lack of regulatory norms on water use, land tenure, and pricing of crops is also counted as a barrier (Goswami et al., 2023, p.13). However, this contrasts with a separate review, WOS2627, looking at 15 programmes in nine countries, which found that "*Small-holder farmers typically experienced the most positive effect sizes due to the agroforestry interventions".*

Transition risks

High initial costs of CSA implementation, coupled with delayed benefits, create additional challenges. Climate-smart practices often require substantial upfront investments in sustainable farming approaches such as organic inputs, crop diversification, and agroforestry. These investments pose significant barriers for small-scale farmers who lack access to credit or financial resources. Furthermore, the transition to agroecology may involve a period of adjustment with lower yields during initial phases, creating financial strain for farmers dependent on consistent agricultural production (Zenda and Rudolph, 2024).

The adoption of CSA is also threatened by limited market access, which risks making yield improvements far less impactful (Khumalo, Sibanda and Mdoda, 2024; Castle et al., 2021; Chettri, Datta and Behera, 2024). One review picked out a global study claiming that *"market or technical interventions were the most important incentives for adopting sustainable agriculture practices that enhanced productivity (Piñeiro et al., 2020)"* (Snapp et al., 2021). The same study noted that *"the inherent complexity and knowledge intensity of agroecology sometimes incurred higher cost and more time compared to conventional agriculture, but this also enabled effectiveness and sustained benefits".*

In mountainous regions, temperature rises will make some areas arable. Intensive agricultural expansion in these areas risks undermining surrounding ecosystem services, particularly from mountainous forests. It is critical that expansions into such areas are environmentally sound (Tzadok et al., 2022).

Knowledge gaps

At farm level, farmer illiteracy, limited access to additional knowledge, and low education limit access to knowledge about climate change and appropriate strategies to deal with it (Saddique et al., 2022; Bracken, Burgess and Girkin, 2023; Nyoni et al., 2024). Extension services can help to address this challenge, creating awareness among farmers on climate change and its effects and enhancing capacity to adopt new technologies. Several studies have found that extension services have had a positive impact on climate change adaptation practices, particularly CSA practices (Thottadi and Singh, 2024). However, extension services can be flawed, unreliable or unavailable (Saddique et al., 2022; Li, Ma and Zhu, 2024). Lack of climate information, or information that is not in a usable and actionable format, also undermines adoption of CSA, as farmers see no value in implementing strategies without knowledge of why they are using them (Li, Ma and Zhu, 2024). Traditional farming practices and knowledge systems are deeply ingrained in farming communities, tied to cultural identities and local perceptions of dignity, identity and self-worth. These social norms can be a further barrier to CSA adoption (Batkai et al., 2023; Etana et al., 2022).

Limited membership of cooperatives reduces farmers' technical capacity, particularly for women-led small-scale farms (Mizik, 2021). This challenge reflects broader limitations in farmers' ability to access the collective knowledge and resources that cooperatives can provide.

Coordination challenges

Poor coordination among institutions and stakeholders significantly impedes effective implementation of CSA interventions (Goswami et al., 2023; Rahman et al., 2024; Guja and Bedeke, 2024; Smith et al., 2021). Conflicting goals among various institutions and rigid regulatory schemes, for example, can create coordination difficulties (Smith et al., 2021). This coordination gap extends to exchanges between key stakeholders such as government agencies, extension services, and farmers, potentially slowing the acquisition of new ideas and the adoption of farming technologies to help adapt to climate change.

> *"In Botswana, Shinn et al. (2014) explained that micropolitics plays a role in shaping differential adaptation responses. They found a disparity between state-sponsored adaptation responses and the preference for farmers to maintain the cultural identity of their livelihood practices, resulting in divergent desires for adaptation. Due to these power dynamics, adaptation may aggravate socio-economic, political, and cultural inequalities (Sovacool, Linner and Goodsite, 2015)"* (Etana et al., 2022, p.726).

Infrastructure limitations

Inadequate infrastructure represents a significant barrier to implementing CSA practices across different regions. Irrigation infrastructure is particularly deficient in many agricultural areas. Only 4% of production areas in Sub-Saharan Africa and 5% of cultivated areas in Africa are under irrigation, compared with 29% in East Asia, 39% in South Asia, and 14% in Latin America (Magesa et al., 2023). Irrigation schemes established in some countries have inadequate technology, limiting their sustainability. For example, in Zimbabwe's Gwanda district, a small irrigation scheme collapsed when a pump broke down and remained unrepaired for an extended period.

Water scarcity represents a major constraint for CSA implementation. According to farmers' perceptions, water availability from canals and rainfall is frequently insufficient to fulfil crop requirements

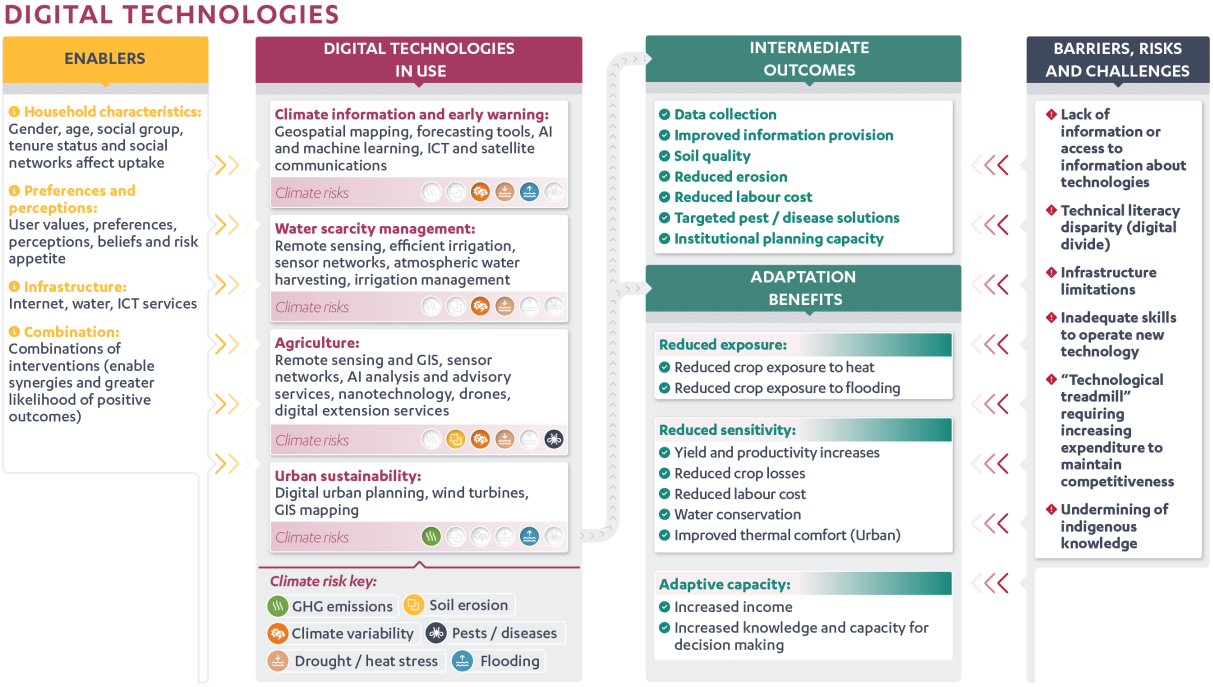
and maximise productivity. Drought can undermine the ability of irrigation to properly enable yield stabilisation (Goodwin et al., 2022).

Implications for practice

- **The effectiveness of CSA interventions hinges not just on the quality of technology or training offered, but on understanding the politics of adaptation and change in different localities.** Particularly in traditional settings, agricultural livelihoods are tied to individual and communal identities. Tailored strategies may be needed to explore, in partnership with those communities, the most appropriate climate-smart adaptations that align with local identities and existing indigenous knowledge and expertise.
- **Barriers to adoption of CSA approaches are significant, and a holistic approach is needed to scale up climate-smart methods.** For example, considerations such as land tenure and land security, affordable and accessible credit, and market access are all preconditions for farmers to feel that the risk of taking up new methods is less than the risk of existing coping strategies.
- **Extension services increase the likelihood of uptake and sustainability of CSA.** Finding ways to deliver appropriate training, information and advice on climate-smart techniques, either through existing systems or through digital approaches, is key to encouraging farmers to sustainably alter existing farming approaches.
- **Social capital can play an important role in spreading CSA approaches.** Many farmers without education or access to information sources learn new techniques from neighbours and friends.
- **Any CSA programme should be tied to dissemination of usable, actionable, local language climate information** that links forecasts to practical advice as to planting times, seed choices, intercropping strategies or soil management strategies.

4.4.3 Digital technologies

Digital technologies take up a growing space in the landscape of adaptation initiatives. *"Digital technology utilises electronic tools to manipulate data in binary format, enabling diverse tasks, [using] computers, smartphones, drones, cameras and more"* (Azlan, Junaini and Bolhassan, 2024). According to Azlan et al., *"it forms the basis for more sophisticated information and communication technologies and systems, as well as current data-driven approaches"*. Climate-smart technological innovations, like water harvesting and modified crop varieties, are prevalent across the literature. As many of these are addressed in the CSA section above, this section will discuss technologies with a "digital" focus.



Confidence in digital technologies as an adaptation to climate risks

Digital technologies are mentioned in relation to all the major climate risks (drought, flooding, variability and heat, and their impact on food security, income and crop yields), particularly in the interventions relating to agriculture, disaster risk management (DRM) and urban infrastructure. In urban contexts, pollution and heat management are the main concern, with responses driven by government authorities. The causal links between interventions and their associated risks, however, are poorly articulated.

Reduced exposure

We have medium confidence in the ability of satellite remote sensing, information systems and geospatial mapping as early warning tools to enable safety measures that reduce exposure to disasters, water stress and livelihood disruptions. While the quality of studies mentioning exposure benefits was high, the limited quantity and scope of the corroborating studies limits generalisability of these conclusions. Some studies failed to provide enough evidence on how technological interventions in the agricultural sector reduced exposure and vulnerability to climate risks. Limitations flagged by several studies included limitations in scope, variability in data sources, lack of empirical field validation, publication bias due to under- or over-representation, and the absence of longitudinal data.

Reduced sensitivity

Confidence in modified crop varieties to reduce sensitivity to drought, pests, flooding, diseases and other natural hazards, especially when combined with other interventions, is high across a range of geographies.

Confidence in the ability of digital technologies, including machine learning and image processing, to reduce farmers' sensitivity to such risks is medium, due to the limited scope and quantity of high-quality studies that support this statement. In Sub-Saharan Africa, wider infrastructural challenges and high costs make effective outcomes more challenging to achieve.

Increased adaptive capacity

We have high confidence in the combined benefits from information and communications technology (ICT) and digital agricultural technologies to help increase the adaptive capacities of farmers. This is due to the high convergence in the studies around the benefits to smallholder farmers' ability to make appropriate decisions. Precision agriculture, through its use of tools including drones, IoT-based robotics, and wireless sensors, has supported intermediate outcomes such as improvements to resource efficiency, improvements to real-time responses to the risks of pests and water stress, and preparedness for extreme shifts in weather patterns. When successful, these interventions have proven to be highly effective as adaptive strategies. Digital technologies can also enhance adaptive capacity by making other interventions more effective; for instance, when digital technologies are made accessible, they significantly improve access to climate information and agricultural advisories. However, adoption is limited by available capital, knowledge and preferences, and infrastructure challenges which undermine potential in the most vulnerable regions, particularly Sub-Saharan Africa.

Barriers of inaccessibility and unaffordability of digital technologies for smallholder farmers undermine adoption of new technology. Several studies with varying levels of quality agree that improved evidence-based decision making among farmers can strengthen adaptive capacity. Given the differences in socio-ecological dynamics and topographies within and across various countries, it is also possible that studies provided an overestimation of the positive impacts of digital technology.

Systematic reviews often feature digital tools in their review of adaptation actions taking place in a variety of sectors. Studies discussing digital technologies for adaptation are typically global in nature, highlighting marked differences between uptake and use of new technologies in middle-income rather than lower-income countries or regions such as Sub-Saharan Africa. Of the 52 studies that addressed both digital and non-digital technological activities, agriculture (28), disaster risk management (DRM) (7), and natural resource management (NRM) (particularly of water) (6), were the most represented sectors. A smaller number of studies also discuss technologies aimed at sustainable infrastructure, heat management, and spatial analysis and visualisation. Across the 54 included studies, the following activities were frequently mentioned:

- **Agriculture:** use of mass media (4), weather forecasting (3), weather and climate information services (3), improved/alternative irrigation (3), Internet of Things (IoT) (2), early warning systems (2).
- **Natural resource management:** water harvesting (2), remote sensing (2), nanotechnologies (2).
- **Disaster risk management:** early warning systems (3), climate and hazard information services/systems (3), geographic information system (GIS) (2), AI/machine learning models (2), forecasting technology (2).
- **Green urban infrastructure:** green roofs (2).

There is a distinction between the principal user types of digital technologies. Some digital tools are best used by institutions involved in planning and response to climate risk, enabling more informed and targeted resource allocation and management. These tools can factor in local-level information. Another user type is individuals or households, for whom digital tools inform decision making and problem solving, for example, through ICT applications and advisory services.

Strength of evidence

Most studies that addressed digital technologies focused on **sensitivity reduction** (40) and **strengthening adaptive capacity** (35). Of these, 13 studies addressing risk sensitivity interventions and 12 studies

addressing adaptive capacity interventions were of high quality. Other high-quality studies discussing digital tools covered exposure reduction (7), poverty reduction (4) and GHG emissions (3). Most of the high-quality studies focused on Sub-Saharan African and Asian countries (excluding the Middle East and North Africa). As a result, the risk of bias occurring in globalised conclusions on digital intervention outcomes and effectiveness remains relatively high. *Table 5* below reflects the often overlapping outcomes that were present across the studies.

Table 5: Strength of evidence by outcome type for digital technologies interventions

Outcome	No. medium-quality studies	No. high-quality studies	Total
Reduced exposure	10	7	17
Reduced sensitivity	27	13	40
Adaptative capacity	24	11	36
Reduced poverty	8	4	12
Reduced GHG emissions	11	3	14

Table 6 presents the number of studies that focused on specific intervention areas across the various sectors. Overall, the quality of evidence addressing commonly mentioned digital interventions was mixed across the included studies, with varying degrees of heterogeneity and reliability due to the size or scope of their evidence bases.

Table 6: Strength of evidence by intervention type for digital technologies interventions

Intervention	No. medium-quality studies	No. high-quality studies	Total
Weather forecasting	5	3	8
Climate information services	2	3	5
Water harvesting	4	2	6
AI/machine learning models	1	3	4
Remote and wireless sensing	2	2	4
GIS and geospatial tools	2	2	4
Media and ICT	2	2	4

Climate information and early warning technologies

Climate information systems (CIS) and early warning systems (EWS) are central aspects of effective adaptation and are covered in more depth in *Section 4.4.6*. Thottadi and Singh (2024) reaffirm that *"for developing countries... ICT is the best method for knowledge dissemination, considering the fewer extension agent resources and budget issues (Kalimba and Culas, 2020). Using ICT-driven weather and climate information, along with advisory services, catalyses farmers to make informed choices regarding adopting technologies and effective management practices"* (Thottadi and Singh, 2024, p.22). For

instance, in India, the dissemination of localised forecasts spanning three days using SMS services proved instrumental in equipping farmers to address potential challenges. Similarly, in Kenya, the radio was an effective communication tool for influencing the use of weather data and smallholder farmers' actions (Muita et al., 2021).

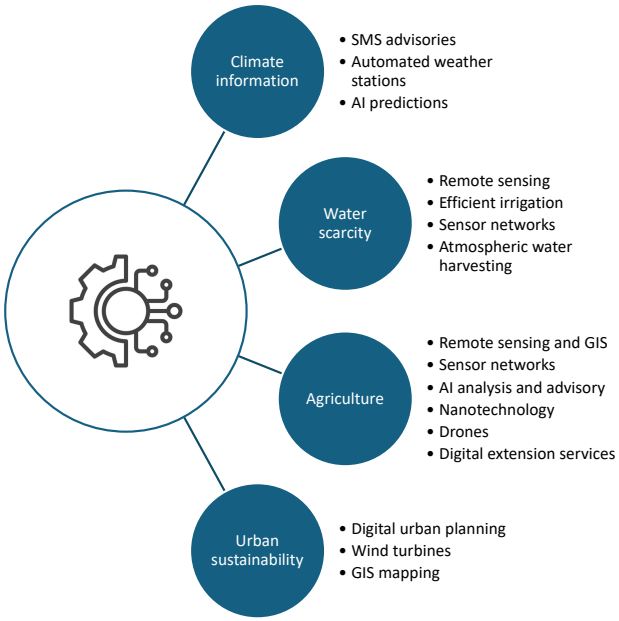
Two studies briefly explore the effectiveness of forecasting technologies and information dissemination in Sub-Saharan African countries for DRM (Nkiaka et al., 2019; Kundu et al., 2020). For example, in West Africa, 10-day weather forecasts helped agricultural stakeholders to make informed decisions on appropriate transport routes, prepare supplementary fodder, identify diseases and help to mitigate *"farmer-pastoral conflicts by guiding the mobility of pastoralists"* (Nkiaka et al., 2019).

Approaches that combine ICT-driven weather and climate information with advisory services can also support farmers' decision making through adaptive technology adoption that improves farm management. For example, in India, "*the installation of automated weather stations in villages allowed for the dissemination of localised forecasts spanning three days via SMS services. This proved instrumental in equipping farmers to address potential challenges from weather fluctuations*" (Thottadi and Singh, 2024, p.22). Four studies address the use of EWS as a means of strengthening farmers' resilience and preparedness in relation to climate hazards and disasters (Hossin et al., 2023; Legide, Feyissa and Karo, 2024; Kwazu and Chang-Richards, 2021; Dorji et al., 2024). Specific technological applications include:

- early warning systems
- geospatial mapping
- weather forecasting tools
- agro-based weather information
- artificial intelligence and machine learning models
- remote sensing
- coastal calculator
- satellite communications.

ICT can also provide critical tools for implementing disaster response efforts, strengthening disaster monitoring and EWS/functions through distributed sensor networks, GIS and big data analytics ahead of climate disasters/hazards. Hossin et al. (2023), for example, find that *"the implementation of AI techniques could help the prediction of impending natural hazards and provide information for rapid evacuation of affected areas"*. This study notes that IoT-based technologies can allow communities to receive frequent updates, providing them with the information needed to take precautions against any incoming disasters or hazards. In Cuba, for example, *"the Risk Reduction Management Center improved their community disaster communication and coordination using scientific evidence and sophisticated mapping technologies. GIS technologies, land use regulation, and safe building codes were also proposed to assess vulnerable healthcare facilities along coastlines or waterways, even with external pressures of rapid urbanization"* (Rublee et al., 2021, p.23).

Figure 7: Digital tools and the sectors they are associated with in the systematic reviews



Technology to address water scarcity

Several studies focus on the application of technology for NRM, with most focusing on water resource management (WRM) (Berretta et al., 2023; Mizik, 2021; Akinyi, Nganga and Girvetz, 2021; Ahmad et al., 2024; Chami et al., 2022; Kotze et al., 2024). Commonly mentioned activities include water harvesting and remote sensing (Kotze et al., 2024; Akinyi, Nganga and Girvetz, 2021; Chami et al., 2022; Brambilla et al., 2022). Water harvesting is a water management strategy involving the collection, storage and reuse of water from one source to another (Akinyi, Nganga and Girvetz, 2021; Brambilla et al., 2022; Abegaz et al., 2024). Given the prevalence of water stress – with about four billion people experiencing severe water scarcity for at least one month of every year (Y. Chen and Gaspari, 2023, p.1) – water harvesting is considered a vital adaptation area in several studies. Chami et al. (2022) note that many integrated WRM interventions had been evaluated in the Near East region due to persisting drought-induced water shortages. While some measures focus on the supply of water, like water harvesting and desalination, others focus on managing demand through the modernisation of irrigation systems, including switching from surface to drip/sprinkler irrigation, which may lead to improved food quality outcomes (Kotze et al., 2024, p.3).

Atmospheric water harvesting (AWH) technologies offer a promising and sustainable solution for providing clean and safe fresh water in both urban and rural settings. One study explores the applicability of AWH technologies on building facades, focusing on specific methods related to fog, humidity, and dew/condensation-based harvesting (Brambilla et al., 2022). AWH methods can be classified as either “active” (which require external energy sources such as vapour compression cycle refrigeration, thermoelectric cooling, and desiccant wheels) or “passive” (which rely on natural resources without the need for external energy input). Dew AWH technologies use radiative cooling condensers to capture condensation on surfaces cooled below the dew point of the surrounding air. Fog AWH technologies employ geometric features, such as meshes and supporting frames, to intercept and collect air droplets. Humidity AWH utilises materials with capacity to absorb air vapour, which is later released

and condensed using solar energy. Although these technologies are not yet widely available commercially, Brambilla et al. (2022) highlight their efficiency and potential to enhance water security in a variety of contexts, even under limiting conditions where fog or dew AWH would not be possible.

Agriculture technologies

Digital technologies are providing farmers with a wide range of services along the agricultural value chain. Most studies discussing the adoption and application of digital technologies focused on strengthening the resilience of affected groups (55) and increasing their adaptive capacities (49). The most studied activities were the use of geo-spatial tools, digital modelling tools, remote sensing, early warning systems, laser land levelling, and weather forecasting. A key advantage of these tools is their ability to support improved decision making. For example, one study explores smart technologies for precision agriculture in Pakistan, highlighting how machine learning and image processing can detect plant diseases for targeted treatment, and how wireless sensor networks can optimise irrigation based on soil moisture levels (Ahmad et al., 2024).

Kotze et al. (2024) review factors influencing efficient water use behaviour in South Africa's agricultural sector, revealing that **remote sensing could be a useful tool for generating data to support agricultural production, but time demands and limited user-friendliness of the technology leave farmers preferring traditional methods.** The study notes that *"farmers do not often have the time to evaluate data from new technologies and these should instead be integrated to supplement existing technologies"* (p.11).

Engineering and digital water-saving technologies have potential to address the challenge of salt-affected soils in Sub-Saharan Africa, but affordability remains a major barrier for rural farmers. One study highlights the importance of innovative approaches beyond traditional WRM, but emphasises that many rural farmers cannot afford to access or adopt the necessary combination of technologies (Ahmad et al., 2024). The authors provide several examples of smart agricultural techniques that leverage digital water-saving technologies, including:

- using drones to conduct water-saving agricultural tasks
- applying machine learning and image processing to optimise resource allocation
- implementing transformative Ag-IoT solutions to improve resource use efficiency
- Deploying wireless sensor networks (WSN) to create soil moisture monitoring systems for more efficient irrigation (Ahmad et al., 2024).

Nanotechnology is also mentioned in relation to NRM, with some evidence of adaptation benefits. Nanotechnology is a form of biological mimicry, involving the manipulation of materials at a micro-scale (specifically, at dimensions as small as one billionth of a metre). This field focuses on creating and utilising structures, devices and systems that possess unique properties and functions, often inspired by those found in nature (Rana et al., 2024, p.2; Solano et al., 2023, p.8). *"The application of nanomaterials to the coating of chemicals like fertilizers, insecticides, herbicides, fungicide and seeds"* has been one of the most common uses of nanotechnology (Rana et al., 2024). The study provides an example of the successful use of zinc fertiliser coated in nanomaterial in India that increased agricultural yields by 20% compared to conventional zinc fertilisers.

Box 6: Smart technologies in agriculture – a review

Ahmad et al. (2024) attempt to summarise the potential of digital technologies in agriculture as follows:

- **Highest impact:** satellite remote sensing and precision agriculture. These interventions have the broadest reach and strongest evidence of improving food security.
- **Moderate to high impact:** drones and machine learning. The technology is promising but still faces accessibility barriers in many parts of the world.
- **Moderate impact:** Ag-IoT, IoT-based robotics and water-saving sensors. Effective where implemented but high costs, infrastructure gaps, and security risks limit large-scale adoption.
- **Localised high impact:** water management using WSN. Crucial in water-scarce regions but its impact depends on local infrastructure and investment.

It is important to note, however, that this review had significant limitations, including variability in data sources. Studies analysed come from diverse sources with different methodologies, making it difficult to draw standardised conclusions across interventions. There is also a lack of empirical field validation. Many studies discuss the theoretical benefits of smart agriculture, but there is limited large-scale, field-based evidence to support these claims in real-world farming conditions.

Artificial intelligence and big data can play a role in advancing agricultural water management. One review examines how these technologies can inform hydro-climatological studies that predict future climate scenarios and support complex decision making through AI "decision trees" (Srivastava and Maity, 2023). This review highlights that integrated technologies – including IoT, big data, AI, smartphones, and cloud computing – enable data-driven, strategic, and real-time actions for both governance and citizen decision making. For example, in Egypt, AI-powered machine learning was used to accurately estimate evapotranspiration and forecast vapour pressure deficit (VPD) in eight regions facing climate challenges. The robust and reliable VPD forecasts became valuable tools for hydro-climatological research and modelling, benefiting not only Egypt but also other African urban environments with similar conditions. This forecasting resource has reportedly become a valuable tool for authorities and policymakers across Africa.

A review by Wanyama et al. (2024) explores the use of AI in irrigation systems for precision irrigation, water demand prediction, crop yield estimation and soil moisture management. However, the study notes that many of these technologies have so far only been tested on a small scale and in highly controlled, project-based settings; findings should therefore be used with caution. Most studies also report greater adoption of these digital tools in middle-income countries, especially in South America, while uptake remains limited in Sub-Saharan Africa due to a lack of essential infrastructure (Srivastava and Maity, 2023). A notable exception is a pioneering IoT smart irrigation system implemented in Kenya:

> *"Maitethia et al. [85] executed a groundbreaking IoT smart irrigation system in Kenya, setting a remarkable precedent for precision agriculture in Africa. By integrating a network of sensors, weather stations, and cloud-based analytics, their pioneering initiative ushered in a new era of data-driven irrigation management. The remarkable outcomes encompassed substantial crop yield improvements, significant water conservation, substantial cost reductions, and enhanced climate resilience, ultimately bolstering food security and elevating the socioeconomic status of local farmers. Although initial investments and the need for comprehensive technical training posed initial challenges, the unparalleled potential of IoT-driven smart irrigation holds the promise of fostering a sustainable and prosperous future for African agriculture"* (Srivastava and Maity, 2023, p.8).

The study also highlights a smartphone application used by 28,000 cassava farmers in Kenya to detect mite and viral infections in maize and cassava. Another study highlights a *"shade tree advice tool"*, providing coffee farmers with guidance on suitable shade tree species for climate regulation (Azlan, Junaini and Bolhassan, 2024).

Digital platforms accessed via smartphones and social media are expanding access to agricultural extension services and empowering farmers, especially women. Less advanced but still impactful digital tools, such as interactive web-based platforms, help farmers receive extension services when in-person interaction with extension officers is not possible. Srivastava et al. (2023), for example, note that by leveraging ICT tools, women gain greater access to knowledge and become more aware of how information can help them address climate risks. This increased awareness encourages female farmers to adopt improved practices, including pesticide management, crop protection, effective harvesting and storage, pest management, and post-harvest techniques. These changes lead to lower input costs, higher productivity, increased income, and greater empowerment for women (Thottadi and Singh, 2024). For male farmers, access to timely information helps to guide financial decisions, particularly in response to forecasts about droughts and floods.

As detailed in *Section 4.4.1*, combinations of interventions are more likely to be effective in delivering adaptation benefits. Thottadi and Singh, for example, highlight how combining CIS and agricultural advisory services with new digital precision tools, like water deficit calculators, has proven instrumental in mitigating the impacts of climate risks. Mizik adds that:

> *"There are many new CSA items on the verge of commercialisation related to the Internet-of-Things, AI [for detection], robotics [for harvesting or multi-robot systems] ..., new machine learning, cloud, and big data-based computing… These items can further accelerate the speed and accuracy of data collecting and processing, and therefore, provide more precise information and recommendations for farmers"* (Mizik, 2021).

Similarly, Ahmad et al. note that *"innovations in ICT within the agricultural sector, including IoT, robotics, precision agriculture and remote sensing, are being used to enhance the crop productivity, improving quality, yield and profitability, while minimising ecological impacts"* (Ahmad et al., 2024, p.2).

Urban settings

Only four studies explicitly focused on the use of digital technology as an adaptation measure to strengthen green infrastructure or engineering. Studies explored a range of technological interventions focusing on smart agriculture techniques, pollution and heat mitigation, disaster risk management, water management, and sustainable urban infrastructure development (Rahmani and Sharifi, 2025; Liu et al., 2022; Kareem et al., 2020). In urban settings, emergent digital technologies support modelling and decision making by municipal authorities as well as offering more practical uses for harvesting water or managing heat stress. In LMICs, risk and particularly heat management technologies like green roofs, solar chimneys and smart windows have been associated with ten benefits, including strengthened sustainable infrastructure, improved thermal comfort, greater energy efficiency, cost efficiency and, to a lesser extent, reduced GHG emissions (Rañeses et al., 2021). The same study also noted that these benefits can occur concurrently from individual interventions.

Rahmani and Sharifi (2025) explore urban heat dynamics across different climates and suggested heat mitigation strategies. Although this is a challenge in some developing countries, they propose a system

called Local Climate Zones (LCZ) that seeks to provide a standardised framework for analysing the physical characteristics in cities that influence urban heat levels. Findings reveal that **remote-sensing technology was the most widely used method for LCZ classification due to its efficiency and accuracy in capturing urban landscapes**. This was followed by GIS-based mapping, which was predominantly used in urban climate research for spatial analysis and visualisation. To a much lesser extent, combined approaches were also used for urban heat mapping. Despite the reported limitations of the LCZ approach and its dependence on data and technology that is not always easily accessible, combined approaches can allow for more accurate mapping and analyses. Another study identified that spatial media technologies could support urban authorities with digitally mapping informal settlements when monitoring and reporting on climate change targets (Kareem et al., 2020).

For thermal comfort and water management, technological advancements have also facilitated a rise in more efficient and affordable urban wind turbine installations (Liu et al., 2022, p.9). Urban wind turbine and ventilation technologies have been associated with "*improved thermal comfort, reduced energy consumption, enhanced health and wellbeing and a reduction in urban carbon emissions*". Nevertheless, there remain several limitations to urban wind energy generation, especially in relation to turbine design, meteorological forecasting and urban aerodynamics.

Outcomes associated with digital technologies

Reduced sensitivity and adaptive capacity

Naveen et al. (2024) report that several studies show how collection, organisation and analysis of diverse data types can improve farmers' adaptive capacity (Ahmad et al., 2024; Guja and Bedeke, 2024; Azlan, Junaini and Bolhassan, 2024; Thottadi and Singh, 2024; Srivastava and Maity, 2023). The role of the technologies covered by the studies in Naveen et al. is to provide information that users can act on in ways that suit their appetite for risk, their experience and their resource capabilities. In India, for example, *"AI–ML [Artificial Intelligence – Machine Learning] models have helped public health authorities to monitor disease spread, understand the climate impacts on outbreaks, and ensure timely and effective healthcare services in urban settings"* (Srivastava and Maity, 2023, p.14). This was particularly effective in developing regions with limited data availability, which several other studies have identified as a key barrier to the effective use of AI-ML technology.

Access to innovation and knowledge via ICT is often intended to have co-benefits. Muita et al. (2021) present evidence that Kenyan farmers are using forecasts to implement strategies to address climate shocks, particularly droughts. For example, *"pastoralists in Isiolo, Kenya would destock their livestock and replace cattle production with camel farming"*. The co-benefits of informed and accurate decision making were targeted at reduced sensitivity through more stable or higher crop yields or increased farm productivity, despite ongoing exposure to climate hazards. Translation of these benefits into adaptive capacity outcomes is not clearly evidenced. Overall, ag-tech [Agricultural Technology] that supports precision agriculture has two types of sensitivity reduction benefit: greater efficiency of agricultural input use such as water, fertilisers, labour etc., and greater yields through optimised farming methods.

Two studies described the outcomes of digital tools in agriculture (Srivastava and Maity, 2023; Ahmad et al., 2024). For example, machine learning and image processing helped farmers detect plant and livestock diseases and optimise resource allocation to ultimately reduce their sensitivity to environmental stresses. Precision agriculture has tackled climate-induced variability and reduces reliance on farming inputs, while

wireless sensor networks tackle farmers' sensitivity to water stress by optimising irrigation based on real-time moisture levels (Ahmad et al., 2024).

GHG emissions

Digital technologies can contribute to emissions reductions or at least help to measure emissions reductions more efficiently. Hossin et al. (2023) discuss the role of information systems (IS) research in supporting companies and countries with offsetting their GHG footprint. Interventions like the Science based Targets initiative (SBTi), for example, could support companies to achieve net zero emissions and automate GHG measurements.[7] Srivastava et al. (2023) also explore how AI and machine learning contribute to reduced GHG emissions. The combined use of smart technologies (like IoT) and heating, ventilation and air conditioning systems helps to improve thermal comfort as an adaptation strategy while reducing the carbon footprint of buildings via lower energy consumption (Tajuddeen and Sajjadian, 2024).

Differential impacts across social groups

Adoption of any new techniques or approaches, let alone digital technologies, requires resources including capital, appropriate knowledge on the potential of the technology, and knowledge on how to apply it. Smallholder farmers in vulnerable contexts typically experience resource constraints (Guja and Bedeke, 2024, p.6). Several studies addressed the digital divide – the gap between those with and without access to digital technologies – in developing regions, along with policy implications for the equitable adoption of digital technologies (Wanyama et al., 2024; Azlan, Junaini and Bolhassan, 2024; Naveen et al., 2024). Despite technological advancements in weather and climate services, the most vulnerable societies in the world still lack access to the climatic information and knowledge generated to support short-term decision making; this has been a notable barrier in Sub-Saharan Africa (Nkiaka et al., 2019, pp.2 and 8).

Access to weather forecast information is crucial for climate risk management in agriculture, but the digital divide limits its benefits for smallholder farmers in East and West Africa. A study by Agyekum et al. (2022) highlights that many households in these regions depend on agriculture for their livelihoods, making them highly vulnerable to climate change. Seasonal data, such as rainfall and temperature forecasts, are essential for farmers to manage climate risks, plan their activities, and implement disaster risk reduction (DRR) measures. However, most farmers lack access to this vital information due to limited access to modern ICT. Senoo et al. (2024) expand on this challenge, noting that *"disparities in access to technology hinder [the] widespread adoption [of smart farming technologies], particularly among smallholder farmers"* (WOS1358, p.22). In contrast, large farmers with greater financial resources and risk-bearing capacity are better able to access technology and adopt CSA practices (Thottadi and Singh, 2024, p.17).

In South Asia, one study notes that: *"establishing training centres for CSA practices, emphasising the use of ICT tools, and training should also target women and elderly farmers to bridge the digital gap in technology adoption"* (Naveen et al., 2024). It also mentions that *"investing in strengthening ICT infrastructure in rural areas, specifically aimed at farmers"* is crucial to increase the adoption of CSA practices, remove barriers, and achieve the Sustainable Development Goals. In the South Asian context, another study provides an example in India on the linkage between education levels, age, and access to technology, where the elderly were more dependent on younger and educated people to teach them how

[7] "The Science Based Targets initiative (SBTi) is a corporate climate action organization that enables companies and financial institutions worldwide to play their part in combating the climate crisis" - more details in link.

to use modern technology like GIS and GPS for livelihood and DRR purposes (Kwazu and Chang-Richards, 2021).

To ensure the equitable adoption of CSA and its associated digital innovations it is *"essential to improve farm infrastructure and enhance public policies to reduce costs for farmers"* (Fragomeli, Annunziata and Punzo, 2024, p.17). Senoo et al. (2024) note that *"effective knowledge transfer mechanisms are essential for bridging the gap between technological innovation and on-the-ground application"*. Another study adds that *"efforts should be made to bridge the digital divide and ensure that smallholder farmers, women farmers, and rural communities have equal access to these technologies. This can be achieved through initiatives that provide affordable and user-friendly technology solutions, promote gender-sensitive approaches, and address socio-economic disparities*" (Wanyama et al., 2024).

Enablers

Several studies explore how demographic, socio-economic, resource, informational and institutional factors, as well as belief systems, can enable and/or hinder the adoption of digital technologies (Thottadi and Singh, 2024; Naveen et al., 2024; Saddique et al., 2022; Nshakira-Rukundo et al., 2023; Shaffril et al., 2020; Etana et al., 2022).

Thottadi et al., for example, discusses how several "empirical studies" highlight the numerous factors that determine the **technological adaptability of a farmer**. Farmers' **household characteristics** and socio-economic features, like gender, age, social group, social capital and social networks, along with farm features, like farm size, land tenure security and access to credit, affect the adaptation of farming technology. Farmers' **unobservable characteristics**, like farmers' preferences, perceptions about technology, knowledge level, ethics, cultural values, and habits, also affect technology adoption. Further, **farmers' beliefs** about farms and native climate, and willingness to accept new technologies, influence the adoption decision. An interesting finding was that in Malawi, *"weaker land rights for males deterred male farmers' knowledge acquisition about CSA adoption and other technologies. On the other hand, females with land ownership acquire more knowledge than female farmers with no ownership rights"*.

For some technologies, the availability of climate information can enable uptake of other types of technologies, particularly those related to CSA. Naveen et al. (2024) note that ICT was found to be a highly and significantly positive institutional enabler for farmers' CSA practice in South Asia. They found that *"ICT tools such as weather forecasting stations, remote sensing technologies, mobile, TV, and radio provide real-time data on weather conditions, crop management, disease monitoring, market information, and financial services such as mobile banking and DBT and allow farmers and agriculture departments to communicate about policy initiatives"*. This is supported by findings in IDEAS81, which also highlights the value of information dissemination through extension workers.

Barriers, limitations and maladaptation risks

Several studies mention the barriers to the use of technology in relation to adaptation (Thottadi and Singh, 2024; Naveen et al., 2024; Etana et al., 2022; Saddique et al., 2022; Guja and Bedeke, 2024). These include lack of knowledge/access to information, limited awareness of the benefits of additional technologies, lack of government incentives/subsidies/funding, resource constraints, and limited market accessibility. Despite the recorded empowerment in agricultural decision making acquired by farmers, there remains a gender disparity in technological literacy because of access to weather forecasts and information. One study presented the higher levels of awareness about climate risks within male-headed households compared to female-headed households (Muita et al., 2021, p.14).

Mizik (2021) addresses some notable drawbacks of CSA-related technologies that farmers ought to be aware of when adopting new digital technologies. These included: "*unstable and slow internet; potential sensor errors that may go over the whole production chain; and inadequate skills and knowledge for a smooth operation"*. The study further highlighted maladaptation and barriers caused by new technologies, such as higher productivity causing higher GHG emissions and the lack of availability and/or access to financial resources to invest in the adoption of CSA tools like sensors and smart devices. Brambilla et al. (2022) corroborated the existence of this maladaptation by acknowledging that despite efforts from past experiments to integrate renewable energy for active AWH interventions, existing systems continue to "*require additional energy to collect water, increasing overall energy consumption"*.

Azlan et al. (2024) note the *"technological treadmill, which drives the erosion of farmer autonomy and flexibility, forcing constant investment in digital tools for competitiveness"*. **This technology trap can undermine application of indigenous knowledge and may be maladaptive if it commits farmers to the use of technologies that may depend on other unreliable infrastructures – particularly energy services, water provision or telecommunication networks.** Further, new technologies can require constant upgrades and updates, each requiring further capital outlay. This process can start to erode traditional skills and labour practices which may be lower-cost, more environmentally sustainable, and effective enough when combined with other interventions.

> *"One of the significant constraints in leveraging Fourth Industrial Revolution technologies for smart irrigation in Sub-Saharan Africa is the limited infrastructure and lack of access to technology. Many rural areas in the region lack reliable electricity supply, internet connectivity, and adequate communication networks necessary for the seamless functioning of smart irrigation systems. The absence of basic infrastructure hampers the deployment and operation of advanced technologies such as sensors, IoT devices, and cloud computing platforms. Additionally, the high cost of technology acquisition and maintenance further restricts the access and adoption of 4IR solutions for smart irrigation in the region"* (Wanyama et al., 2024, pp.111-12).

Implications for practice

- The uptake of new technologies in key sectors is seen more in Asia and South America than in Sub-Saharan Africa. Policymakers should consider the influence of regional economic structures, particularly in agriculture, when designing interventions, and tailor strategies to address local barriers and opportunities. Some emergent technologies, such as atmospheric water harvesting, have widespread potential application but are not yet commercially viable.
- Digital tools, such as those leveraging the IoT and sensor-based technologies, have significant potential to enhance municipal and local government climate risk modelling and planning. However, these technologies are still emerging. Investment in pilot projects, capacity building, and knowledge sharing may help to accelerate their maturity and adoption.
- Smartphone-based applications that provide diagnostic and advisory services to farmers are already being used at scale and have demonstrated practical benefits. Projects and programmes could prioritise the expansion and refinement of these proven tools, although targeted digital inclusion strategies are essential to ensure equitable access.
- Reliable digital infrastructure remains a critical bottleneck, particularly in agricultural regions and particularly in Sub-Saharan Africa. Policy and investment should focus on expanding connectivity,

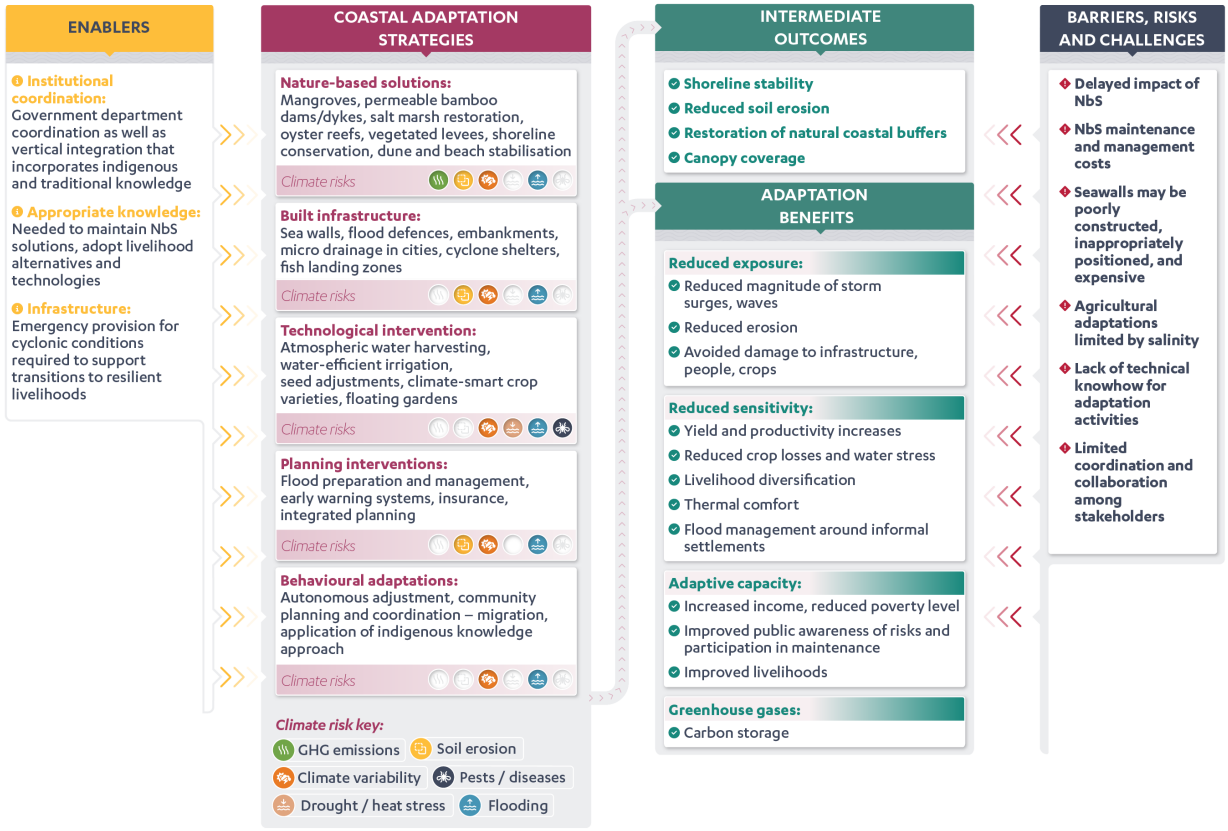
improving affordability, and ensuring that digital infrastructure is robust enough to support widespread and cost-effective deployment of adaptation technologies.

- The introduction of digital technologies carries risks, including high initial costs, the potential loss of valuable indigenous knowledge, and the possibility of investment failure. Mitigating these risks will require adopting participatory approaches that engage communities from the outset, integrating local knowledge systems, and prioritising capacity building. All digital adaptation efforts should be implemented with careful risk assessment and ongoing monitoring to maximise benefits and minimise harm.

4.4.4 Coastal adaptation

Coastal regions are often affected by a similar set of impacts. Extreme weather events such as cyclones and storm surges can cause loss of life and damage to ecosystems and property. Key ecosystems supporting fisheries, aquaculture and tourism also face threats from storms, saline intrusion, and erratic rainfall, which compound existing challenges such as overfishing and poor resource management. In coastal cities, flooding frequently recurs as a seasonal problem, where climate risks intersect with rapid urbanisation and the attendant environmental pressures, creating layered challenges. It is notable that more than 21% of the reviewed studies discussed coastal adaptation options. Of the 23 studies covering coastal adaptation, 16 referred specifically to coastal measures (including mangrove interventions), while the others included coastal adaptation alongside multiple intervention types. Four studies focused exclusively on Bangladesh, reflecting its acute vulnerability to coastal climate hazards and its comprehensive efforts to adapt.

COASTAL ADAPTATION



Confidence in coastal adaptation as an adaptation to climate risks

Coastal adaptation interventions in the literature respond to flooding, cyclones, storm surges, high winds, sea level rise, saline intrusion, and coastal erosion. These risks are addressed through infrastructure, nature-based solutions, planning, and information systems. Effectiveness of interventions is diverse and depends on specific contexts. Institutional and policy frameworks like good governance, planning, functioning legal frameworks, and co-management were considered to be the enablers to contribute to effective outcomes. Most coastal adaptations focus on reducing exposure and sensitivity to specific risks, although some reviews also assess social vulnerability adaptations.

Nature-based solutions (NbS), especially mangrove and wetland protection and restoration, emerge as an important contributor to reduce exposure to flooding, tidal surges and soil erosion (high confidence), fostering economic benefits. NbS were reported to have a co-benefit on mitigation due to their carbon sequestration potential. Livelihood diversification and migration serve as a coping mechanism in response to shocks only if support from social networks is provided. Construction of cyclone shelters and fish landing zones is crucial for physical security and resource protection in times of disaster and is considered a high-confidence adaptation measure.

We have medium confidence in permeable bamboo and brushwood dams; although effective for reducing exposure, the key concern is limited longevity (three-to-seven years) and associated costs. Early warning systems are considered crucial non-structural solutions for flood risk management, but their direct linkage to reducing exposure and sensitivity in the literature was missing.

We have low confidence in built infrastructure (seawalls, high-cost flood defence structures), excluding water-efficient irrigation, due to a tendency to underestimate the scale of climate risk in design, and degradation risks over time. Although flood risk management components are expected to reduce the sensitivity of the flood-affected region, the literature does not provide strong data on impacts of flood risk management approaches. Some agricultural practices like prawn cultivation can provide socio-economic benefits, but are harmful to the local environment, causing soil degradation, pollution, and loss of farmlands for local farmers.

Twenty-three studies mention coastal adaptations, with 16 focusing specifically on coastal geographies. Coastal areas are often studied in conjunction with other geography types like wetland (freshwater), urban/industrial, forest, mangroves, riverine, and mountain areas. Most of the studies saw coastal adaptations linked to sensitivity and adaptive capacity. Around 10 studies were global, and the majority focused on South Asia and Sub-Saharan Africa. Only a single study each was found in Latin America, the Caribbean and the Middle East and North Africa (MENA) region. Studies detailed a range of interventions, often in combination. Out of 23 coastal-focused studies, most interventions mentioned were NbS (15), but these were often in combination with forms of built infrastructure, institutional planning, and technological options. Interventions recorded different objectives – with some seeking to reduce the harms caused by coastal hazards, and others seeking to reduce the vulnerability of people living in coastal areas to losses. Several papers were more concerned with mapping emerging adaptations than detailing causal outcomes, which makes attribution of change to specific interventions challenging.

Table 7: Strength of evidence for coastal adaptation

	No. medium-quality studies	No. high-quality studies	Total
SRs mentioning climate information and forecasting	15	8	23
Exposure	8	5	13
Sensitivity	11	5	16
Adaptative capacity	12	7	19
Poverty	2	2	4
GHG emissions	1	1	2

Nature-based solutions

NbS dominated coastal adaptation options and include a variety of ecosystem-focused actions. Mangrove protection and relocation appears to be a very commonly discussed activity, mentioned in multiple contexts as key adaptation strategy (Yasmeen et al., 2024; Sultana et al., 2023; Klöck and Nunn, 2019). It is linked to increased accretion of lands and carbon sequestration (Thongchaithanawut, Borderon and Sakdapolrak, 2024). Other interventions include salt marsh restoration (Yasmeen et al., 2024), oyster reefs creation/restoration, vegetated levees, permeable bamboo dams, sand dune and beach stabilisation (Yasmeen et al., 2024), and coastal deforestation (Kundu et al., 2020), shoreline conservation, wetland protection, fishery management, and floating garden and community-based projects. A global study of coastal and agricultural adaptations identified NbS as *"the only intervention that has positive effects across all outcome categories in both sectors"*. Evidence is most clear about the contribution of NbS to reducing

immediate risks and impacts from climate change in the coastal sector and promoting economic benefits in the agricultural sector.

These solutions are not foolproof. Mangrove recolonisation takes time and does not satisfy communities who need protection from coastal climate hazards urgently, rather than in several years' time (Kundu et al., 2020). *"People perceive mangroves as a slow NbS solution for coastal erosion protection, and it requires proper management and maintenance costs that community people can hardly bear from their pocket"* (Yasmeen et al., 2024). Likewise, permeable bamboo dams can degrade between three and seven years after construction, requiring resources and governance processes to ensure they are maintained and repaired. Thus, hybrid options (e.g., NbS and bamboo fencing) are often preferred.

NbS are highlighted as having positive effects across all outcome categories with high confidence, whereas coastal megacities have shown a tendency to favour structural approaches to flood management, potentially neglecting non-structural complementary solutions (Thongchaithanawut, Borderon and Sakdapolrak, 2024).

Built infrastructure

Seawalls have long been a solution to coastal inundation. However, these did not receive a positive review in much of the literature. In Belize, villagers found that they "were largely ineffective", and the temporary sea defence that the national government erected "was showing signs of decay". In Yadua Village (Nadroga), Fiji, villagers turned to mangrove replanting after "seawalls repeatedly collapsed". In Tarawa, Kiribati, erosion occurred at the ends of some of the walls shortly after construction, with interviewees describing the seawalls as "sub-standard", "poorly done", and "built wrong" (Klöck and Nunn, 2019).

> *"Another major concern raised by scholars about high-cost flood defence construction is the fact that this type of solution has design constraints (e.g. 100-year flood), and may not be effective in the long term, considering the constantly increasing flood risks facing CMDN (Duy et al., 2018; Ke, Haasnoot and Hoogvliet, 2016; Yin et al., 2015). A study by Gilbuena et al. (2013a) revealed that structural measures could not protect Manila from the flood created by typhoon Ondoy in 2009 because these structures were designed using only 10-year and 30-year discharge return periods for the drainage works and flood protection works, respectively"* (Ogie, Adam and Perez, 2020, p.135).

Local infrastructure to support coastal livelihoods is also an option, including shelters, embankments, irrigation systems etc (Kundu et al., 2020). However, construction can be beyond the reach of many people and can have trade-offs – for example, *"embankments might protect land downstream, but the water has to go somewhere and thus may affect those upstream"*. These examples demonstrate multiple conditions that can fail hard infrastructure solutions, including poor-quality design, poor-quality construction, limited application of climate models leading to high-regret options, and unexpectedly damaging climate hazards, as well as natural wear, tear and decay that requires ongoing inspection and maintenance.

Planning interventions

In large cities, efforts to address climate risk almost by default must address wider planning issues relating to the presence of informal settlements and degradation of local water resources. One study therefore identifies data collection, planning and communication techniques that institutions can use in advance of

interventions, including a "Rapid Impact Assessment Matrix", participatory scenario planning, the use of water level sensors to detect flooding, integrated urban water management, and multi-criteria decision analysis that considered flood extent estimates and costs to determine which measures to use (Ogie, Adam and Perez, 2020). The same review also points out that large Asian cities often neglect flood risk management measures – early warning systems, flood risk information dissemination planning, building codes, stakeholder engagement, flood insurance, and environmental programmes. However, it draws on a paper from 2015, and it is likely that much has changed in the priorities of megacities since then.

Local citizens dependent on natural resources for their livelihoods in some coastal regions are also at risk. A review focusing on Bangladesh highlights how fishers can be caught in a "social-ecological" trap, whereby their limited access to alternative livelihoods pushes them deeper into unsustainable fishing practices (Sultana et al., 2023). The same review highlights government efforts to incentivise fishers to refrain from fishing during the fish breeding season, with 40 kg bags of rice and developing aquaculture microenterprises to boost and diversify incomes. Such approaches have encountered equity problems when they have not adequately incorporated the perspectives of fishing communities or investigated alternative livelihood opportunities. This PES approach is also used to preserve habitats such as mangroves that buffer destructive impacts.

Behavioural adaptations

Autonomous behavioural adaptations are documented in SIDS, reacting to climate variability rather than taking long-term strategic actions to address future risk. *"Many strategies indicate high adaptive capacity – at least with regard to current climate variability – and highlight the importance of sharing and spreading risk, notably through social networks and through livelihood and income diversification"* (Klöck and Nunn, 2019). Communities get "cyclone ready", storing food for emergencies and switching to different fish or crops to cope with the coming lack of available resources. In some cities, households are known to dig trenches and erect their own household-level barricades to reduce flood incidence.

It is not surprising that behavioural adaptations relate more to the adaptation of local livelihoods. Proactive adaptations – changing planting times, cropping patterns etc, or taking up aquaculture (prawns, crabs, integrated prawn-fish-rice farming) – can have *"social, economic and environmental benefits"* (Kundu et al., 2020). However, as the study points out, these do not address all the climate impacts experienced, such as tidal surges. In Bangladesh, migration is used when local adaptation is not effective. Compounding impacts – saline intrusion, flooding and erosion – encourage young people to migrate and take up non-farming activities.

Some adaptations – migration and adoption of alternative livelihoods – result in *"other problems because of a lack of good planning, rules and regulations. In addition, effective responses to these challenges on a massive scale demand improved effectiveness of local and national institutional arrangements and collective strategy development and action to develop a more resilient system"* (Kundu et al., 2020, p.13).

Outcomes reported in reviews of coastal adaptation

Despite the diversity of adaptation responses, their effectiveness and sustainability often remain unclear. Many of the systematic reviews focused little on adaptation benefits and more on immediate consequences of interventions.

Reduced exposure

NbS in relation to coastal adaptation are mostly associated with reduced exposure to climate risks. The establishment of mangrove plantations was repeatedly discussed. *"Mangrove plantation by government and development agencies in the coastal zone is one of the key adaptation strategies to protect against exposure features such as cyclones, storm surges, and erosion and limit saltwater intrusion"* (Sultana et al., 2023). Other nature-based interventions such as shoreline protection through restored vegetation (mangroves/salt marshes) (Yasmeen et al., 2024; Villamayor-Tomas et al., 2024), bamboo encasement, dams (Villamayor-Tomas et al., 2024), restoration of natural coastal buffers, e.g., oyster reefs, vegetated levees, geotextile tubes, and breakwater reefs with recruited oysters (Villamayor-Tomas et al., 2024), successfully reduced wave heights/wave energy, provided better stability in sediment movement from the intertidal bed, and reduced erosion in the controlled site and stabilised the shoreline, thus reducing the exposure (Villamayor-Tomas et al., 2024). However, the extent to which these are effective will likely be heavily dependent on context, design processes and enabling conditions.

Box 7: Reduced exposure of property and communities in Bangladesh

One Bangladesh study identified avoided costs because of mangrove plantations (Smith et al., 2021)

> *"…avoiding damage worth approximately $1.56 billion per year on average (Menéndez et al., 2020). Villages protected by mangroves experienced about half the monetary loss from flood and wind damage to houses, property, crops, livestock, and aquaculture stock during Cyclone Sidr (TK 69,726 or approximately $1,025 per household), compared to villages without such protection.*
>
> *A 100-meter-deep strip of healthy mangroves can reduce storm surge velocity for a storm of similar magnitude by up to 92%, significantly reducing embankment maintenance costs (Dasgupta et al., 2019).*
>
> *The CREL project planted 565,000 mangrove seedlings on 512 hectares, delivering an estimated $485 million in storm protection services and $684 million in annual co-benefits. It also restored 20 hectares of sand dunes with 562,000 seedlings of Nishinda and Dholkolmi (Ipomoea carnea) to reduce erosion and storm surge impacts and enhance habitats for indigenous species."*

The same study also identified the avoided costs from protecting and restoring terrestrial forests:

> *"Catchments with regenerating or planted trees and other vegetation had 3–4 times less soil erosion, 4–35 times less nutrient loss, 16% less annual runoff and the peak flow was seven times lower than a catchment that had been cleared for agriculture (Gafur et al., 2003).*
>
> *Local tree species with deep tap roots could successfully stabilize steep slopes at risk of landslides although this is only suitable for slopes of less than 70 degrees. (Islam and Rahman, 2019)"*

Infrastructure investments are also associated with reduced exposure, although with many challenges and often in combination with other interventions. Cyclone shelters (Yasmeen et al., 2024), dynamic seawalls that dynamically adjust wall height, rubber dams, injection wells and flood control infrastructure

(Kundu et al., 2020) were associated with reducing exposure by improving structural flood mitigation design.

Reduced sensitivity

Given the emphasis on exposure-reducing interventions in coastal adaptation, sensitivity and exposure-reducing interventions cannot be easily separated. Where exposure outcomes focus on reducing the severity and power of flooding and tidal surges, sensitivity outcomes focus on improving the functioning of livelihoods in the face of those impacts. Diversification of livelihoods and investment in infrastructure or agricultural techniques all improve crop yields which in turn, when coupled with other key conditions, lead to more stable or increased income.

One indicator of reduced sensitivity is canopy coverage provided by trees, which mitigate the effects of climate change by providing shade and reducing heat island effects (Majizat et al., 2016). Evergreen species maintain foliage throughout the year, ensuring continuous benefits like air purification and temperature regulation (Hwang and Roscoe, 2017) and thus reducing sensitivity of heat exposures. In Southeast Asia, NbS are particularly valuable as they provide multiple benefits, such as reducing urban heat, managing stormwater, reducing coastal erosion, enhancing air quality, and protecting urban areas from storm surges (Tun et al., 2024). *"Built infrastructure/NbS show relatively high positive mean effects for decreased social/economic vulnerability"* (Villamayor-Tomas et al., 2024).

> *"In Bangladesh, the government's fishing ban initiatives is considered to restore fish stock and ensure food security throughout the year. The government provides 40 kg of rice to the fishing households as payment for ecosystem services to not go fishing during the breeding period. Along with these, Community supported fisheries for selling fresh and locally obtained fish could be one approach to lessen reliance on moneylenders when attempting to adjust to the effects of natural disasters, such as cyclones and tidal surge. Aquaculture is stated in many studies as a means of diversifying livelihood and alternatives to open-catch fishing as well"* (Sultana et al., 2023).

Studies highlight that salt-tolerant rice varieties are an immediate response to increased salinity. However, plants still have limits as to the level of salinity they can tolerate, thus salt-tolerant crop varieties may be a temporary solution in a context of higher emissions scenarios (Kundu et al., 2020).

Along with coastal, nature and livelihood protection, the other sector covered was coastal megacities and the use of small-scale solutions in the informal settlements of those cities. One of the examples of reducing sensitivity mentioned was to introduce micro-drainage and integrate it seamlessly in formal drainage networks in Rio de Janeiro, Brazil. *"This solution is a useful contribution to the enormous challenge of managing the environmental impacts of slum dwellings, particularly because it can be adapted to the unique needs of other developing coastal megacities such as Jakarta, Lagos and Manila"* (Ogie, Adam and Perez, 2020).

Increased adaptive capacity

Adaptation interventions increase adaptive capacity where they enable people or institutions to mobilise resources to informed strategies in response to specific climate risks. In Thailand, the use of permeable dams made of bamboo and brushwood for coastal protection not only increased public awareness of

climate risks but also increased public participation in designing and maintaining the intervention (Yasmeen et al., 2024). In Cotonou, Benin, a proactive approach was taken to relocate communication, transport and hotel infrastructures away from the coastline due to the mounting threats from rising sea levels and coastal erosion. Communities collectively engaged in labour to clear blocked drains and used measures such as sandbags for floods. Construction of wooden bridges facilitated mobility from flood events, and desalinising of water helped urban coastal dwellers have access to fresh water (Ansah et al., 2024).

Many of the related adaptive capacity adaptations identified in systematic reviews for coastal areas related to autonomous actions in which people used their own existing resources to cope with coming climate risks.

> *"The focus on adaptive capacity suggests that the approach in Bangladesh is focused on using innovation and technology to adjust with climate change while largely maintaining the same approaches to agriculture and development. The question remains, however, whether this will be enough in coastal Bangladesh, where multiple climate change impacts are increasingly changing the landscape, especially through sea-level rise and accompanying salinity"* (Kundu et al., 2020, p.13).

The table below from the Kundu et al. (2020) review is included, as it is demonstrative of the way in which compounding climate risks demand multi-pronged and holistic approaches to coastal climate impacts. The implication is that coastal adaptation needs to take a holistic approach to address multiple climate challenges and their implications.

Table 8: Number of studies that investigate adaptation measures based on major themes against climate stresses

Theme	Adaptation measures and activities	Salinity	Cyclones	Seasonal change	Tidal surge	Sea level rise	Temperature & precipitation
Agricultural Adaptation	Prawn culture, crab culture, integrated farming, mixed farming, agricultural practices homestead farming, floating garden	8	1	2	-	1	2
Alternative Livelihoods	Migration, non-farm employment, small business, wage employment	3	3	3	3	5	-
Infrastructure development	Establishment shelter, embankment building, irrigation system management, construction of ponds	2	5	1	-	2	-
Technological advancement	Salt tolerant rice variety, HYV rice, new varieties of other crops, area specific weather forecasting, weather-index insurance	4	1	2	-	-	1
Ecosystem management	Biodiversity conservation, aquatic & terrestrial ecosystems management, coastal afforestation & reforestation programmes, reducing deforestation & forest degradation	7	5	-	2	5	-

Policy development	Policy development, mainstreaming adaptation to climate change	2	2	-	-	2	1

(source: Reproduced from Kundu et al., 2020)

Many coastal adaptations, while intended as exposure benefits, can lead to adaptive capacity co-benefits – particularly if they use NbS. Chan et al. (2012, 2013, 2014) and Yin et al. (2015) expressed concern that coastal megacities in Asia are overly dependent on structural approaches to flooding, while little or no attention is paid to sustainable flood risk management, which transcends hard engineering measures to include non-structural complementary solutions, such as early warning systems, improved access to flood risk information, emergency evacuation planning, building codes, wider stakeholder engagement, land use, flood insurance, and environmental education programmes (Ogie, Adam and Perez, 2020). Villamayor-Tomas et al. (2024) highlight the use of hybrid NbS infrastructure, including nature and engineering techniques for coastal adaptation, and the creation of permeable bamboo dams (T-Dams) for shoreline stabilisation in Indonesia. *"Aside from the physical benefits, the intervention notably increased public awareness of coastal erosion and promoted integrated coastal management (ICM). The initiative strengthened community recognition of nature-based approaches. It fostered a sense of ownership, particularly as locals expressed readiness to maintain and replicate these structures if provided with funding and technical support"*. This is a good example of a low-cost, nature-based approach co-managed by local communities.

GHG co-benefits

Most GHG-related outcomes result from the use of NbS – particularly mangrove plantations, which act as sinks for GHGs. One review offered figures for carbon storage of mangroves.

Box 8: Carbon storage of mangroves

1. Protecting and restoring mangroves:
    a. Carbon storage: 219 tC/ha. Rahman et al. (2017)
    b. Carbon storage: 257 tC/ha, of which 63% below ground in the soil and roots. Abdullah-Al-Mamun et al. (2017)
    c. Carbon storage (global averages): 400 tC/ha for oceanic mangroves; 2000 tC/ha for estuaries.
    d. Average for Indo-Pacific region: 1,023 tC/ha. Conversion to aquaculture by excavating >2 m of sediment can release 70 tC/ha. Sequestration: 1.5 to 6 tC/ha/y (global range) Global review. Chow (2018)
    e. Sequestration: 1.7 tC/ha/y, four times more than mature land-based forests. Offset 1.5% of Bangladesh's fossil fuel CO2 emissions in 2014 Global review. Taillardat et al. (2018)
    f. Sequestration: Sundarbans sequestered 4.8 Mt CO2/year from 1997 to 2010. Offset 10% of Bangladesh's CO2 emissions. Abdullah-Al-Mamun et al. (2017)
    g. Plantations carbon storage: roadside social forestry plantations in south-western Bangladesh store almost 200 tC/ha although this is less than native woodlands. Rahman et al. (2015)
2. Agroforestry sequestration: 115–135 tCO2/ha/y (equivalent to 31–37 tC/ha/y) 7 years after planting for three typical fast-growing species. Hanif et al. (2015)
3. Home gardens carbon storage: a) average 118 tC/ha in above-ground biomass, much higher than home gardens in India, thought to be due to higher tree density. Nath et al. (2015)

4. b) Carbon storage: soil organic carbon 0.12–1.65%; positively correlated with tree species diversity and density, probably because more diverse systems are more productive due to niche complementarity. Islam et al. (2015) [SCO154]

Reduced poverty

Although poverty reduction is associated with livelihood outcomes, only one paper directly quoted poverty reduction benefits resulting from coastal interventions. The study points to the finding that *"NbS can have positive effects of crop diversification, water conservation and coastal habitat restoration on crop-yields, food security and poverty reduction, respectively"* (Villamayor-Tomas et al., 2024, p.5). Another paper includes economic benefits related to poverty reduction but also mentions that an overly strong focus on interventions with economic benefits may not effectively build resilience to all climate change impacts (Kundu et al., 2020, p.10). *"Anticipatory adaptation practices, such as changing planting times, cropping patterns, soil management, etc., not only reduce climate change impacts on coastal livelihoods but also result in potential economic benefits.*"

Enablers

The enablers of effective adaptations differ according to intervention type. For interventions targeted at coastal livelihoods, behavioural change and the availability/lack of availability of specific resources, along with infrastructural investment, are the major enablers for coastal adaptation. *"Some fishers have turned to a subtle strategy of part-time fishing engagements in response to declining catch yields"* and *"Fishers often use their traditional knowledge to understand fish movement, the fluctuation of the fish stock depending on the changes in the weather, and the reproductive and feeding behaviours of the fish"* (Villamayor-Tomas et al., 2024). Similar enablers were also raised in Sultana et al., 2023; Klöck and Nunn, 2019; Ogie, Adam and Perez, 2020; and Fan et al., 2022.

More broadly, livelihood adaptations and transitions need to be accompanied by infrastructure that reduces exposure of those livelihoods, enabling them to transition and establish themselves. Cyclone shelters and structural flood management approaches are key to create space and reduce loss of life and property as a result of cyclone-related stress (Sultana et al., 2023; Jayasinghe et al., 2024; Klöck and Nunn, 2019; Ogie, Smith and Perez, 2020).

Effective coastal adaptation that addresses multiple climate risks requires coordination between government departments. For example, between teams responsible for infrastructure, mangrove and environmental restoration, and coastal livelihoods. *"But in reality, there has always been a vacuum in integrating such a holistic approach to coastal erosion protection due to the conflict of interest between the coastal protection and preservation engineers"* (Yasmeen et al., 2024; Sultana et al., 2023). Limited coordination and collaboration among stakeholders generates challenges in assessing the level of risk and vulnerability of environments they are exposed to over time (Jayasinghe et al., 2024; Klöck and Nunn, 2019). Local politics also plays a role – political influences can prioritise large, costly projects that do not target the real problem, while at the same time, political groups with interests can derail flood control projects (Ogie, Smith and Perez, 2020).

Institutional processes *"involving Indigenous communities in climate-related policy making is crucial to capitalise on IK in building adaptation and resilience to climate change. It requires an inclusive approach to decision-making, planning, and management of climate policies and to shift the focus to a bottom-up approach and in engaging multiple stakeholders"* (Villamayor-Tomas et al., 2024).

Findings from Ogie, Smith and Perez (2020) suggest that other factors, including flood return periods, institutional aspects of governance, topography, societal exposure, and experience with past extreme events can influence in-depth decision making regarding priority-based selection of flood protection measures. It also follows that reversing the barriers described above can enable more effective coastal adaptation – for example, addressing the coordination challenges between government agencies.

Barriers, limitations and maladaptation risks

There is a high risk of maladaptation, particularly in relation to grey infrastructural investments and in a context where autonomous adaptation is already underway. Local adaptations such as bamboo dykes or bamboo breakers can be easily destroyed, and shorelines can be undermined by activities such as unregulated shrimp farming (Yasmeen et al., 2024).

A small number of studies point to potential negative environmental consequences from some nature-based adaptation efforts. For example, one study of NbS in the Himalayas noted that tree planting for landslide control might compromise groundwater recharge (Mehta et al., 2023). Natural solutions in Sub-Saharan Africa are not all effective in reducing flood risk: most reviewed results showed that headwater wetlands (dambos) produced an *increase* in flood magnitude (with an exception in Malawi), due to their rapid saturation (Acreman et al., 2021). Another risk is the perception of ineffectiveness of interventions if maintenance and support are not sustained in the long term (e.g., Yasmeen et al., 2024, for coastal interventions).

Infrastructure of any kind, including NbS, requires financial capacity which may be beyond the capacity of governments or communities to facilitate. Communities may aim for less expensive hybrid solutions such as bamboo dykes, but as detailed below, these can degrade or be overwhelmed by some tidal surges (Yasmeen et al., 2024; Sultana et al., 2023). Technical know-how and equipment for adaptation activities are repeatedly said to be lacking. In one example in Fiji, there was only a single manual water pump available for purchase, which broke shortly after installation and could not be repaired or replaced quickly (Dumaru, 2010; see also Frankland et al., 2012). SIDS face significant gaps in understanding, knowledge, and data on climate change as well as adaptation options, not least because of limited human resources (Klöck and Nunn, 2019). This makes planning the size and scale of coastal adaptation challenging, and increases the risk of underestimating the future scale of impacts. Lack of data impedes industry stakeholders' ability to navigate with minimal disaster impact (Jayasinghe et al., 2024; Klöck and Nunn, 2019; Kundu et al., 2020; Brambilla et al., 2022).

Our review noted a tendency in the literature to occasionally report on negative impacts of adaptive measures (which increase vulnerability), but without offering generalisable conclusions that link particular interventions to corresponding maladaptations. In practice, this means that maladaptations are context-specific. For example, prawn cultivation in Bangladesh has been harmful for the local environment, and the Great Garuda Sea Wall in Jakarta is linked with poor planning, elite capture, and limited focus on environmental sustainability (Kundu et al., 2020, p.15; Ogie, Smith and Perez, 2020, p.133).

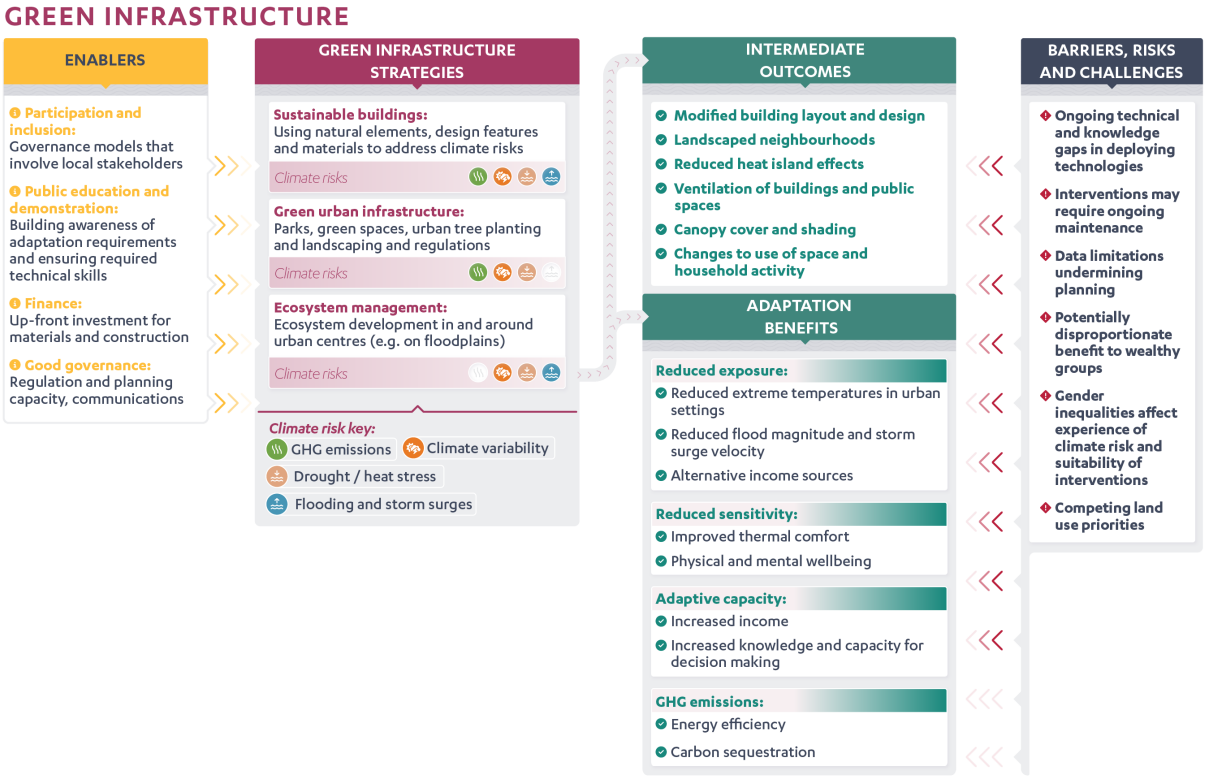
Implications for practice

- Nature-based solutions repeatedly emerge as an effective approach to long-term reduction in exposure to a range of coastal hazards. However, hybrid approaches are needed which recognise that NbS can be slower to see results – for example, integrating temporary barricades that have an impact while NbS takes hold.

- NbS also require management and maintenance, which will likely require community support. Developing this will require education and investment into community priorities and needs, so that communities can be confident that their time invested in ecosystem management will reap rewards through more stable or enhanced livelihoods.
- In coastal cities, it is particularly important to recognise that climate change is just one of many likely problems, as rapid urbanisation places pressure both on authorities and on local environments. Informal settlements are particularly vulnerable to flooding, and residents need to be part of solutions to ensure that flood risk management and flood reduction infrastructure is relevant and effective.
- Infrastructure of all kinds can be more expensive, particularly in coastal regions which are highly vulnerable to degradation from storms, tidal surges, and salinity. Innovative mechanisms might be needed to provide financing for infrastructure that can withstand the pressures of coastal climate hazards.
- Grey infrastructure must be used with caution. If such infrastructure is to be used, design must consider extreme climate risks – i.e., "100-year-floods" – to ensure it is robust enough to withstand a range of possible and unknown climate futures. Combinations with other strategies are also essential, including NbS, as well as flood risk management – early warning systems, education, and rapid emergency evacuation capabilities.

4.4.5 Green infrastructure

Green infrastructure (GI) takes various forms and as such corresponds to various climate risks. For instance, structural and design features of buildings and urban green spaces are aimed at reducing impacts from variable temperatures, especially heat stress. A smaller number of studies consider the use of GI to address urban flood risk. In both categories, adaptation benefits are realised chiefly through directly reducing exposure to physical events and reducing the sensitivity of local households and communities to their effects. However, some studies also posit benefits through adaptive capacity, via improved knowledge of sustainable options to manage climate extremes.



Confidence in green infrastructure as an adaptation to climate risks

We have medium to high confidence in the ability of building design and green spatial interventions and strategies (e.g., construction materials, tree planting) to address climate variability and heat stress risks, by reducing thermal variation and discomfort. Although few studies examine the scale of these effects in detail, some robust, quantified results are found across multiple geographies, both in the present and in future scenarios under significant further climate change. Low to medium confidence can be established in the impacts of green spaces, neighbourhood and urban landscaping to improve individual, household and community wellbeing. Despite a general scarcity of evidence, important case studies include improved income and livelihood options from urban gardens in Sub-Saharan Africa.

We have low confidence in the ability of these interventions to reduce (net) GHG emissions: within one systematic review, a large number of studies note impacts on building energy efficiency (and reduced energy demand). A smaller number note carbon sequestration. Both of these impacts are only occasionally quantified. The reduction in building energy use varies widely depending on the specific intervention and the geography it is applied in – for instance, insulating materials can increase energy use in hot climates.

Strength of evidence

Literature focusing on GI was limited, covered in 20 studies. These studies were identified through a manual review of the data extracted: both the intervention type and the more detailed activities within interventions were checked for aspects of infrastructure with nature-based, low-carbon, or other intentional, environmentally sound characteristics, in urban or rural settings.

Table 9: Strength of evidence for green infrastructure

	No. medium-quality studies	No. high-quality studies	Total
Intervention	13	1	14
Exposure	7	1	8
Sensitivity	11	1	12
Adaptative capacity	8	1	9
Poverty	0	0	0
GHG emissions	3	1	4

The overall quality of the studies addressing GI is moderate. The nature of the evidence varied across the different activity types described below. In general, quantified outcomes from GI interventions are comparatively rare, with only six studies offering any kind of quantification. However, qualitative effects (such as reducing high temperatures) are consistent across sub-groups of studies which look at similar intervention and activity types. Importantly, the findings and examples described in the remainder of this section refer to the most traceable and specific occurrences available in the literature, while the numbers in the table above also include a small number of studies that mentioned GI at a high level as part of a wider set of interventions, which makes associations with specific outcomes less clear. Readers should treat the figures as indicative and exercise caution over interpreting them as statistics.

All the studies in the group are academic, peer-reviewed publications, which might introduce a positive bias on results. There was good variety in the geographic contexts: half were global, while Sub-Saharan Africa, South Asia, and East Asia and Pacific were all accounted for among region-specific studies. Some studies provide more detail about robust methods in the primary reviewed studies from which they draw their conclusions (e.g., a study by Rahmani and Sharifi (2025) describes experimental methods for interventions at the building level).

Built and urban environments are the focus of around half of the literature in this sample. Some studies focus on specific technologies targeted at thermal comfort, with energy saving co-benefits, while others mention the use of GI within urban planning more broadly to achieve adaptation outcomes for the urban population. Examples of activities under GI within the built environment arena include:

1. Sustainable buildings – which may use building elements (including natural elements like green roofs or walls), passive design (including ventilation), or other technologies (e.g., assessment tools) to achieve thermal comfort and energy efficiency.
2. Green urban infrastructure – such as parks and other green spaces, tree planting, and other urban landscaping, e.g., restrictions on the expansion on certain kinds of grey infrastructure.

Studies focused on general urban-level activities with GI are slightly more commonplace than those focused closely on building-level activities, although some urban-focused studies also note the use of sustainable and green building features as part of broader urban strategies (e.g., Rahmani and Sharifi, 2025).

Outcomes reported in reviews of green infrastructure

Outcomes from GI, especially in the built environment, have impacts which are not neatly separated between exposure and sensitivity: they typically reduce the incidence of physical climate risks in the immediate area or locality, thereby benefiting the household, community, or city level in terms of overall sensitivity to climate change impacts.

Reduced exposure

Building-level measures and other forms of urban GI are shown by several studies to reduce resident exposure to high temperatures. Multiple reviews, with global scope, highlight that integrated approaches are important to reduce urban exposure (Kareem et al., 2020; Ayo-Odifiri, 2024; Rahmani and Sharifi, 2025; Tun et al., 2024; Liu et al., 2022). Features of GI include building layouts, building density, neighbourhood-scale landscaping, and specific green landscape elements (parks, urban forests, green roofs), often requiring local government planning approaches as part of a combined intervention. A study in Nigeria (Ayo-Odifiri, 2024) quantifies the benefit of tree planting around housing, by finding a 5.4°C indoor-outdoor temperature differential in the unsheltered building, and 2.4°C in the tree-covered building during hot seasons. Reduced pollution is a co-benefit reported by some studies, particularly of measures for ventilation (Liu et al., 2022).

Passive design, ventilative cooling, reflective and green roofs, shading, and insulation show potential for energy savings and reduction in thermal discomfort under different climate scenarios, sometimes improving comfort by 50% as far out as 2080 (Tajuddeen and Sajjadian, 2024). Some building techniques and materials (such as natural ventilation and phase change materials (PCM), which *"store a large amount of latent heat within a narrow temperature range, regulating heat flow between indoor and outdoor environments"* have been studied using experimental methods, demonstrating statistically significant benefits by observing reductions in peak temperatures. One example is a 4°C reduction in indoor temperatures from corn husk composite material versus standard brick construction (without mechanical cooling), registered in Islamabad, Pakistan. Window-wall ratios, window glass type, and efficient air-conditioning equipment are also shown to lead to positive outcomes for exposure to heat and co-benefits.

Reduced sensitivity

The benefits of built environment GI interventions extend to reducing urban heat island effects and improved health outcomes, thereby reducing sensitivity at a community level, as shown by multiple studies across geographies (Tajuddeen and Sajjadian, 2024; Rahmani and Sharifi, 2025; Tun et al., 2024). A single study in the dataset examined atmospheric water harvesting (AWH) technologies, another form of GI that helps to reduce sensitivity by improving water supply and reducing stress on water infrastructure (Brambilla et al., 2022).

Integrating NbS into urban planning is recognised to reduce sensitivity to heat- and water-related climate risks. These impacts are illustrated by a small number of studies, including in Southeast Asia (Tun et al., 2024) and China (Rahmani and Sharifi, 2025), and Sub-Saharan Africa – for example, one study suggests that improving the municipal landscape in Port Harcourt, Nigeria produced a "significantly" lower local land surface temperature (Guja and Bedeke, 2024). Green spaces and tree planting can contribute to several benefits in this regard, through important effects like shade and evaporative cooling. Access to green spaces also promotes physical and mental wellbeing, which can be considered to reduce sensitivity (and promote adaptive capacity) among individuals and communities. Evergreen species are noted as

especially valuable for maintaining foliage throughout the year, ensuring continuous benefits like air purification and temperature regulation (Tun et al., 2024).

Increased adaptive capacity

Designing liveable buildings and cities and protecting communities using GI can raise adaptive capacity both through improving wellbeing (e.g., Tun et al., 2024) and promoting improved understanding of sustainable approaches. However, tangible evidence of urban wellbeing outcomes was limited in the literature. Raising income and food security are mechanisms for increased adaptive capacity through GI interventions, observed in a small number of studies. For instance, residential and urban green spaces (e.g., home gardens) in cities in Nigeria were also shown to have strong socio-economic benefits for households (Ayo-Odifiri, 2024); this finding was confirmed in other settings in Sub-Saharan Africa (Durban, Cape Town) (Solomon, Singh and Islam, 2021).

Reduced poverty

Explicit poverty reduction outcomes are rarely observed from these interventions; however, several studies indicate that increases in income resulting from these measures can contribute to poverty reduction benefits.

GHG co-benefits

Mitigation outcomes of GI – including carbon sequestration and reduced energy use from an improved built environment – are regularly reported but rarely quantified. One study across a wide range of built environment interventions finds that improved energy efficiency appears in the literature around half as frequently as improved thermal comfort (26.5% compared with 50.8% of the literature), suggesting that these outcomes are not always strongly associated (Rañeses et al., 2021).

Energy efficiency from tree planting around buildings is estimated at around 22% annually from one study in Nigeria (Ayo-Odifiri, 2024) while another, with unclear geographic scope, finds that cool roofs (which are highly reflective of light through use of materials, therefore reducing surface temperature changes) can reduce total energy demand by around 7% (Tajuddeen and Sajjadian, 2024). Carbon sequestration estimates for a range of existing GI are found for Bangladesh (e.g., 219 tC/ha for mangroves, 200tC/ha for roadside social forestry plantations) (Smith et al., 2021); the geographic generalisability of such figures is unclear.

Differential impacts across social groups

Although poverty reduction outcomes are not recorded, poor households are nevertheless sometimes targeted by urban interventions like city-level plans, green structures, and neighbourhood improvements like green roofing (Kareem et al., 2020). Women are also identified as beneficiaries of some of the same sets of interventions. For example, urban and residential green spaces in Sub-Saharan Africa have been shown to benefit gender equality by positively impacting women's decision making, income, food security, and bargaining position within households and communities (Solomon et al., 2021).

Maladaptation risks

Urban greening projects could disproportionately benefit more affluent groups, potentially diverting resources from marginalised areas, especially when directed by technocratic, top-down decision making (Tun et al., 2024). Furthermore, one study (Solomon et al., 2021) identifies the importance of gender-

responsive urban adaptation. Climate-resilient spaces at the household, community, and city-wide levels are affected by gendered vulnerabilities and inequalities. For instance, differential access to green spaces can arise due to issues of comfort and safety; an example is given of Khulna, Bangladesh, where poor planning and patriarchal norms have impeded and restricted women's mobility.

Enablers

Participation of citizens and/or representatives is mentioned frequently, in both rural and urban settings. For instance, a review of NbS for urban resilience in Southeast Asia (Tun et al., 2024) suggests the importance of prioritising *"cultural significance and demands and willingness of residents"*, which requires *"inclusive and participatory governance models that involve local communities, private sector stakeholders, and government agencies in the planning and implementation"*. To build awareness and community support, several studies also recommend public education and demonstration projects (Tun et al., 2024; Ayo-Odifiri, 2024; Smith et al., 2021).

Good governance systems, incorporation of types of knowledge, and institutional support are also noted to be important by several studies describing GI interventions. In the urban context, governance has several crucial dimensions: regulation capacity (planning frameworks and design guidelines), understanding economic costs and benefits, and securing public acceptance through, for example, data visualisation and community engagement. An example of integrated governance and learning can be found in emerging cities in China implementing urban ventilation corridor plans within broader city master plans, entailing evaluation of local climate and wind dynamics and appropriate corresponding design choices (Liu et al., 2022; see also Ren et al., 2018).

Barriers

Institutional barriers are prominent. For instance, many cities grapple with fragmented policies, inadequate funding, and weak coordination which inhibit development of urban GI (Tun et al., 2024). Lack of funding is tagged in nine out of 21 GI-related studies.

Technical and knowledge gaps and shortcomings in readiness to deploy technologies are considerable barriers, particularly to NbS and to advanced building materials and tech like AWH (Ayo-Odifiri, 2024; Brambilla et al., 2022). Within implementation bodies (government or community), these gaps can include a lack of local technical capacity, reliable data, and uncertainties about performance metrics. Long-term maintenance and sustainability challenges, particularly for NbS, including the costs and practicalities of ongoing management, can affect their lasting effectiveness.

Land use constraints and competing priorities, such as land acquisition issues and the prioritisation of other development objectives over green spaces, can limit their application in urban areas. One study provides extensive qualitative evidence on the constraints on GI in coastal megacities in developing countries, including the pressures of rapid urbanisation, despite the observed limitations of grey infrastructure (Ogie, Adam and Perez, 2020). These include the pressures of rapid urbanisation – supressing natural retention areas and removal of natural vegetation – and vested interests among political elites (e.g., in Jakarta) favour continued and exclusive reliance on hard engineered infrastructure over GI for urban flood defence.

Implications for practice

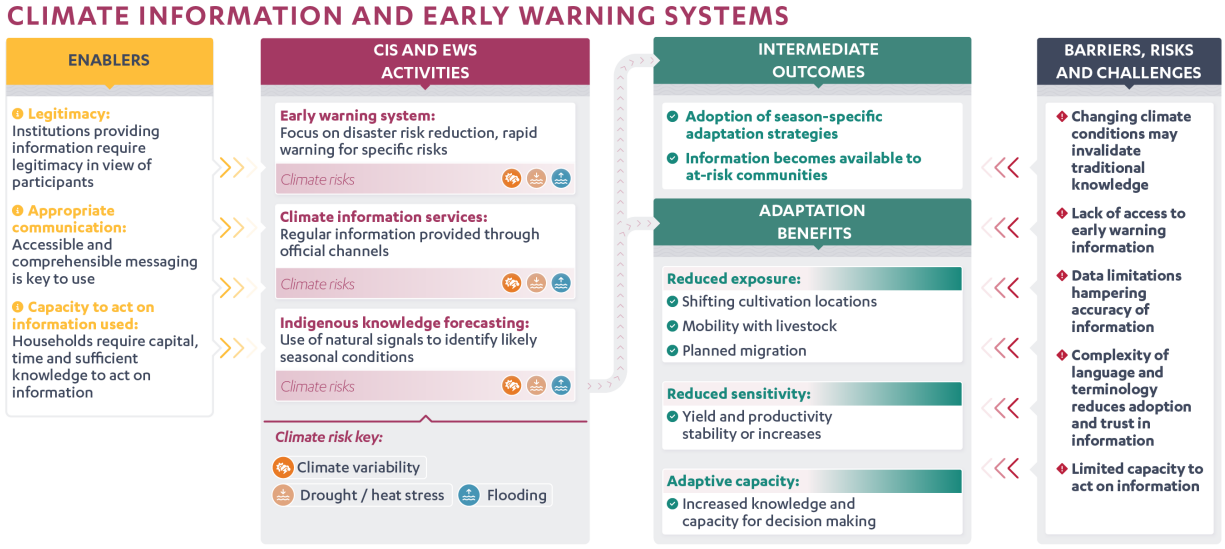
- **GI interventions are effective at reducing exposure and sensitivity to heat-related risks**, and they have potential co-benefits for climate mitigation. Funders and decision makers should include

them in programming at multiple scales – from building-level measures (e.g., green roofs, passive ventilation) to city-wide green spaces.

- **Research is needed to understand not only which building-level measures are most effective, but which are cost-effective and accessible** in different geographic and climatic regions. Local, technical capacity for using materials and design techniques is a requirement for these interventions to benefit developing countries at scale. Funders should support green building training programmes in LMIC cities with a strong research and monitoring component, to share and scale up lessons for further practice.
- **GI interventions are likely to be best scaled and sustained through integrated planning approaches, particularly those which engage communities** and link multiple interventions (such as green spaces with efficient building layouts and designs). However, planning requires additional institutional capacity and political will. Funders should make sure that green planning programmes by relevant authorities are adequately supported. Support should facilitate community participation and establish clear responsibilities and funding mechanisms for ongoing management, to avoid the perception (and reality) of intervention ineffectiveness.
- **GI interventions can benefit marginalised groups when they are sufficiently targeted.** However, there is a risk that affluent groups may disproportionately benefit if projects are not designed inclusively. Policies and support should ensure equitable access and avoid reinforcing existing inequalities, particularly through participatory planning and gender-responsive approaches.

4.4.6 Climate information and early warning systems

Climate information services (CIS) and early warning systems (EWS) are key to adaptation to all types of climate risks. However, the literature has clear limitations: the clearest findings from systematic reviews are limited to specific countries, and the links between use of information and adaptation benefits are not well defined. Further, much of the evidence in this review draws on papers from the last ten years, in a field which has changed rapidly in that time, reducing its value.



Confidence in climate information and early warning systems as an adaptation to climate risks

We have medium to high confidence that CIS can enable many kinds of other adaptation interventions. Appropriate information leads to decision making that has exposure and sensitivity benefits. In particular, EWS can be effective at reducing exposure by facilitating risk management and evacuation strategies, particularly in areas prone to climate hazards and natural disasters. CIS and extension programmes that incorporate local knowledge have been shown to be effective at increasing adaptive capacity where they enhance farmers' decision-making abilities. Whether this translates to poverty reduction or social vulnerability benefits is not clear. CIS are mostly accessible to farmers with more resources, education, ICT, credit, and extension access.

The literature offers medium levels of confidence in the role of indigenous forecasting, which can be effective but may be invalidated by climate conditions. That said, we can be more confident that integration of indigenous knowledge with science-based information builds trust, reliability and utility of information, making it more likely to be used and applied to local livelihoods.

Among the studies reviewed, approximately 22 discuss climate information and early warning systems, albeit to varied degrees. Forecasting is the central focus of two studies (Muita et al., 2021; Nkiaka et al., 2019), and features prominently in three studies discussing indigenous adaptation (Mbah, Ajaps and Molthan-Hill, 2021; Srivastava and Maity, 2023; Hossin et al., 2023). It is more generally mentioned in relation to CSA, where it can enable more effective outcomes.

Strength of evidence

Table 10: Strength of evidence for climate information and early warning systems

	No. medium-quality studies	No. high-quality studies	Total
SRs mentioning climate information and forecasting	14	8	22
Exposure	7	3	10
Sensitivity	12	6	18
Adaptative capacity	9	7	16
Poverty	3	2	5
GHG emissions	1	0	1

Of the five studies in which climate information and forecasting is most prominent, three studies are of medium quality, and two studies are of high quality. The studies mainly linked to sensitivity and adaptive capacity benefits. All studies discussing climate information are published in academic journals, and publication bias is a risk – albeit an unlikely one, since most of the studies focus on mapping and categorising ongoing adaptation or identifying links between climate information and an existing intervention, location or climate hazard. Since fewer than 25% of systematic reviews mentioning climate information or forecasting keep it as a primary focus, and these have a smaller geographic spread, generalisations about adaptation benefits resulting from certain types of climate information provision are difficult to make, reinforcing the importance of context-specific approaches.

There is notable heterogeneity in evidence. While a small number of studies offer clear evidence of the role that CIS play in supporting adaptation, the majority make no clear link between information and how

it leads to adaptation benefits, except as an enabler for interventions such as CSA. In most papers, it is not possible to attribute specific adaptation benefits directly to the availability or mode of CIS delivery. There is also a split between types of climate information. Several studies focus on indigenous forecasting approaches, others focus more on data-driven forecasts disseminated to communities, and many mention combined approaches. Further, geographies tend to be biased towards well-studied African countries such as Ghana, Kenya, Senegal, Nigeria and Ethiopia, with Asian contexts such as Bangladesh and Pakistan featuring to a lesser extent. South American countries are mentioned in only three studies.

Climate information definitions

Climate information encompasses weather and climate forecasts delivered at different temporal and geospatial scales, depending on the need of the user and sector. There is some distinction between EWS and CIS, in that the former is often referred to alongside disaster risk reduction, which can have different connotations depending on the context. For example, the nature of EWS for cyclones in urban centres might be very different to that for drought in arid and semi-arid areas. CIS tend to refer to institutionalised systems for disseminating climate information in various forms, usually delivered by government actors including meteorological agencies and local agricultural extension officers.

Broadly, the literature explores how access to and the use of climate information (CI) and EWS increases adaptive capacity and resilience across communities and sectors, particularly in relation to agricultural outcomes and disaster risk management. The literature examines CI and EWS as a specific intervention and as an enabling factor. Some papers focusing more specifically on CIS also discuss barriers to the use and effectiveness of CIS, as well as instances in which they may act as a barrier in and of themselves, depending on contextual factors like accessibility, and social norms such as gender relations.

It is notable that the **none of the studies discuss CI in terms of long-term scenario planning** and how interventions might consider future uncertainty of climate risks. The typical timeframe in this literature set for climate forecasts ranges between a few days and a season, not over five or ten years or longer.

Indigenous knowledge (IK) forecasting has ongoing relevance to people's efforts to adapt, particularly where meteorological forecasts remain unavailable, inaccessible or mistrusted (Nkiaka et al., 2019; Nyoni et al., 2024). Indigenous peoples rely on accumulated observations of environmental, biological and astronomical phenomena, including animal behaviour, plant cycles, insect activity, celestial patterns, and hydrological flows to forecast weather patterns and extreme climate events. This knowledge is codified into traditional seasonal calendars that inform socio-economic planning, agriculture, mobility, and disaster risk management. Empirical studies have demonstrated that in certain contexts, like Ghana's Sahel region, IK-derived forecasts match the accuracy of national meteorological department outputs (Nkiaka et al., 2019). Further, IK forecasts are feeding directly into local adaptation strategies (Shaffril et al., 2020).

Several studies highlight the interaction of IK with more "top-down" CIS as well as other adaptation and resilience interventions. IK influences both uptake and effectiveness of adaptation strategies. In many communities, the introduction of scientific CI interacts with pre-existing indigenous forecasting systems, influencing decision-making processes at the local level. Studies have shown that where CI is perceived as reliable and useful, it has been successfully integrated with IK to improve farmers' management of climate risks (Muita et al., 2021; Ansah et al., 2024).

For instance, in Kenya's Machakos and Makueni counties, the combined use of sub-seasonal and seasonal forecasts with indigenous forecasting methods has significantly strengthened farmers' ability to navigate increasingly volatile weather patterns.

> *"Indigenous Forecasts (IFs) are perceived to be reliable and useful in the management of climate risks in Machakos and neighbouring Makueni counties. However, availability and use of sub-seasonal and seasonal forecasts to farmers from the two counties have encouraged the successful combined use with IF and resulted in increased farmers' ability to manage changes in weather patterns"* (Muita et al., 2021, p.10).

Dorji et al. (2024) provide a comprehensive review examining the contribution of IK to adaptation and resilience. IK is simultaneously a repository of historical environmental data and a dynamic, evolving system. The use of indigenous forecasting facilitates increased accuracy in planning and risk assessments (which can then be used in EWS), while embedding social, cultural and ecological perspectives which are often absent from purely scientific models.

Table 11: Thematic breakdown of early warning systems and climate information and how they are discussed in the literature

Theme	Discussion
Adaptive capacity and resilience	EWS/CI are critical tools for enabling communities to anticipate hazards and take proactive measures. They increase resilience, particularly in urban settings.
Agriculture	CI/EWS guide cropping systems and planting decisions, and there is evidence of meaningful yield improvements. Examples include farmer reliance on forecasts and traditional indicators like plant phenology and animal behaviour.
Disaster risk management	EWS is a key non-structural intervention for flood and disaster risk management; used in planning and evacuation strategies.
Enabling factors	EWS/CI function as enablers for adaptation, particularly in agriculture. Access to CI via mobile phones and social networks helps facilitate timely and appropriate decision making – supporting CSA including seed choices, planting times, and microclimate management.
Intermediate outcomes	EWS can be framed as a precondition/intermediate step for achieving larger adaptation goals, such as planning via GIS to reduce exposure.
Barriers	Top-down, technocratic approaches and poor communication limit effectiveness. Gender, education, access to technology, and trust gaps affect uptake. Barriers include limited reach of information, inaccessibility, and perceived irrelevance of forecasts.
Local and indigenous knowledge	IK is used for weather prediction and preparedness. Communities rely on traditional indicators (moon, clouds, animal behaviour). Involves storytelling and oral transmission. Combining IK with formal CI is ideal for managing climate variability.

Outcomes reported in reviews of CI and EWS

ClS interventions provide an immediate adaptive capacity benefit through provision of information and knowledge that then contributes to exposure and sensitivity co-benefits.

Reduced exposure

Early warning and climate information provides the impetus to make temporary or permanent migration decisions, or decisions that reduce exposure of key assets. In the case of urgent disasters, information may lead to temporary migration away from affected areas until the threat has passed, before returning (Shaffril et al., 2020). Seasonal forecasts may lead to labour migration of household members, reducing the burden on the household while creating opportunities to receive remittances. Long-term shifts in climate, when they are properly understood, can lead to increasing importance of migration as a strategy for dealing with variability, which may become permanent if traditional livelihoods become untenable (Legide et al., 2024; Kundu et al., 2020). Indeed, pastoralist communities are well known for using mobility as a strategy for managing climate variability (Kratli, 2015). With indigenous forecasts as well as data, pastoralists reduce exposure of both people and assets by diversifying their herds with multiple species and sending them to multiple locations to minimise losses to drought (Legide et al., 2024). CIS might also lead to efforts to reduce exposure of key assets. For example, CIS might lead to *"shifting cultivation in response to increasing temperatures at lower altitudes... and crop rotation... to help spread risk across space and time"* (Mbah et al., 2021).

Reducing sensitivity and increasing adaptive capacity

Benefits to reduced sensitivity and increased adaptive capacity tend to overlap in relation to CIS. Information about rain timings may influence seed selection, planting locations, and livestock migration routes. Outcomes are characterised in terms of agricultural yields, adoption of new farming practices, and post-harvest losses (Nkiaka et al., 2019). It is important that the timing and methodologies used for these studies is unknown, and that yield increases do not necessarily imply systemic resilience. However, the systematic review implies that useful climate information influences decision making with tangible agricultural results.

> *"Ghana indicated that the use of WCS by farmers helped to increase maize yields by an average of 44% (Tarchianiet al, 2017). A separate study in Burkina Faso reported that the use of forecasts by farmers induced changes in farming practices among 75% of the target farmers; leading to a 30% increase in grain production and substantially reduced post-harvest losses (Roudieret al, 2014). Results from the same study also indicated that 10 d forecasts were more useful to farmers than seasonal forecasts."*
>
> *"A survey of 289 farmers in Senegal found that: 78% used WCS to guide their farming decisions at the onset of the rainy season, 96% expressed satisfaction with the farming decisions taken after receiving WCS and 78% reported of a substantial increase in crop yield"* (Ouedraogo et al., 2018).
>
> *"In Benin, 95% of 354 maize farmers involved in an assessment of the economic benefits of WCS, indicated that they changed their farming decisions after receiving WCS. Results from a study covering both Senegal and Kenya showed that more than two-third of the farmers who participated in the study attributed the increase in crop yield to their ability to change farming decisions based on the accessibility to and use of WCS (Knivetonet et al, 2015). Likewise, in Ghana, Kenya and Senegal farmers reported a substantial increase in crop yield after using climate services* (Onyango et al., 2014; Anuga and Gordon, 2016; Mckuneet et al., 2018)." (Nkiaja et al., 2019)

Only one systematic review discusses climate information in urban settings, drawing on one of its constituent studies to discuss the importance of integrating CIS into flood management strategies to reduce impact (Ogie, Adam and Perez, 2020).

One review explored EWS and its contribution to the tourism sector. Where portions of a population may be less familiar with geographic trends and evacuation routes (and especially within high-risk geographies like low-lying coastal zones), EWS has been utilised as an effective component of disaster risk reduction (DRR) strategies to bolster preparedness and resilience against hazards. The study does not mention economic benefits but indicates how EWS can enable localised management of climate risk with appropriate packaged information (Jayasinghe et al., 2024).

Reduced poverty

While there is no explicit study dedicated to examining these tools as a strategy for poverty reduction, sources indirectly touch on climate information and weather services leading to reductions in poverty through improved livelihoods and increasing resilience, with the mechanism typically as follows:

Use of climate information and weather services → Tailored strategies → Improved outcomes (e.g., agricultural yields) → Higher incomes = Poverty alleviation

However, the nature and extent of any poverty reduction is not discussed.

Differential impacts across social groups

The studies reviewed were rarely explicit about the social characteristics of beneficiaries of climate information, outside of their livelihoods or their characteristics as indigenous populations. Within low-income urban contexts characterised by densely populated informal settlements, EWS increases adaptation against sudden-onset disasters by providing residents ahead-of-time notice that disaster will strike, allowing them to evacuate and/or prepare accordingly (Ansah et al., 2024).

One study notably mentions technical and social barriers, whereby top-down approaches in disaster risk management can exclude women within societies where women have limited access to technology, making them dependent on men for early warning information (Solomon et al., 2021). Nyoni et al. (2024) highlight how most CIS are mostly accessible to farmers with credit access, education, extension support and ICT access.

Enablers

The effectiveness of CIS is limited without consideration of enablers that build trust in and usability of communication formats.

The legitimacy of the information and its providers plays a crucial role in whether information is acted upon. IK systems tend to have greater legitimacy and historical reliability within their context (Dorji et al., 2024). Thus, integrating data with indigenous forecasting through approaches like participatory scenario planning can increase credibility and uptake, respecting the validity of both epistemologies. When farmers and forecasters sit at the same table, sharing perspectives and negotiating the terms of prediction, the resulting forecasts improve accuracy and cultural legitimacy. Trust is strengthened when users are engaged throughout the process, from production to dissemination.

The communication format influences whether forecasts are used. One systematic review looking across evidence in Kenya notes: *"Use of short messages through mobile phones, provision of information through*

officers from the agriculture office and the KMD [Kenya Meteorological Department] has improved the making of appropriate decisions on farming methods and production" (Parita et al., 2012; The Ministry of Agriculture, Livestock and Fisheries, 2017). It is likely that consideration is needed with participants in each target location to identify preferred methods.

Adaptation benefits are more likely to be realised from CIS when there is sufficient coordination with other agencies and integration with ongoing programmes. Collaboration between different actor types, hydrologists, climate scientists, extension workers, relevant ministries, farmers and their representatives is needed to ensure that coordination is appropriate and useful (Nkiaka et al., 2019; Jayasinghe et al., 2024). Where climate information is required for specific purposes – such as warning tourists away from risk – special consideration might be needed that relies on previously unusual collaboration between stakeholders.

Nkiaka et al. (2019), a study focusing specifically on CIS in Kenya, Ghana, Senegal and Nigeria, notes the following enabling conditions for CIS to increase resilience to risks:

> *"...establishing more social protection mechanisms that users can rely on when the forecast fails; and (v) facilitate access to loans for the timely purchase of farm inputs, equipment for land preparation, and the purchase of fodder for pastoralists. The implementation of these developmental activities have the potential to enable users of WCS [weather and climate services] to continue to realise substantial benefits from using weather and short-term climate information".*

Integration with agricultural and market information, or with suppliers of seeds and agricultural inputs, can also boost access, while enabling farmers to make decisions based not just on the forecast but local opportunities (Muita et al., 2021; Nyoni et al., 2024).

Box 9: Using IK for pastoralism in Ethiopia

"Afar and Borana pastoralists in Ethiopia effectively utilize IK for weather forecasting, along with their access to traditional meteorological data. This enables them to make informed decisions, such as relocating their herds to areas with available water and pasture or storing pasture for periods of drought, thus reducing their vulnerability to drought (Balehegn et al., 2019; Debela, 2017). Additionally, Mclean and Nakasima (2012) argued that the indigenous weather forecasting system adopted in Eastern African countries helps address the gaps in formal seasonal forecasting conducted by public institutions, with the support of agricultural extension agents… Many African countries' formal climate information services have been criticized for their inaccessibility and lack of adaptation (Basdew et al., 2017). In contrast, indigenous weather services are easily accessible through indigenous social networks, making them a more accessible and user-friendly option (Balehegn et al., 2019; Rahman, 2020)" (Legide et al., 2024, p.407).

"IFs are perceived to be reliable and useful in the management of climate risks in Machakos and neighbouring Makueni counties (Gichangi et al., 2015). However, availability and use of sub-seasonal and seasonal forecasts to farmers from the two counties have encouraged the successful combined use with IF and resulted in increased farmers' ability to manage changes in weather patterns (Speranza et al., 2010)." (Muita et al., 2021, p.10).

Climate information is not useful unless there is capacity to act on information received. Financial resources, agricultural inputs (such as seed variety), technological knowledge and institutional support enable users to act on EWS and CI. These tools should be paired with broader support systems like social safety mechanisms, extension services and DRR frameworks.

Barriers, limitations and maladaptation risks

The different types of climate information described are associated with different types of barriers and limitations.

Climate change may invalidate past assumptions on which indigenous forecasting has been based. In some places, signs that once indicated certain climatic behaviours are now unavailable or no longer predictive (Muita et al., 2021). Further, younger generations in a community, having experienced formal education, can in some places fail to value indigenous knowledge (Legide et al., 2024), undermining its longevity. That said, adaptation also takes place: *"Indigenous Knowledge is not static; it is continuously evolving and is actively used to enhance climate change adaptation and resilience by integrating traditional practices with new information"* (Dorji et al., 2024).

Similarly, CIS from meteorological sources can be wrong – particularly given climate uncertainty, inaccessible, or delivered in formats that are perceived to be irrelevant or confusing (Nkiaka et al., 2019; Muita et al., 2021; Shaffril et al., 2020).

In relation to climate information delivered by formal institutions, a reported barrier to EWS and CI discussed in the literature is a lack of access to early warning information (Muita et al., 2021; Nkiaka et al., 2019; Jayasinghe et al., 2024). Particularly in rural areas, access to dissemination channels such as radio may be limited, and particularly linked to gendered access to these kinds of resources. For example, in the Lake Victoria region, a study found that 70% of interviewed stakeholders in sectors such as fishing and transport reported no knowledge of the availability of weather services for safety (Nkiaka et al., 2019). Increasingly, climate information is communicated using ICT systems. However, the high cost of owning and using devices (such as smartphones) through which EWS and CIS are communicating can also be a barrier (Nkiaka et al., 2019). During severe climate hazards, communication infrastructures can fail due a lack of available energy or degraded physical infrastructure (Hossin et al., 2023). That said, many of the systematic reviews draw on studies taking place over the last ten years. The pace of change of the availability and affordability of ICT has been rapid, which may mean that the status of information access is not accurately reflected in the literature reviewed.

Institutions need to be able to generate accurate and downscaled forecasts with information relevant to specific locations. These efforts are hampered by limited local infrastructure for weather observation, which prevents localisation of data and undermines accuracy (Muita et al., 2021; McDowell et al., 2019). Information needs to be accessible and in formats considered useful by recipients. Information can be delivered too late to be useful, insufficiently localised, and with communication practices that do not suit recipients (Muita et al., 2021). Forecasts that are not tailored to the temporal or geographic needs of users, such as smallholder farmers who require hyper-local, seasonal data, are unlikely to support effective decision making. Nkiaka et al. (2019) and Jayasinghe et al. (2024) found that complexity of scientific language, inconsistent terminology across agencies, and lack of translation into local dialects contribute to misunderstanding and disengagement by users. Trust in climate services remains fragile, particularly where official systems compete with long-established indigenous knowledge (Shaffril et al., 2020). There is a risk that forecasts provided by state meteorological agencies may be perceived as

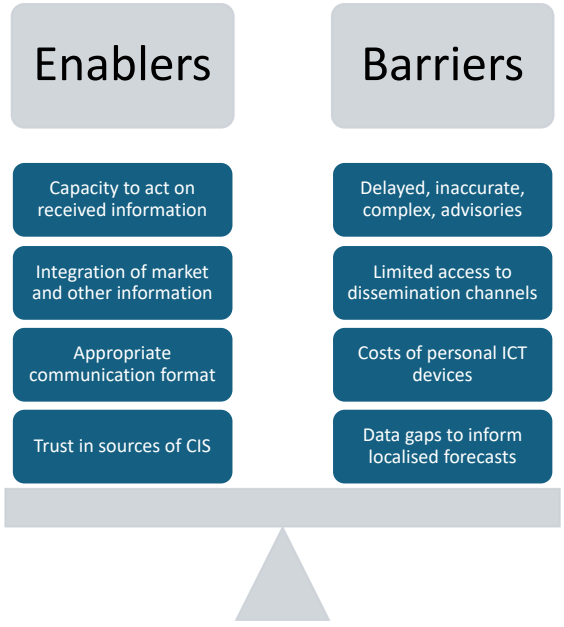
unreliable, especially if past predictions did not materialise or if communities have no direct relationships with the institutions disseminating the data.

EWS/CI is only as useful as the capacity of recipients to act on that information (Muita et al., 2021). Constraints such as poverty and limited mobility prevent the translation of warnings into adaptation measures by affected people. Limited capability within institutions to interpret and apply information is also a significant challenge. For example, in cities where flood risk management is required, an understanding not only of approaching weather patterns but also of how they will interact with the built environment is needed to develop appropriate information for residents.

> *"Poor knowledge of the topological connectivity of waterway networks, and of the hydraulic conditions of upstream and downstream network flows, complicates flood control decisions (Kuan, 2015). For example, cities such as Jakarta and Shanghai have hundreds of man-made canals and several interconnected rivers that interact in complex ways to influence flood control outcomes; poor knowledge of these waterway networks can undermine flood control efforts"* (Ogie, Adam and Perez, 2020).

Poor coordination between forecast providers and other stakeholders can undermine uptake. For example, in emergency scenarios, there is a lack of communication between forecast providers and humanitarian response teams, hindering uptake of EWS (Nkiaka et al., 2019).

Figure 8: Enablers and barriers to effective climate information service delivery, identified in the papers reviewed



Implications for practice

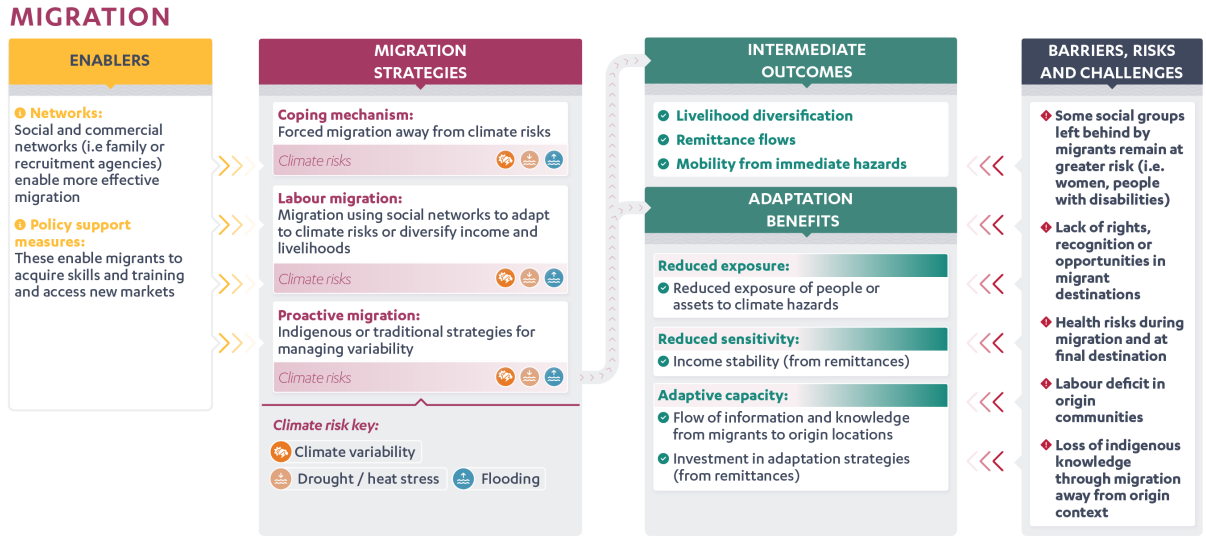
- Early warning systems are essential for contexts faced with repeated and urgent climate-related hazards, such as flooding in coastal cities, cyclones, or drought.
- Climate information works best when it actively seeks to incorporate indigenous knowledge forecasting. This can be through co-production of forecasts and advisories with local users, making

explicit indigenous knowledge forecasting signs alongside scientific data, or using indigenous forecasters as part of the dissemination strategy for climate information.

- Coordination between institutions is important for uptake and effectiveness of both early warning and climate information systems. Simply building capabilities of meteorological agencies is not sufficient. Encouraging greater knowledge and awareness among government institutions and local humanitarian response teams facilitates more coordinated action around the latest data and information.

4.4.7 Migration as an adaptation strategy

Migration is used to address fast- and slow-onset climate risks. Desertification, soil degradation, unpredictable rainfall patterns, and sand temperature fluctuations are widely discussed, particularly in Sub-Saharan Africa, due to their persistent effects on ecosystems and livelihoods. Impacts undermine the capacity of available resources to support productive agriculture. Migration from droughts and floods is more commonly discussed in relation to South Asia, reflecting their immediate and often severe consequences for affected communities. Salinity and land degradation are noted as significant risks, particularly in coastal and agricultural settings where these factors can undermine both food security and economic stability.



Confidence in migration as an enabler of adaptation to climate risks

The literature suggests that migration can reduce exposure to environmental threats and enhance adaptive capacity, particularly when it enables households to receive remittances and benefit from the transfer of knowledge and skills acquired by migrants. Labour migration in agricultural contexts is noted as a crucial adaptation strategy for smallholder farmers, offering opportunities to diversify livelihoods and strengthen resilience through risk spreading and increased access to resources.

The effectiveness of migration and related interventions is not uniformly positive. We have confidence that indigenous migration, for example by pastoralists, is highly effective when it is allowed to function. Labour migration, however, without due consideration, can be high-risk, as migrants may fall into urban poverty traps and other types of risks and vulnerability. Origin communities may also suffer from lost labour and knowledge.

Planned relocations, intended to move populations away from high-risk areas, sometimes fail to reduce vulnerability if the new sites remain exposed to environmental hazards.

A major limitation in the literature is the lack of detailed outcome data regarding migration interventions. Many studies mention these strategies only briefly, offering limited analysis of their long-term effectiveness or potential unintended consequences. As a result, the evidence base is fragmented, and the overall efficacy of migration and related interventions as climate adaptation strategies remains uncertain.

Overall, our confidence in the effectiveness of migration interventions in delivering adaptation benefits is generally moderate to low. High confidence is found only in a few areas, particularly where multiple studies, most notably those examining remittances and livelihood diversification, consistently report positive outcomes for adaptive capacity and resilience. For many other interventions, confidence remains low due to the small number of studies that focus on migration as a primary theme, a frequent lack of detailed outcome data, and a limited emphasis on documenting negative or maladaptive effects.

Migration was a recurrent theme across the literature, mentioned in over 24 studies as a response to climate risks, although the sole focus of only one study. The literature demonstrates that migration is increasingly considered a viable tool for vulnerable people to manage and work with variability in their context.

Strength of evidence

Table 12: Strength of evidence for migration

	No. medium-quality studies	No. high-quality studies	Total
Intervention	18	6	24
Migration as a coping mechanism in response to environmental threats and changes	2	1	3
Migration as a proactive adaptation to environmental threats and changes	2	0	2
Migration as a form of labour mobility or livelihood diversification	6	2	8

Of the 24 studies that mentioned migration, 18 were of medium quality and six were of high quality, according to the quality assessment. The one study that focused exclusively on migration was of high quality; however, it was geographically restricted to Southeast Asia, so it is not universally applicable. Very few studies had migration as a primary theme. Most often, it was one of many adaptation strategies mentioned in the study. This may be due to a dearth of research on the outcomes of migration as a climate adaptation strategy more generally; Thongchaithanawut et al. (2024) note that *"There is a lack of research examining the aftermath of migration in the place of destination, particularly relating to the success or failure of adaptive strategies"*.

The 24 studies covered a range of outcomes. However, as many studies covered several interventions, the outcomes are not necessarily associated with or attributed to the adaptation strategy of migration. The most common outcomes in the studies were reduced exposure (16), reduced sensitivity (20) and increased adaptive capacity (20), with a few studies covering reduced poverty (5) and reduced GHG emissions (3). However, when looking at outcomes specifically tied to migration, five studies included

reduced exposure as an outcome, one study included reduced sensitivity, and three studies included increased adaptive capacity. All 24 studies were from peer-reviewed publications, which indicates they have been through a review process, but introduces the risk of positivity bias.

Overall, the evidence on migration was weak, given its dilution in papers covering several interventions and the lack of clear links between the activity of migration and specific outcomes. Much of the evidence was anecdotal and not systematic. There were, however, several useful, detailed examples of the maladaptive effects of migration, and the nature of migration as an adaptation strategy used by smallholder farmers. Many of the studies (10) were global in geographic focus, with eight focusing on South Asia, five on East Asia and the Pacific, four on Sub-Saharan Africa and two on Latin America and the Caribbean. There was some diversity in the types of migration activities described, e.g., labour migration, migration from environmental disaster etc. There was also variety in the types of migrants described in the studies, including smallholder farmers, indigenous people, people living in hard-to-reach areas, urban dwellers, and others.

Migration as an adaptation strategy

Migration, sometimes referred to as "mobility", is framed several ways. It is most typically seen as either "planned migration" – a strategic choice to seek alternative livelihoods and opportunities, or "forced" migration because of increasing non-viability of livelihoods in the original location (Guja and Bedeke, 2024; Owen, 2020; Sultana et al., 2023; Zenda and Rudolph, 2024; Saddique et al., 2022). However, the most comprehensive review, focused on mobility in Southeast Asia, highlights that *"the task of differentiating voluntary and involuntary mobility remains problematic"* (Thongchaithanawut et al., 2024). People do not typically frame their experience in these terms, and there is little detail on the experiences of migrants once they have migrated. However, framings of migration include:

A coping mechanism in response to environmental threats and changes (Thongchaithanawut, Borderon and Sakdapolrak, 2024; Rijal et al., 2022; Kundu et al., 2020). Migration can be *"a response to the gradual impacts of climate change such as desertification, soil degradation, unpredictable rainfall patterns, and temperature fluctuations"* (Legide et al., 2024). People may migrate to urban centres, but rural-rural migration is also common (Rijal et al., 2022).

A proactive adaptation to environmental threats and changes (Legide et al., 2024; Shaffril et al., 2020). Indigenous peoples have often used migration as an adaptation strategy during extreme weather events. Pastoralists have long used temporary migration with livestock to maximise productivity during rainy periods and minimise losses during dry season and drought. *"During difficult weather conditions such as drought or stressor on resources, the mobility ability of the Dzumsa community in India assisted them in lessening the impacts (Ingty, 2017)*" (Shaffril et al., 2020).

A form of **labour migration or livelihood diversification** usually in agricultural contexts. When challenges arise in agricultural contexts, some people migrate to find other work (temporarily or more permanently) (Etana et al., 2022; Kundu et al., 2020; Magesa et al., 2023; Brambilla et al., 2022; Legide, Feyissa and Karo, 2024; J. Chen, Zhong and Sun, 2022). This migration can be internal to other parts of the country, or external to other countries perceived to have more job opportunities (Rijal et al., 2022). Both internal and external migration may result in remittances sent home to support the livelihoods of non-migrant community members (Magesa et al., 2023; Thongchaithanawut et al., 2024). One study presented migration as a last resort, noting that *"outbound migration is recognised as an alternative livelihood strategy in cases where local adaptation measures are partially or fully unsuccessful"* (Kundu et al., 2020).

Labour migration is also very typically discussed in relation to sending remittances back to families in the original location.

Migration is perceived quite differently across locations. Whereas in some places it is recognised or even valorised as a viable adaptation strategy to buffer and reduce vulnerability to variability, elsewhere it can be seen as shameful, with communities seeing a greater dignity in *"surviving in the existing way of life"* (Etana et al., 2022). Further, different regions are more likely to see different types of migration. Southeast Asia is prone to cyclones and tidal surges that drive people away at short notice, while Sub-Saharan Africa faces slow-onset risks that encourages more planned labour migration.

> *"Unlike the Rimaiibe community that adapted to rainfall variability through livelihood diversification such as labor migration and women's involvement in income-generating activities, the Fulbe community were less involved in these activities due to norms and values such as maintaining freedom and personal integrity, proving worthiness by surviving in the existing way of life, and considering the above-mentioned strategies as shameful"* (Etana et al., 2022).

Outcomes reported in reviews of migration

Reduced exposure

The immediate adaptation benefit of migration is reduced exposure of people to geographically located climate risks. In cases of forced migration, where livelihoods are no longer viable due to lack of sufficient quality resources, this is likely to be a permanent "benefit", albeit with risks (see below). Assessing this benefit is challenging because people may move to locations with a new set of climate risks. For other types of migration, reduced exposure may be only a temporary benefit, as people move away from extreme hazards before returning, travel to urban centres for temporary or seasonal work or, in the case of pastoralists, travel to dry- or wet-season grazing areas.

Increased adaptative capacity and reduced sensitivity

Through the sending of remittances, migration can be a way to increase the adaptive capacity of households of origin. Magesa et al. (2023) noted that migration has been recognised as an *"an important way to diversify agricultural-based livelihoods, particularly in sub-Saharan Africa… It enables risks to be spread in households, increasing resilience back home."* The same study indicates that labour mobility can help members of the household access food in times of livelihood shocks, and finance the acquisition of social, human, physical and natural capital. A more comprehensive study from Southeast Asia highlights how the flow of remittances back to households of origin supports day-to-day spending as well as specific adaptations to extreme weather events (Thongchaithanawut et al., 2024). However, the study notes that sending remittances may constitute an excessive burden for migrants.

"This review highlights the significance of remittances, whether financial or social, as a pivotal mechanism of migration in upholding adaptation to environmental uncertainties. Remittances play a part in ensuring sustainability and enhancing the resilience of sending households in the Global South."

An additional adaptive capacity benefit may be the flow of innovation and knowledge that migrants gain at their destination and transfer to their home communities, facilitating increased adaptation and wellbeing. There is some evidence of increasing skills and knowledge by learning from migrants' experiences in other places (Thongchaithanawut et al., 2024).

Differential impacts across social groups

The social groups mentioned in the literature in relation to migration were the extreme poor, women and youth. In relation to extreme poverty, labour migration, usually from agricultural contexts, is discussed as a mechanism to reduce poverty and as a last resort measure for people in extreme poverty or who are dealing with extreme weather events and other environmental challenges. However, poorer people are less likely to be able to move due to the high associated costs. Magesa et al. (2023) note that *"migration is often only an option available for the privileged. Those populations or families with no financial or social capital to move can be left in situ in risky situations."*

Women in are more likely to be left behind when men migrate. This can leave them at greater risk from extreme weather events because women are less likely than men to have knowledge of how to access and respond to available early warning systems (Solomon et al., 2020). Youth were mentioned as a social category that was more likely to migrate, leading to potential labour deficits in their original communities (Mizik, 2021) and a break in the link of indigenous knowledge (Magesa et al., 2023). However, youth migration was also framed as a way to support home communities through remittances (Chettri, Datta and Behera, 2024), leading to greater financial stability.

Enablers

Social and commercial networks are referenced by one review as important enablers (Thongchaithanawut et al., 2024). Social networks of relatives are important for securing jobs and accommodation on arrival in the new destination. Commercial networks such as recruitment agencies and employment brokers are particularly important for safe overseas migration. Kwazu and Chang-Richards (2021) point out the importance of **policy support measures** to help new migrants acquire the skills, technology and training needed to create new markets/access existing markets in their new communities.

Barriers, limitations and maladaptation risks

Except for indigenous or pastoralist communities for whom mobility is regularised, migration is typically a high-risk endeavour. Migrants to urban areas may struggle to access jobs or welfare, leading to a *"climate-induced poverty trap"* (Etana et al., 2022). The expense of migration may create debt, with little support from government sources (Thongchaithanawut et al., 2024). Some migrants from agricultural contexts may find it difficult to access land or housing, which forces them to settle in riskier, flood-prone and often informal urban settlements (Thongchaithanawut et al., 2024). And some migrants move to secure jobs that may not exist at their destination (Kwazu and Chang-Richards, 2021). In Hanoi, *"migrants without residential registration in a particular ward or commune are not eligible to receive support from district-level governments during flood events"*. Thus, these migrants – already in a precarious position due to their flood-prone housing – may be thrown into further precarity during extreme weather events. This poses a risk for the city at large, due to difficulties with flood management (Ogie, Adam and Perez, 2020).

Two reviews explore the intersection of **health and migration**, with negative health outcomes arising from increased migration to urban areas. One looked at health risks, focusing on the higher prevalence of chronic diseases (cancer, hypertension, diabetes) and infectious diseases (TB, HIV, malaria) in migrant communities compared to host communities (Mazhin et al., 2020). The other study looked specifically at mental health and wellbeing outcomes of climate change migration (Flores et al., 2024). Migration may also affect social networks and social wellbeing by disrupting children's education and reducing men's involvement in social activities and local networks (Shaffril et al., 2020).

There are also consequences of migration in origin communities. Migrants may leave a labour deficit, a limitation on the community's ability to diversify its economy, and a loss of local and indigenous knowledge (information on EWS, for example) (Kwazu and Chang-Richards, 2021; Solomon et al., 2021). One review specifically discussed passing on indigenous knowledge, noting that when young people leave their home communities, elders can no longer pass on accumulated knowledge on climate change adaptation (Mbah et al., 2021). Land may also be abandoned, and food security may be affected (McDowell et al., 2019). One review included evidence that farmers who had used temporary migration as a climate change strategy tended to have lower production and income compared to others (Villamayor-Tomas et al., 2024).

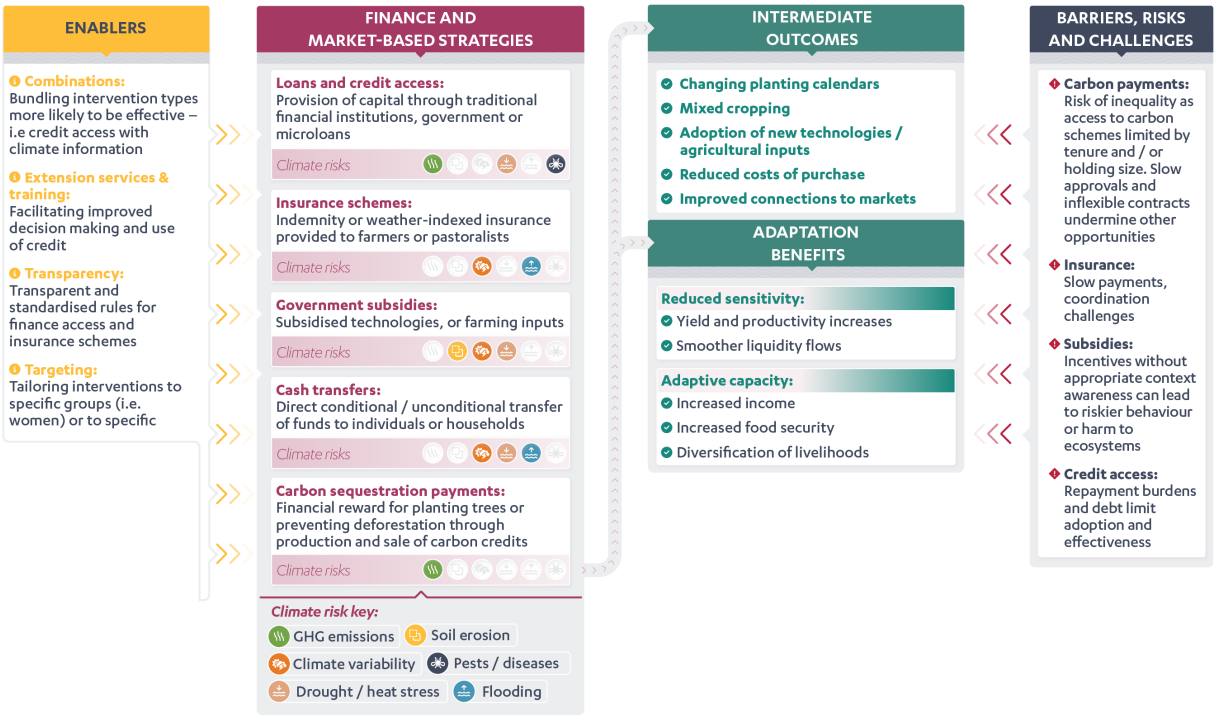
Implications for practice

- The frequency with which migration as a strategy occurs in the literature indicates that it is an inevitable response to increasingly severe climate risk. However, focused studies that explore the contributing factors to migration, and the outcomes for migrants and their families, are not common. As hazards become more severe, migration will have highly varied impacts on the migrants and the households and geographies they leave behind. FCDO might consider how to develop tools that can understand migration in different contexts.
- The risk to migration is reduced when migrants can access supportive services that facilitate their transition from one place to another, and their capacity to send remittances home. Supporting countries in establishing policies and systems that can support internal migrants with a social safety net and access to work can reduce the risk of maladaptation and the pressures that migrants can bring into new environments.
- Remittance flows from migrants are likely to increase, offering a potential resource for vulnerable rural households to cope with and directly adapt to climate risk. This may present an opportunity for innovative financing approaches or tailored adaptation training or education.
- Supporting governments and other stakeholders to support adaptation as a natural strategy to reduce vulnerability to variability and climate risks can be a proactive approach to a phenomenon that is likely to continue to grow. This might involve incorporating migration into national adaptation plans and strategies, rather than resisting or ignoring it.

4.4.8 Finance and market-based adaptation interventions

Financial tools and mechanisms refer to credit or market-based interventions that facilitate adaptation practices. These might include provision of credit, government subsidies, cash transfers, or insurance programmes. Few systematic reviews focused specifically on these kinds of mechanisms as adaptation interventions.

FINANCE AND MARKET-BASED MECHANISMS



Confidence in finance and market-based mechanisms to adapt to climate risks

Financial mechanisms can be mobilised to target specific risks or to support wider adaptive capacity. The literature generally describes financial mechanisms such as credit support, insurance or cash transfers in relation to other, multi-faceted interventions. Four major types of mechanism are discussed in the literature – cash transfers, credit support, insurance and government subsidies.

We have low confidence that credit access can facilitate adaptation to a range of climate risks. Confidence is limited by the fact that the nature of credit provision can vary, with little detail offered on design considerations. Most studies concur that issuing credit for adaptation can be high-risk where there is high variability of climate and other risks. Credit can enable adaptation to risks including drought, flooding and soil erosion, and pest control, but may be subject to high repayment rates that erode benefits or reduce adoption. It also has greater potential when combined with knowledge building, information on risks, or new technologies.

We have low confidence that insurance schemes can facilitate reduced sensitivity or adaptive capacity to shocks. Most studies mentioning insurance are of medium quality. Weather-indexed approaches can influence incomes and facilitate quicker recovery from shocks and enable targeted technology purchase to respond to a range of risks. But the nature of delivery is critical to success and depends very much on design and context, making a generalisable assessment of insurance mechanisms as an adaptation intervention challenging. Indemnity insurance is generally considered a poor option, with inadequate payouts and high coordination requirements.

We have low to medium confidence in subsidies to facilitate sensitivity and adaptive capacity benefits. When appropriately structured, subsidies can make insurance affordable and incentivise the adoption of new technologies and approaches. However, they can also create perverse incentives if poorly designed – for example, for high-risk, high-reward strategies in the face of climate variability, focusing on income rather than ecological management or adaptation to risks.

Quality assessment

Most of the systematic reviews mentioning financial and market-based adaptation mechanisms were of medium quality. It is important to recognise that few studies focused specifically on these kinds of approaches, with most identifying them as part of a wider intervention, often in relation to CSA or agroforestry. Some systematic reviews mentioned multiple types of finance mechanisms, and these have been double-counted purposely in the table below.

There is considerable heterogeneity in the nature of the evidence under review, reducing our confidence in the certainty of particular adaptation benefits arising from the use of financial and market-based mechanisms. For example, in some studies, interventions such as cash transfers, the provision of credit, or government subsidies are discussed as standalone interventions, and in others they are mentioned in passing as enablers of other types of interventions. The volume of systematic reviews means that there is a wide geographic focus for papers mentioning these kinds of mechanisms.

The studies reviewed made it difficult to glean a precise understanding of adaptation pathways and effectiveness. Few systematic reviews provide clear information on the nature of causal links or impact pathways from financial or market-based interventions through to specific adaptation benefits. Indeed, in most cases, it is often not possible to generalise the attainment of adaptation benefits because of specific financial mechanisms. Many reviews also pointed out significant risks from financial and market-based mechanisms, but these are highly context-dependent, as a range of contextual factors can influence the level of risk associated with credit or types of insurance policy. Specific links from financial mechanisms to adaptation benefits – and the associated risks – are detailed below, often drawing on examples from specific primary research mentioned in the systematic review.

Table 13: Strength of evidence for finance and market-based adaptation interventions

	No. medium-quality studies	No. high-quality studies	Total
Total SRs mentioning financial tools and mechanisms	30	14	44
SRs mentioning loans and credit access	13	7	20
SRs mentioning insurance schemes	17	7	24
SRs mentioning subsidies	4	4	8
SRs mentioning cash transfers	0	4	4

Table 13 indicates the number of studies mentioning different types of market-based or financial adaptation intervention. Identification of studies linking the intervention to specific adaptation benefits is not possible due to the cursory description of the intervention and its impacts in most papers reviewed.

Credit access often features as part of a bundle of combined adaptation activities, or as something that enables adoption of new techniques or technologies. Broadly, the aim of improving credit access is to facilitate investments in adaptation techniques or technologies, or in diversifying livelihoods.

> *"Availability of credit will enable farmers in northern Nigeria to meet other requirements for adapting to climate such as purchasing of improved crop varieties*

> *(heat-, drought, pest and disease-resistant). Access to finance will provide financial capital and also enable the acquisition of natural capital such as new farmland, which are essential for the sustenance and improvement of rural livelihoods"* (Onyeneke et al., 2019, p.982).

Credit can be linked with other kinds of information, such as market information or advice on agricultural techniques (Li, Ma and Zhu, 2024). Some studies found that access to credit was positively associated with mixed cropping, changing plant calendars, and use of organic fertiliser. It is, however, also associated with high repayments, particularly when credit comes from traditional financial institutions, which can discourage farmers from taking the risk of high interest rates. This is also true of microloans. A related intervention is the provision of cash transfers, in which funds are transferred directly to individuals or households on a conditional or unconditional basis.

Weather- or climate-indexed insurance offers payouts when certain climatic conditions are reached, or when some data sources reach a certain threshold. These might be related to remote sensing technologies, satellite data, or hydrological data, or changes in the price of saleable products including crops (Goodwin et al., 2022). One of the benefits of automated indexed insurance is the speed of repayments, particularly using mobile money. One article, looking across financial interventions, noted that *"index insurance was most frequently described as having a positive influence on outcomes"* (Goodwin et al., 2022). More traditional indemnity insurance is also a financial option, though it is less frequently discussed in the literature and is often commented on for its high institutional demands and costs.

Payments for carbon sequestration pay farmers to plant trees or prevent deforestation. These have been through independent payment for ecosystem services programmes – for example, in Indonesia (Guja and Bedeke, 2024). Much of the evidence comes through the experience of the Reducing Emissions from Deforestation and Forest Degradation (REDD+) programme. The evidence suggests that REDD+ has led to increased income payments but comes with a risk of alienating some communities from customary land. The programme has caused division due to deepened inequality, as those without capabilities to sell carbon lose out to those who can sell it, often dependent on who had land and resources before the onset of the programme. Carbon credit programmes are also mentioned, albeit in relation to challenges such as the high transaction costs of small projects, a slow and costly approvals process, and long contract periods that take some time to pay off, leading farmers to forego other opportunities (Muthuri et al., 2023).

Government subsidies incentivise the use of new techniques or technologies – for example, to establish water reservoirs, or take up agricultural strategies that foster resilience (Muthuri et al., 2023). Subsidies may go direct to consumers or businesses to adopt new technologies or agricultural inputs, or go to suppliers to reduce purchase costs (J. Chen, Zhong and Sun, 2022). They can take the form of grants, cash transfers or vouchers (Saran et al., 2024). In India, the government subsidised electricity to encourage additional income-generating activities and build financial resilience to absorb drought (Nelson et al., 2022).

Outcomes reported in reviews of financial mechanisms

Reduced sensitivity and increased adaptive capacity

Credit access enables farmers to invest in drought-tolerant seeds, yield-improving technologies, or any number of potential adaptation measures including acquisition of new land, irrigation technologies or

improved connections to markets. In agricultural settings, this might lead to more stable or improved yields, thereby increasing incomes and food security. Access to credit also offers a wider range of choices, particularly to farmers (Saddique et al., 2022). Other benefits include a smoothing of liquidity flows and the potential to diversify livelihoods (Li, Ma and Zhu, 2024; Goodwin et al., 2022; Onyeneke et al., 2019). Combinations of interventions that bundle credit access with training or the provision of new technologies are more likely to be effective in producing adaptation outcomes (Ulibarri et al., 2022; Fan et al., 2022). As detailed below, however, there are important barriers to effectiveness and limitations to who can benefit.

Insurance mechanisms are linked to improved risk management and income smoothing. Two types of insurance mechanisms are typically mentioned – indemnity schemes or policies that ensure crops for an agreed fee, and weather-indexed policies that pay out against an agreed meteorological condition. Both types have pros and cons, but insurance typically supports recovery from climate shocks (Guja and Bedeke, 2024), assuming that payments are suitably timely. One study in Burkina Faso found that weather-indexed insurance promoted subsequent access to credit and protected assets from climate change risks. As a result, it stimulated use of improved farm technologies and practices (Guja and Bedeke, 2024).

> *"Adoption of climate finance schemes (weather insurance, credit access): Weather/climate index insurance is another form of ex-ante risk reduction opportunity that smallholders get engaged to recover from various climatic risks and price instability without diminishing their future productive assets."*

A GCF review of its own programmes found the following: *"Findings indicate that insurance for losses due to flood and drought interventions presents a large positive but statistically insignificant effect on income. Given the small number of studies, this result should be interpreted with caution."* A common theme is the idea that the scheme had to be administered and coordinated properly to be effective.

Subsidies can support uptake of new technologies when they are appropriately structured (Nelson et al., 2022). This might include subsidies for water reservoirs and storage to reduce sensitivity to drought (Owen, 2020), subsidised loans or microfinance to invest in new apparatus (Goodwin et al., 2022), or subsidised insurance schemes to reduce the impact of damaged or lost assets. Subsidies are often mentioned in relation to farming inputs, making the uptake of approaches such as CSA more likely for poorer farmers.

Differential impacts across social groups

Equity considerations are not discussed in great detail. In relation to financial access, poorer and less-educated farmers with smaller land sizes and without access to irrigation facilities were generally described as being disproportionately affected by drought and less likely to access financial dispensation, credit or insurance schemes (as found by Habiba et al., 2014; Bordey and Arida, 2015; Gaurav, 2015; Dewi et al., 2018; Brown et al., 2019; Senapati, 2020). These characteristics were also associated with farmers' propensity to migrate to urban areas or to be trapped in cycles of debt.

Enablers

Coordinating financial interventions and multiple techniques will have more significant adaptation benefits (Guja and Bedeke, 2024; Goodwin et al., 2022). For example, credit access coupled with climate information services, knowledge and information on possible investment decisions (Akinyi et al., 2021; Li,

Ma and Zhu, 2024), can better enable positive outcomes. As with much investment in CSA, extension services can be an important facilitator of more impactful farming choices and strategies.

Insurance is more effective when there are transparent and standardised rules to declare drought and issue compensation (Goodwin et al., 2022). Stakeholder collaboration and ease of administration also contribute to the scheme remaining attractive. Insurance schemes can require a fair amount of coordination and management, which must be within the capacity of the insuring institutions to offer. The sensitivity benefits are only possible if payouts are timely, sufficient and enable action to respond to variability (Karimi et al., 2023). Membership of larger organisations can support access to both credit and insurance. For example, farmers' unions can share information, advice and opportunities with members, as seen in Brazil (Owen, 2020).

Appropriate targeting of financial interventions can also support greater impact. For example, schemes may be tailored to women or young people or associated with capacity-building and extension services targeted at low-income farmers (Ulibarri et al., 2022). The tailoring of subsidies is also important – for example, subsidising fertilisers or electricity may be more effective than diesel irrigation, as seen in India (Goodwin et al., 2022).

> *"Given the development imperative of maintaining healthy and productive food systems, targeted financing instruments are crucial to enabling smallholder farmers to make the necessary investments that will avoid crop losses"* (Guja and Bedeke, 2024).

Barriers, limitations and maladaptation risks

A range of challenges arise in relation to financial mechanisms which can make or break their effectiveness, including challenges for smallholders and for institutions running a scheme. Credit access, while linked to income increases, is also linked to repayment burdens and resultant debt, with risks borne by already vulnerable people (Goodwin et al., 2022). High interest rates can put farmers off opportunities to borrow, and knowledge of formal borrowing opportunities is often unevenly spread. Even when opportunities are available, lack of tenure to act as loan collateral, or access to formal financial institutions may drive borrowers to local money lenders (Rijal et al., 2022; Mizik, 2021; Ntawuruhunga et al., 2023; Li, Ma and Zhu, 2024). Further, farmers may not have enough land to meaningfully make certain kinds of investments (Goswami et al., 2023).

"The results of this review, albeit based on diverse literature using different methods in different settings, suggest that there may not be one optimal financial intervention (Aakre et al., 2010) but rather country and context-specific solutions (Clarke et al., 2017)" (Goodwin et al., 2022).

Indemnity insurance schemes are challenging both for those purchasing the insurance and, if run by a government agency, for the administrative capacity of the institution. One systematic review found that indemnity insurance was negatively associated with income in 54% of the articles reviewed, *"because the premium was considered a financial burden… and secondly, because crops could be damaged by drought, but the farmer did not receive any insurance payment (Singh and Agrawal, 2020)"* (Goodwin et al., 2022). For the implementing agency, the costs of administering the scheme, reviewing applications and processing numerous transactions forced it to divert funds from elsewhere.

Traditional insurance schemes were reported as an inefficient use of tax revenue (Ghosh et al., 2021), and often not financially sustainable (Singh and Agrawal, 2020) due to high running costs (Alam et al., 2020).

Many schemes had not accounted for non-economic losses that might include health impacts, damage to wildlife or loss of biodiversity (Bahinipati, 2020).

Crop and livestock insurance has been less successful in India: *"About 90% of the households were not inclined toward renewal of their livestock insurance due to poor insurance delivery mechanism, high premium, lack of trust in the insurance provider, no indemnity when faced with losses, no information in the renewal process and difficulty in availing insurance"* (Goswami et al., 2023).

While subsidies had some positive impacts, they could also create perverse incentives. Goodwin et al. (2022) highlight that some farmers invested in higher-income, less sustainable, "undesirable" land management practices. In Thailand, farmers opted for riskier, higher-income activities that were less resilient to climate shocks. Subsidies must be tailored in the right way to be effective. For example, they must be perceived as sufficient and easy to access.

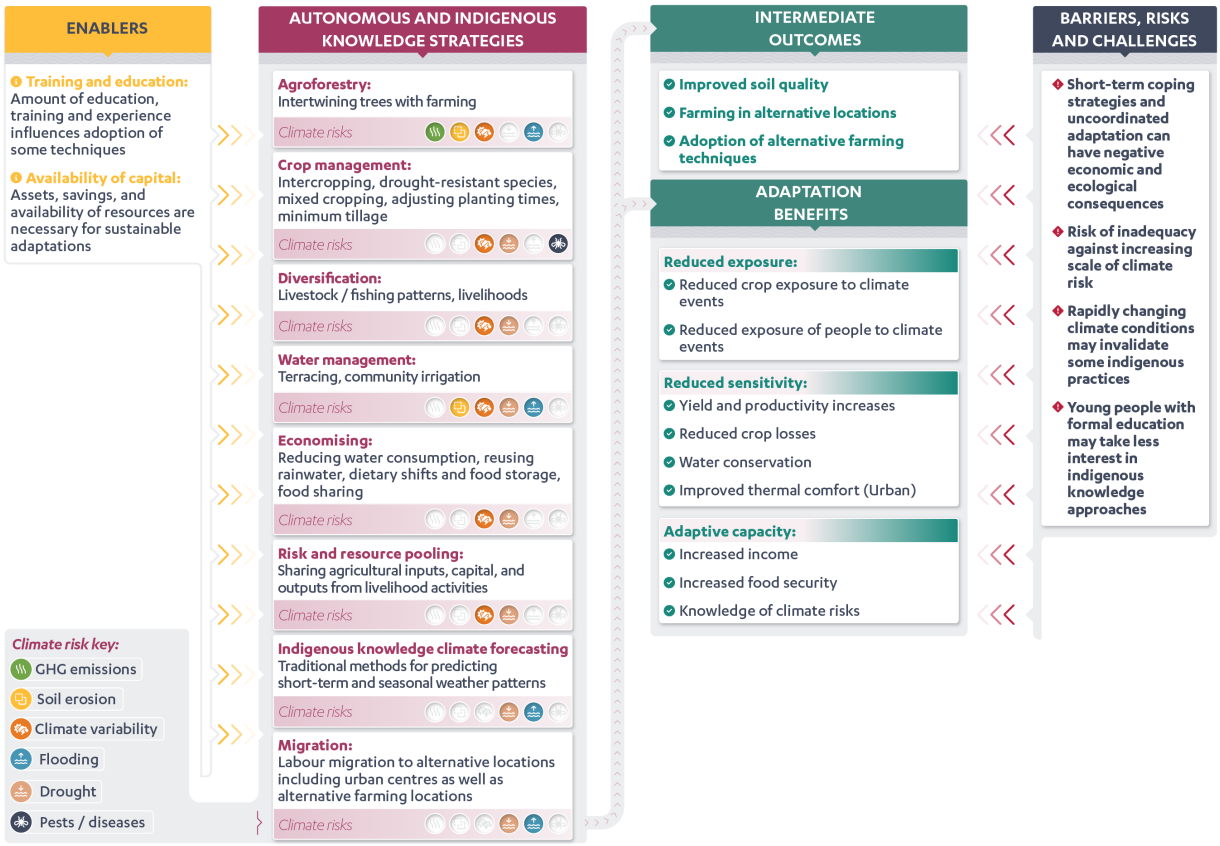
Implications for practice

The results of this review, albeit based on diverse literature using different methods in different settings, suggest that there may not be one optimal financial intervention (Aakre et al., 2010) but rather country- and context-specific solutions (Clarke et al., 2017) (Goodwin et al., 2022, p.9).

- **Access to credit is an essential enabler of adaptation action**, but the format of that credit will need to vary depending on local conditions and pre-existing incentives and interests.
- **Insurance schemes can help to reduce sensitivity** but come with significant administrative burden cost if run by a public institution. Indexed insurance schemes provide greater flexibility, particularly when payment can be prompt.
- **Combinations of financial mechanisms will be needed** to ensure that people not deemed typically creditworthy are still able to reap benefits of financial access.

4.4.9 Autonomous and indigenous knowledge-based adaptation

Many of the systematic reviews in this umbrella review include, as either a primary or a secondary focus of their studies, examples of how adaptation is happening autonomously. That is, how people affected by climate change are altering their behaviour or otherwise intervening in their livelihoods to reduce risk, to mitigate the negative impacts of climate change, or to increase their capacity to react to factors associated with climate change.



Confidence in autonomous and indigenous knowledge as an adaptation to climate risks

Autonomous adaptations that include application of IK are by their nature highly context-specific. This category includes reactive strategies to cope with climate hazards as well as more planned adaptations. Most instances of autonomous adaptation (AA) and IK in the documents reviewed were applied in agricultural settings. Climate risks being addressed related to low rainfall, drought and water scarcity; increased temperatures; variable weather patterns; and, to a lesser extent, soil quality/erosion, ecosystem loss and natural disasters – particularly increased flooding events.

Certain types of AA offer greater confidence in their effectiveness across contexts. In particular, social and behavioural changes that facilitate collective action and information sharing that then leads to wider adoption of new agricultural techniques such as soil and water conservation. Farmers facing increased environmental change can use crop diversification measures to spread farm-related risks and reduce sensitivity to climate risks. Enablers for success in this regard include access to finance, levels of existing education and/or access to IK, and strong social bonds or community participation.

The literature offers a medium level of confidence in the use of IK in approaches to reduce sensitivity to adverse weather impacts and climate shocks and a high level of confidence in the use of IK to improve adaptive capacity. It is frequently noted across the literature that applying IK to planned adaptation interventions can improve the effectiveness of those interventions and is, at the same time, an important enabler of adaptation.

A number of studies refer to the importance of AA in improved coping strategies, enhanced decision-making power, and a greater willingness to engage in new practices and access weather and climate information. While

few studies focused explicitly on poverty reduction, livelihood diversification and engagement in off-farm employment were reported to lead to better poverty-related outcomes across a range of medium- and high-quality studies.

Autonomous adaptation (AA) is important to understand because research suggests that most adaptation spending takes place through AA as citizens respond to and cope with climate risks as they experience them (Eskander et al., 2022). AA refers to self-driven, spontaneous, citizen or community-led responses to climate change, often driven by changes to resource availability and climate variability. AA is motivated by need and carried out by individuals or small groups using a variety of resources that might be available, and their own knowledge. Across the systematic reviews, there are many examples of AA that are not explicitly defined as such. We found 22 studies where AA was discussed either as a focus of the study or as one of the activities described within a wider category of intervention areas. Most studies (21) describing AA interventions report on how AA occurs in the agriculture sector. Only one study looking at AA interventions had a non-agriculture focus; this was a study looking at how communities adapt collectively in the face of water scarcity.

Adjacent to the literature on AA were a significant number of systematic studies that explored the importance of local and/or Indigenous knowledge (IK) for adaptation effectiveness. The use of IK and indigenous resources has been found to promote self-organisation and facilitate decision making (Onyeneke et al., 2019). Six studies explicitly investigated IK, although the importance of IK is noted across the literature on AA (and indeed across development literature more widely). IK is important as it has been tested and used for years by communities and is a trusted source of knowledge and practice (Muita et al., 2021). In comparison to AA interventions, IK-led strategies are considered to be generally associated with actions that are *proactive* as opposed to actions that are *reactive* (Mbah, Ajaps and Molthan-Hill, 2021).

IK is not only an enabler of AA, but can be used in conjunction with planned interventions to enhance effectiveness. The IPCC's AR6 report finds, with "*high confidence*", that IK systems *"represent a range of range of cultural practices, wisdom, traditions and ways of knowing the world that provide accurate and useful climate change information, observations and solutions"*.[8] The IPCC further notes that IK can be particularly useful when integrated into adaptation planning, and *"is proven to enhance resilience in multiple contexts"*.[9] Top-down interventions such as Reducing Emissions From Deforestation and Forest Degradation, plus (REDD+) programmes have been criticised for not paying due attention to indigenous rights and IK in their development and implementation and could be made more effective by integrating IK into their delivery models (Hajjar, Engbring and Kornhauser, 2021). Indigenous forecasts, and the sharing of IK and indigenous practices through social networks, can be leveraged by more formalised CIS interventions using scientific forecasting to enhance effectiveness (Nyoni et al., 2024). A subset of the systematic reviews looked specifically at this question of how IK can integrate with scientific knowledge and information availability to improve the targeting and effectiveness of adaptation interventions. We included three studies that focus on the interaction between IK and scientific knowledge in adaptation interventions, although this relationship was also referenced across the literature on AA.

8 Schipper et al. 'Climate Resilient Development Pathways', in Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022) p.2713.
9 ibid, p.2667.

Quality of studies

The quality of studies published on AA and IK is mixed, with most studies being of medium quality, and only seven studies – approximately 20% – considered to be of high quality. This quality ratio was similar for each of the types of self-led adaptation included in this section. The studies often combined different sets of intervention types and reported on multiple adaptation outcome areas. In the table below, therefore, the numbers reflect all instances where intervention areas or adaptation outcomes are reported, and there is necessarily an element of double-counting.

Table 14: Strength of evidence by outcome for autonomous and indigenous knowledge-based adaptation

	No. medium-quality studies	No. high-quality studies	Total
Studies focusing on autonomous adaptation	17	5	22
Studies focusing on indigenous knowledge	5	1	6
Studies focusing on the integration of IK with planned interventions	2	1	3
Agriculture, agroforestry, nature, conservation	19	5	24
Social/behavioural adaptations	12	5	17
Technology and built environment	14	3	17
Cultural practices/information sharing/knowledge and education	11	3	14
Reduced exposure	8	2	10
Reduced sensitivity	19	5	24
Enhanced adaptive capacity	21	7	28
Reduced poverty	4	1	5
Reduced GHGs	6	1	7

Geographic coverage across is broad, with Sub-Saharan Africa and South Asia featuring in 14 studies each, and East Asia and the Pacific featuring in 10 of the studies. Latin America and the Caribbean and Middle East and North Africa featured in fewer studies (two each). Six studies were global and did not specify any countries or regions.

Agriculture, agroforestry, nature and conservation

Twenty-four studies look at AA in agriculture, ecological practices and conservation, with significant overlap with the CSA and Agroforestry sections. In this section we identify only those interventions driven by farmers' own, local or indigenous knowledge and implemented in an autonomous or spontaneous way – outside the structure of planned adaptation facilitated by a government, donor or other external actor.

Several systematic reviews refer to the use of planting trees by farmers as a form of AA. This is separate to planned agroforestry practices that have been introduced through an external intervention. Often these are practices that farmers have learnt and implemented themselves. Guja and Bedeke (2024) note that in Kenya, farmers are adopting practices considered to be agroforestry techniques to mitigate the

negative effects of climate change. Autonomously developed agroforestry practices have also been observed in Nigeria and northern Ethiopia to mitigate high temperatures and combat soil erosion (Legide, Feyissa and Karo, 2024). In the Himalayas, agroforestry has been used as a practice by farmers looking to combat rising average temperatures (Chettri, Datta and Behera, 2024). In South Africa, one study notes that agroforestry is just one aspect of a range of wider agroecological practices that farmers employ as a strategy for adapting to the impacts of climate change, as a means to improve water retention and soil fertility and reduce the risk of soil erosion (Zenda and Rudolph, 2024).

Farmers are also adjusting the time that they plant based on changing weather patterns, increased average temperatures and other climate-related variability. This practice is noted in two studies (Guja and Bedeke, 2024; Sultana et al., 2023). Farmers in Nepal, for instance, have shifted maize cultivation from the monsoon to the winter season, preferring to grow rice in the maize fields during monsoon (Dorji et al., 2024). Planting ahead of time is another practice that has been observed in the Philippines to avoid frost but also to make plants hardier in cases of heavy rains.

IK may shape these processes by, for example, influencing selection of tree species or other crops that will combine well with food crops, as seen in Kenya and in Ethiopian smallholder coffee farms (Akinkuolie et al., 2024; Legide, Feyissa and Karo, 2024; Zenda and Rudolph, 2024; Shaffril et al., 2020). In Nigeria, a practice known as “alley cropping” has been used to increase the nitrogen content and organic content of soils. This is a practice that is particularly useful to tropical urban environments (Akinkuolie et al., 2024).

Many practices detailed in our dataset relating to CSA can also be seen in indigenous farming systems. Crop rotation, intercropping drought-resistant crops, and introducing drought-resistant species are important adaptive techniques that are mentioned across the literature. Intercropping drought-resistant crops, such as sweet potato, sorghum and cassava, with maize is seen in Tanzania, Ghana and Kenya (Legide, Feyissa and Karo, 2024) while intercropping maize, beans and squash is reported in Central America (Akinkuolie et al., 2024) as a means of improving crop resilience, ensuring soil health and reducing pest disturbance. Selection of drought-tolerant maize varieties is also widely seen in indigenous systems globally (Shaffril et al., 2020; Thottadi and Singh, 2024).

Traditional pastoralist systems are also changing, with herders in Nigeria and Tanzania diversifying herds with camels, cattle and goats to minimise losses from droughts (Legide, Feyissa and Karo, 2024). Fishing communities change their fishing practices in response to changing fish patterns, or indeed may move to aquaculture instead of open-net fishing (Sultana et al., 2023). The application of IK is associated with traditional methods such as mixed cropping, terracing and water conservation (Akinkuolie et al., 2024).

Social and behavioural adaptations

Across the systematic reviews we find examples of people adjusting their livelihoods, lifestyles and home environments in response to experienced risks. We found 17 studies that looked at AA from the perspective of behaviour change, usually in terms of adapting domestic or professional practices to respond to climate change. Five of the studies were of high quality.

Many behaviours around food production and consumption that could be called “economising” can be considered forms of AA when driven as a response to climate change. Establishing home gardens and cultivating fruit trees provides additional and varied nutrition sources as well as shade, seen particularly in South and Southeast Asia (Kundu et al., 2020; Chao, 2024). Farmers have been found to reduce domestic water consumption, diverting this for use in agriculture, as well as reusing rainwater during droughts (J. Chen, Zhong and Sun, 2022). In addition to growing food to respond to climate change, people

are also changing the ways they are consuming, storing and sharing it. Moving towards cheaper and more readily available or more consistently available foods is a way in which households can adapt to climate-induced price shocks and periods of non-availability (Chettri, Datta and Behera, 2024). Traditional communities in Africa have responded to climate-induced food insecurity by adopting new food processing and preservation techniques, including setting up food-sharing networks to respond to periods of low availability (Legide, Feyissa and Karo, 2024).

Where livelihoods are directly affected by climate change – for instance in the case of farming and fishing – people will often engage in alternative sources of employment to reduce their sensitivity to climate shocks. Livelihood diversification activities include manufacturing of handicrafts, setting up small businesses, or seeking waged employment (often linked with migration, which is captured in *Section 4.4.7*) (Guja and Bedeke, 2024; Rijal et al., 2022). Communities and families may look at ways to build financial resilience through collective mechanisms that pool risk and/or resources. Setting up small family-run businesses (also an example of livelihood diversification) is a way of bolstering financial sustainability in the face of climate variability. At the community level, village savings and loans organisations can provide financial security during times of crisis. This has been noted in Zimbabwe, where villagers work as a collective group, raise savings, and lend to those in need during difficult times (Thottadi and Singh, 2024).

Technology/built environment

Most of the 17 AA examples that refer to built or structural adaptations relate to traditional or community-led irrigation systems and water conservation practices. Home-grown or traditional irrigation and water management systems, such as trenches, ponds, dams, stone bunds and mulching, are reported in studies in North and East Africa to increase water efficiency, store water during dry seasons, retain soil moisture and ultimately boost crop yields (Chami et al., 2022; Magesa et al., 2023; Bracken, Burgess and Girkin, 2023; Guja and Bedeke, 2024). Built infrastructure is relevant here too in the sense that improved physical security can help build resilience to extreme events – improving the quality of storerooms for harvested crops to withstand cyclones, for example. However, infrastructure can be expensive and unavailable to many (Kundu et al., 2020).

Cultural practices/information sharing/knowledge and education

IK is often closely tied to cultural beliefs, shaping harvest times, hunting patterns or governing activities which restrict access to crops, animals or trees at particular times of the year (Dorji et al., 2024). Wu et al. detail several examples of traditional knowledge exchange and cultural practices that can enhance sustainability – for instance, ceremonial burning practices in central Brazil that contribute to community conservation efforts (Wu, Greig and Bryan, 2022). Local knowledge exchange and IK is often crucial in managing and implementing community-based adaptation and disaster risk management processes. Where IK is perceived to be a more trustworthy source of information, this can be a motivating factor in encouraging participation (Macatulad and Biljecki, 2024).

The use of IK in weather forecasting is reported across the literature as being instrumental in addressing climate impacts (Mbah, Ajaps and Molthan-Hill, 2021; Rijal et al., 2022). In Ethiopia, pastoralists use IK weather forecasts to help them to make informed decisions about where to locate their herds. Studies demonstrate how IK-based weather forecasting and the utilisation of local climate knowledge has been helpful across Africa more generally, in instances where formal seasonal forecasting and climate information is missing or incomplete (Legide, Feyissa and Karo, 2024). IK weather services may also be perceived as more accessible and user-friendly than formal climate information which may require access

to chains of communication with public institutions or extension agents and may not be communicated in local languages or dialects.

Outcomes associated with AA and IK

Given the broad range of intervention types, practices and sectors associated with AA and IK, there is a mix of effectiveness across different contexts and circumstances. AA strategies are often reactive in nature and may have been implemented without a structured planning or risk assessment process. Rijal et al. (2022) note that AA practices have therefore often been found lacking when faced with the rapidly increasing risks and vulnerabilities associated with climate change. However, the effectiveness of AA, or IK-led adaptation, can be improved when combined with (or implemented alongside) planned interventions, scientific knowledge and technology (see *Section 4.3.3.* above).

Reduced exposure

Ten studies – eight of medium quality and two of high quality – reported findings on reduced exposure, often via interventions that involve changing practices or shifting location to avoid the incidence of climate impacts. Eight of the 10 studies linked reduced exposure to agricultural adaptation and behavioural adaptations, while technology and built infrastructure was linked to reduced exposure in six of the studies and information and knowledge sharing was linked to reduced exposure across four studies.

Traditional practices including agroforestry and soil and water conservation techniques can be effective at reducing crop risk exposure to climate events (Thottadi and Singh, 2024). Planting date adjustments can lead to increased crop yields through reduced exposure, and can be crucial as an adaptation strategy on rain-fed land (Onyeneke et al., 2019). A study conducted in Burkina Faso, reviewing an optimum planting date adjustment approach, indicated that *"20% maize yield increment could be achieved in water limited regions"* (Guja and Bedeke, 2024). In China, the same study found that the *"sowing date for wheat could be delayed by 10–20 days in wet and 20–25 days in the dry years to adjust the soil water condition to phonological development so as to get higher possible yield"*. In the Middle East and North Africa (MENA) region, deficit irrigation (applying irrigation during predefined growth stages but otherwise minimising water application) has been found to help to minimise drought-related crop losses and improve water efficiency compared to other forms of irrigation (Chami et al., 2022).

In a similar vein, where applicable, altitudinal adjustments can be made to farming practices, locating crops in higher altitudes where heat exposure can be reduced. For instance, *"to cope with increasing temperatures, Himalayan farmers adopted altitudinal farming methods. With the rise in average temperature, it is reported that the high hill areas, which were previously neglected, were now suitable for cultivation. Agroforestry is also practiced in this regard. Further, farmers incorporated better water management systems, pest management, use of chemical fertilisers, and soil conservation techniques to enhance crop productivity"* (Chettri, Datta and Behera, 2024).

Migration is an increasingly prevalent strategy for reducing exposure through AA. Although it comes with several costs, including dislocation and loss of income, it is a widely practiced adaptation. In Nigeria, labour migration is *"a crucial climate change adaptation strategy adopted by smallholder farmers… migration assumes growing significance as a component of rural livelihood strategies in Tanzania, particularly in response to the gradual impacts of climate change such as desertification, soil degradation, unpredictable rainfall patterns, and temperature fluctuations"* (Legide, Feyissa and Karo, 2024). This has also been found to be the case in India, where *"Migration is another effective adaptation strategy*

practised by the indigenous peoples... During difficult weather conditions such as drought or stressor on resources, the mobility ability of the Dzumsa community in India assisted them in lessening the impacts" (Shaffril et al., 2020).

Reduced sensitivity

Twenty-four of the studies included in our sample reported outcomes related to reduced sensitivity. Of these studies, five were of high quality and 19 were of medium quality. Outcomes relating to reduced sensitivity were linked to agricultural adaptation in 18 studies, to behavioural changes in 15 studies, to technology and built infrastructure in 15 studies, and to interventions involving information sharing and education in 10 studies.

The adoption of AA practices such as soil and water conservation measures, use of traditional irrigation methods, moving to minimum or no tillage, and mulching in farming are seen as cost-effective ways of reducing crop loss and increasing crop yields which can have a positive effect on farmer incomes (Thottadi and Singh, 2024; Guja and Bedeke, 2024).

Farmers facing increased environmental change can use crop diversification measures to spread farm-related risks. Mixed cropping and agroforestry can protect and enhance soil structure and health, reduce erosion, and benefit water retention. The use of traditional water management systems also reduces the need to resort to some short-term coping strategies such as reducing domestic water use (Akinkuolie et al., 2024; Zenda and Rudolph, 2024; Chami et al., 2022). Adopting drought-resistant varieties is an effective way to manage water variability: a systematic review focusing on Nigeria's agriculture sector notes that *"Drought-resistant maize varieties cultivation has been found to increase productivity by 617 kg/ha and of 240 kg/ha compared to cultivation of non-drought-resistant maize varieties, in mild drought-prone areas"* (Onyeneke et al., 2019).

The application of IK is associated with several sustainable agricultural practices associated with increased resilience and reduced likelihood of crop failure, including collective water management (Chami et al., 2022), soil management (Kotze et al., 2024), and crop selection (Dorji et al., 2024). **Moreover, findings from Kotze et al. suggest that farmers using IK are generally more likely to employ mixed strategies.** Mixed farming methods, using indigenous crops as part of a diverse cropping system, are associated with enhanced resilience, for instance in India where indigenous farmers practise intercropping to maximise income and food production (Dorji et al., 2024). Cultivating traditional and high-yield crop varieties has proven to be a way of maximising yield while reducing risk (Onyeneke et al., 2019). Livelihood diversification into off-farm activities such as small businesses and crafts, or seeking wage employment, is also seen as a way of reducing vulnerability to climate shocks by stabilising income and, in some cases, increasing it (Macatulad and Biljecki, 2024; Chettri, Datta and Behera, 2024).

Increased adaptive capacity

Many autonomous adaptations also seek to increase the position or capacity of households to cope with future climate risk. Adaptations can lead to further increased adaptive capacity if carried out well. However, these adaptations may often not be enough given the scale and intensity of climate hazards. Food security outcomes are often a key target of adaptations that establish greater stability within households.

Outcomes relating to changes in adaptive capacity were reported in 28 studies, seven of which were of high quality. Changes in adaptive capacity from agricultural interventions were reported in 21 cases, while

improved adaptive capacity because of technological innovations was reported in 15 studies. AA involving social or behaviour change was reflected across 14 of the studies, while interventions focused on information and knowledge were present in 13 of the studies.

AA practices at the family or household level, such as home gardens, planting more diverse and indigenous crops, traditional soil and water management practices, and planting trees for shade, are all measures that may have positive outcomes for smallholder farmers and households but also benefit nature and biodiversity: *"Guatemala's "huertos familiares" (family gardens) … community-managed gardens promote sustainable urban agriculture, integrate traditional knowledge with modern requirements, and strengthen social cohesion and cultural continuity"* (Akinkuolie et al., 2024).

IK is an important resource for rural and farming communities that have used it in their practices over the long term, enhancing local adaptive capacity (Chami et al., 2022; Dorji et al., 2024). The application of IK has been reported to be effective not only as a means for diagnosing climate-related issues but also as a tool for identifying potential adaptation strategies – given the often site- and context-specific nature of adaptation, IK can be vital in providing localised and specific data (Ogunyiola, Gardezi and Vij, 2022). For example, the adoption of mulching and conservation practices has increased the food security of farmers in Zimbabwe, with high-level adopters reporting better levels of food and nutrition security than low-level adopters (Thottadi and Singh, 2024). Rural and farming communities often have thoroughly tested practices and a well-tested understanding of local land needs that has been developed over several years. Leveraging this knowledge and understanding is important for enhancing adaptive capacity (Wu, Greig and Bryan, 2022).

Reduced poverty

Outcomes related to reduced poverty were reported in five studies, only one of which was judged to be of high quality. Four of these studies linked reduced poverty outcomes with interventions in agriculture, while three studies reported on reduced poverty outcomes in the cases of social and behavioural interventions and technological interventions. Only one intervention found outcomes relating to reduced poverty for information sharing and knowledge-related interventions. This study also reports more on avoided costs from disaster risk preparedness rather than poverty reduction per se (Macatulad and Biljecki, 2024).

As noted above, livelihood diversification and off-farm employment are ways in which individuals are reducing climate-related income shocks (Macatulad and Biljecki, 2024; Chettri, Datta and Behera, 2024). **The extent to which this leads to reduced poverty is highly variable and context-dependent. In many cases, these diversification strategies may be more accurately said to lead to "avoided poverty" rather than "reduced poverty".** We have therefore classed livelihood diversification as an outcome related to adaptive capacity rather than reduced poverty due to this variable nature.

Autonomous practices, and particularly traditional and indigenous practices, may lead to lifestyle enhancements beyond reduced poverty. Including IK and traditional ecological practices in environmental management has been reported to lead to improved wellbeing and better human-nature connectedness, and can even have a positive impact on equity outcomes in adaptation practice, whereby elevating traditional knowledge and promoting IK can work towards addressing imbalances in the governance of adaptation interventions (Ogunyiola, Gardezi and Vij, 2022).

Reduced GHG emissions

Outcomes related to reduced GHG emissions are reported in seven studies, with only one of these judged to be of high quality. Of the studies reporting GHG outcomes, six are linked to interventions in agriculture, three to behaviour and social change, three to interventions using technology or built infrastructure, and two to adaptation interventions using information sharing, knowledge and education.

The impacts of AA on GHGs are complex and non-linear. Practices that may lead to a reduction in GHGs are agroforestry, conservation agriculture, use of organic fertilisers, and moving to traditional agricultural practices (Ogunyiola, Gardezi and Vij, 2022; Thottadi and Singh, 2024; Zenda and Rudolph, 2024) such as conservation tillage practices that can significantly reduce GHG emissions and enhance soil organic carbon content (J. Chen, Zhong and Sun, 2022) By contrast, other adaptations such as resorting to chemical fertilisers, deforesting to collect firewood as an income source, or leaving agriculture entirely to take up employment in polluting industries could be said to have a negative impact on GHGs (J. Chen, Zhong and Sun, 2022).

Enablers

Training and education are important enablers for all forms of adaptation, including AA. In Pakistan, one study found that limited education and technical training are significant barriers for poor farmers in choosing adaptation measures (Saddique et al., 2022). Onyeneke et al. (2019) found that professional training programmes are not only desired by farmers, but also help to create network building opportunities and communities of practice. A systematic review of adaptation strategies in Asia reports that *"Education plays a pivotal role in the farming community. Therefore, workers or family members who have a higher level of education could influence farmers to change or adapt to climate change. Both formal and informal training are useful in the farming sector"* (Diana et al., 2022). The same study found that while farmers with higher levels of education had better adaptive capacity, experience could have a variable effect on adaptive capacity, with older, more experienced farmers less likely to adopt new methods.

Barriers, limitations and maladaptation risks

Some AA or risk mitigation activities can result in negative consequences for people and ecosystems. For example, taking out short-term loans on poor terms can have negative repercussions over the longer term. Livelihood diversification towards riskier or unhealthy jobs such as the sale of charcoal and fuelwood has negative implications for respiratory health and deforestation (Guja and Bedeke, 2024). Meanwhile, some short-term adaptations such as short-term migration, pooling of common resources, or diverting water from domestic use to agriculture are unlikely to build long-term resilience (Rijal et al., 2022). Available resources are likely to shape the nature and quality of adaptation – households with appropriate assets, savings and knowledge are more likely to make sustainable, independent adaptations. Two-thirds of the sources noted that lack of funding and lack of technical capacity were limiting constraints on the ability to adapt autonomously.

As unplanned and spontaneous activities, individual autonomous adaptations, when summed across a community, may have an overall negative impact. Employing traditional practices as an adaptation may help at a household level but may work against planned adaptation strategies from government or external actors (Zenda and Rudolph, 2024). For example, stream bank cultivation, cultivating crops in wetland areas and near water sources, and valley bottom cultivation – all tempting adaptations given the scale of climate hazards – contribute to sedimentation, pollution and resource degradation. Without

coordination, water abstraction from rivers and streams for irrigation damming or water storage, excessive fertiliser use, and vegetation clearing for crops production are reported to contribute to wetland loss which in turn affects important ecosystem services (i.e., flood regulation, climate regulation, soil erosion and infiltration of water) (Magesa et al., 2023).

One limitation to AA (as a practice) is its inadequacy against increasing climate change risk. As an unplanned, spontaneous action, AA can be very useful at a household level as a reactive adjustment to a sudden change in circumstances, but such interventions are usually practised at a limited scale and may have low scalability overall (Tajuddeen and Sajjadian, 2024). Therefore, while AA is an important consideration, it may not represent an effective longer-term adaptation strategy.

IK is rooted in long-term observations of local conditions and is therefore highly context-specific. IK can be a rich source of localised information, making it highly effective in targeted cases, but may lack generalisability (Shaffril et al., 2020). Further, IK techniques, such as IK-led weather forecasting, are normally reliant on local flora and fauna indicators. The disappearance of natural environments and changes in climatic patterns is making this more difficult, thus making IK-led weather forecasting less effective (Mbah, Ajaps and Molthan-Hill, 2021).

There may be policy barriers to integrating IK with institutional support or access to finance, which may prioritise other forms of knowledge in their application. This focus on the primacy of one type of information over another is a significant barrier to the effectiveness of IK (Dorji et al., 2024). Other political dynamics, and power imbalances, may discourage the integration of IK and scientific approaches to adaptation in situations where the use or non-use of an adaptive strategy is reflective of those power relationships and cultural differences (Etana et al., 2022).

The continuing effectiveness of IK is undermined by social and environmental factors. Socially, generational transmission of indigenous or traditional knowledge techniques is in decline as young people migrate to urban centres for non-traditional jobs or learn "scientific" techniques at school that valorise non-indigenous farming methods. In some studies of IK, young people and women were found to be hesitant to use IK (Mbah, Ajaps and Molthan-Hill, 2021). Clearly, specificities of each context will shape the extent to which IK is useful.

Mafongoya and Ajayi (2017) argue that people with formal education and the younger generation do not value IK as highly as older generations. Alem et al. (2018) note that inadequate documentation of indigenous practices has contributed to the declining use of IK as an adaptation strategy. Balehegn et al. (2019) and Debela (2017) also report that young people and educated individuals, including agricultural extension workers, often pay limited attention to IK. This trend poses a threat to the future application of IK for climate change adaptation.

Implications for practice

The main takeaway for FCDO programmes is that adaptation interventions are more effective when they combine indigenous and scientific knowledge.

- For interventions relating to climate information services, disseminated information can be more reliable, more locally relevant and more trustworthy to rural communities when it explicitly combines predictions from both indigenous and scientific sources (Legide, Feyissa and Karo, 2024). The opposite can also be true: where IK could enhance local livelihoods but there is a pre-existing bias towards western approaches, communicating both together does not necessarily

enhance uptake (Shaffril et al., 2020). The complexity therefore arises in how this information is combined and communicated to account for the needs and receptivity of different social groups.

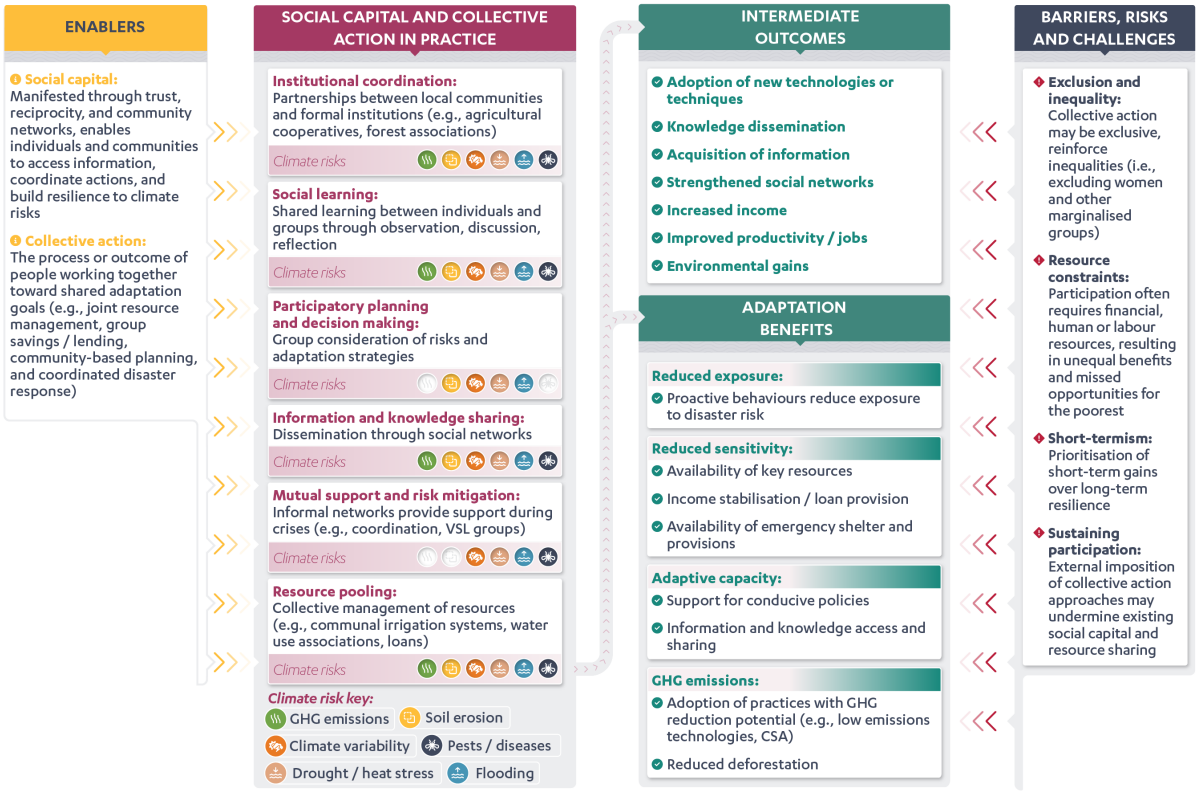
- For interventions relating to agriculture, drawing on IK as a basis before introducing additional, non-traditional techniques can improve uptake and ownership of the process. Participatory plant breeding, or co-development of sustainable farming practices relevant to context, can contribute to the shared development of new technologies, incorporating both scientific and indigenous knowledge and drawing on local knowledge of soils, crop types, seeds and other relevant conditions (Chami et al., 2022; Kc, Tzadok and Pant, 2022).
- While some autonomous adaptations may be effective in the short term, their potential negative trade-offs and impacts depend on local context and risks. However, the SRs reviewed indicate that IK tends to be proactive or planned rather than reactive. As a result, adaptations informed by IK can be considered more strategic actions that help build longer-term resilience.

4.4.10 Social capital and collective action

Social capital and collective action are related but distinct concepts. Social capital is frequently referenced as the networks, relationships, trust and norms that facilitate cooperation and knowledge sharing among individuals, households and institutions. It is highlighted as an enabler of adaptation through access to information (e.g., climate information services, extension services), trust and reciprocity within communities (e.g., savings groups, informal support during crises), and bridging connections between formal and informal actors (e.g., links between government extension services and farmer groups). Social capital is often described as a precondition for effective collective action, but also as a standalone factor that can enable or constrain individuals' adaptive capacity, even outside of organised group efforts.

Collective action, on the other hand, is referenced as the process or outcome of people working together towards shared adaptation goals (e.g., joint resource management, group savings/lending, community-based planning, and coordinated disaster response). The literature includes explicit examples where collective action is the mechanism for adaptation – for example, collective water management, group-based savings models, and participatory planning. As above, collective action is sometimes enabled by strong social capital but is also presented as a separate intervention type or outcome – requiring organisation, leadership, and sometimes formal institutional support.

SOCIAL CAPITAL AND COLLECTIVE ACTION



Confidence in social capital and collective action as an enabler of adaptation to climate risks

The types of climate risk being addressed through social capital and collective action are wide-ranging. Climate variability and change are regularly referenced in relation to shifts in weather patterns, rainfall and temperature, while soil erosion, land degradation and water scarcity are noted as consequences of climate impacts and variability. Drought is repeatedly referenced as a major risk, especially in agrarian communities in Sub-Saharan Africa and South Asia, and flooding is cited as a significant hazard in several studies. GHG emissions are discussed both as a risk and (in terms of their reduction) a co-benefit of certain adaptation interventions.

We have high confidence in the effectiveness of interventions that build on strong local social capital and collective action, particularly in reducing sensitivity to droughts and floods, improving adaptive capacity, and providing safety nets during shocks. However, we note that some interventions can reinforce existing inequalities if marginalised groups are excluded, reducing overall effectiveness. Focusing on short-term benefits over longer-term resilience can also contribute to cycles of vulnerability.

Social capital is central to realising adaptation benefits via social vulnerability, for example through knowledge sharing and capacity building for adaptive decision making or through strengthened social resilience and mutual support during shocks. Benefits can also be realised through collective efforts to address the risk or hazard directly, for example through participatory planning and collective action to reduce exposure and sensitivity to floods and other hazards.

We have high confidence in the role of social capital and collective action in increasing adaptive capacity, reducing sensitivity to droughts and floods, and improving food security and poverty outcomes. This is supported by numerous studies across diverse contexts, with a balance of medium- and high-quality evidence. Community-

based adaptation approaches that build social networks and facilitate resource sharing have been shown to enhance adaptive capacity where they have facilitated information sharing and risk pooling. We have moderate confidence regarding the ability of these interventions to address GHG emissions and long-term resilience, as some evidence points to context-specific risks and unintended consequences. Confidence is lower in interventions where exclusion, inequality, or maladaptation risks are present, or where external interventions disrupt local networks.

Social capital and related concepts like collective efficacy, social networks and community support are mentioned as factors influencing adaptation interventions in several studies (14 studies explicitly reference social capital, while other studies refer to aspects of social capital such as networks). Collective action is explicitly mentioned in 10 studies. Several studies mention both concepts, sometimes in the same context, but do not treat them as synonymous. For example, one study on water management in India and Iran discusses how *"greater social capital"* increases the likelihood of *"collective efficacy"* and collective action but also notes that collective action can be undermined by poor coordination or social divisions (Mzimela and Moyo, 2023). Another study on savings groups in Zimbabwe describes how *"collective action generates economic and social sustainability"*, while also referencing the underlying social capital (trust, norms) that makes such action possible (Thottadi and Singh, 2024). Other studies focus exclusively on social capital (e.g., as a network for information flow) or on collective action (e.g., as a mechanism for resource pooling), reinforcing their conceptual distinction.

Quality of the studies

The quality of studies on social capital and collective action is relatively well balanced between medium- and high-quality categories, as shown in *Table 15* below. Many studies focusing on these topics span multiple types of intervention, and social capital and collective action are frequently discussed together. As a result, the numbers in *Table 15* therefore reflect all instances where either social capital or collective action is reported, which has led to some double-counting.

Table 15: Strength of evidence for social capital and collective action

	No. medium-quality studies	No. high-quality studies	Total
Studies focusing on social capital	8	6	14
Studies focusing on collective action	1	2	3
Reduced exposure	2	1	3
Reduced sensitivity	6	4	10
Enhanced adaptive capacity	6	6	12
Reduced poverty	4	1	5
Reduced GHGs	3	0	3

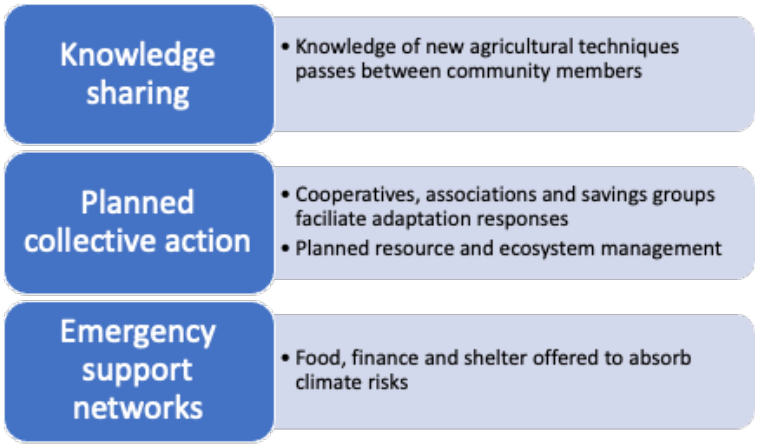
The systematic reviews discussing social capital and collective action are predominantly focused on Africa and Asia, with only four studies including countries from Central and South America or the Middle East. Only two studies are country-specific, one focusing on Kenya and one on Nepal. Most studies include several countries across at least two continents. Three multi-country studies focus only on Africa, and one multi-country study focuses only on Asia.

Findings indicate that social capital and collective action are most prevalent and effective in agrarian communities facing droughts and floods. Sub-Saharan Africa and South Asia exhibit the strongest evidence of effective social capital and collective action, although inequities persist. This finding may be linked, at least in part, to the regional weighting of studies included in this review.

Social capital

Across the literature, social capital consistently plays a role in facilitating access to information and knowledge sharing, enabling collective action and community-level adaptation, providing support networks and risk mitigation strategies, and influencing the adoption and effectiveness of adaptation technologies and practices. Social capital is discussed in different geographical contexts (Africa, Asia, global) and in relation to various types of adaptation interventions (CSA, CIS, water management). This strengthens the generalisability of the findings.

Figure 9: Characterising social capital and collective action



Social capital is most often discussed in relation to agriculture, and especially CSA. Rijal et al. (2022), for example, note that *"strengthening social capital in the form of local institutions such as agriculture groups and forest user groups is an important adaptation strategy"* (Aryal et al., 2018; Maharjan et al., 2017; Sujakhu et al., 2018). In Thottadi and Singh (2024), social capital is also listed as a factor affecting the adaptation of CSA technologies. This study notes that female farmers in Kenya *"leaned on social networks, including neighbours and friends, to acquire CSA-related information"*. The same study also highlights village savings and lending (VSL) as a risk mitigation strategy. This implies a form of mutual support within the community that connects social capital to technological options and risk mitigation strategies.

Etana et al. (2022) similarly discuss social capital in relation to risk, looking at both informal social networks and formal locally based institutions. However, while informal networks based on reciprocity are mentioned as a risk-averse strategy for poor households, the study notes that the most vulnerable households may still be excluded as the availability of labour and economic resources is important for participating in and benefiting from reciprocal social support networks and livelihood diversification. Silici et al. (2021) also highlight the need to consider social differentiation in relation to social learning to ensure inclusion, while Li et al. (2024) flag that female farmers are less likely to access CSA-targeted NGO projects and CSA practices as they have weaker social capital than male farmers.

Nyoni et al. (2024) state that social capital and human capital resources can be strengthened for climate information services (CIS) through participatory methods. The study states that strengthening social and human capital resources through participatory methods, like participatory integrated climate services for agriculture (PICSA), can improve awareness, access, use, value, and uptake of CIS by smallholder farmers. Social networks favour sharing information and bridge education gaps, increasing farmers' ability to incorporate CIS and therefore strengthening adaptive capacity. This associates social capital with informational/educational interventions and knowledge sharing. Hajjar et al. (2021) and Silici et al. (2021) similarly mention social networks in the context of knowledge sharing and information dissemination. Hajjer et al. note that "*social networks and extension services play a crucial role in disseminating information",* while Silici et al. highlight how farmers often rely on their social connections (friends, family, neighbours) to learn about and adopt new agricultural practices, including those related to climate change adaptation.

Silici et al. emphasise the importance of social networks as a key aspect of social capital that enables farmers to access information and make decisions about climate change adaptation strategies. The study portrays these networks as vital channels for knowledge sharing and support within farming communities. It suggests that these informal networks can be crucial for disseminating information and building trust in new approaches, especially in situations where formal extension services may be limited or inaccessible. It also implies that strong social capital within farming communities can enhance their capacity to adapt to climate change by facilitating knowledge exchange and collective action. If information is crucial for effective adaptation, and social networks are crucial for information dissemination, then social networks (a form of social capital) are an enabling factor for effective climate adaptation interventions.

> *"Farmers' social structures, and especially networks based around knowledgeable actors, or sustainability champions can often help achieve desired environmental outcomes at the local scale, and social capital in the form of collective action is also extremely important"* (Silici et al., 2021).

In one study, collective efficacy (CE), which is related to social capital, is discussed as being important for adaptation, particularly in the context of water scarcity (Mzimela and Moyo, 2023). It is linked to collective action and community-level adaptation. This study notes that socio-demographic variables like age, gender, and education level can shape farmers' CE. It also mentions the importance of social capital for CE to take hold, increasing public support for adaptation policies – e.g., higher levels of CE were positively correlated with greater support for water conservation policies. This indicates that social capital can influence policy outcomes by fostering collective support for adaptation measures.

Fan et al. (2022) similarly explore how local networks and social relations can be used as social capital in China, providing effective resource and non-resource income channels for farmers to build stable and diversified livelihoods (Liu et al., 2019). Efforts made by the Chinese government in promoting agricultural cooperatives have also provided security for farmers' agricultural production (Yang and Liu, 2012). Similarly, in Niger, connections with agricultural associations benefited farmers greatly in terms of social support (Ado et al., 2019). In both cases, associations provided information including but not limited to climate, markets and policy measures. Rijal et al. (2022) similarly note that *"strengthening social capital in the form of local institutions such as agriculture groups and forest user groups is an important adaptation strategy"* (Aryal et al., 2018; Maharjan et al., 2017; Sujakhu et al., 2018).

Collective action

Collective action is widely identified as a critical enabler of climate adaptation across diverse contexts, primarily through resource pooling, institutional coordination, and social validation. Its success depends on inclusive participation, strong local institutions, and deliberate efforts to address equity and power imbalances. As with social capital, collective action is discussed in several different contexts.

Kc et al. (2022) describe collective action as *"common pooling of resources and social action"*, including communal irrigation systems and shared labour to address drought and climate risks. These collective strategies are locally led and help buffer communities against shocks by distributing risk and resources across members. One study describes how, in Zimbabwe, villagers organise collectively to pool savings and provide loans during droughts, serving as a crucial safety net and source of finance for the most vulnerable (Thottadi and Singh, 2024). Wagner et al. (2021) describe how, following flood events in Nigeria and Ghana, the most widely practised measure was seeking support from the community, providing labour, financial, or material support, and sharing shelter or food. Such mutual aid and collective provision of assistance are central to community-level adaptation and recovery. This collective action can also reduce dependence on external aid and enhance economic resilience.

Collective action is also discussed in relation to institutional coordination and governance. Brazil's national school feeding programme, for example, helped to create *"structured demand for diversified food products from smallholders"*, incentivising crop diversification and agroecological practices. This institutional approach leverages collective action among smallholders and links them to stable markets, improving both resilience and food security (Brandão et al., 2020, in Dagunga et al., 2023).

Myhre et al. (2024) explore how community-based stakeholders respond to climate change's direct and indirect health impacts in anglophone Caribbean countries, including a focus on participatory planning. Collective action approaches are used to address health and climate challenges, with communities engaging NGOs, government, and other stakeholders. The literature emphasises the importance of collaboration, network building, and shared governance for effective adaptation. Watkins and Collins (2024) also explore the importance of collective action in participatory flood risk management, where community engagement and co-production of knowledge and solutions are key.

Outcomes associated with social capital and collective action

Social capital is associated with a range of positive outcomes related to climate change adaptation, including increased adaptive capacity, reduced sensitivity and reduced poverty.

Reduced sensitivity

Social capital contributes to reduced sensitivity by helping communities manage and absorb climate-related shocks and hazards without suffering significant negative impacts. In Côte d'Ivoire, for example, traditional social systems have incorporated diverse agricultural practices that enhance ecosystem resilience.

Community-based financial mechanisms also serve as critical safety nets that reduce sensitivity to climate shocks. In Zimbabwe, for example, villagers in the Chedriz district developed a VSL model, a form of social capital and collective action that helps manage financial risks and provides support during difficult times. Villagers work as a collective group to raise savings and support lending to those most in need. Defe and Matsa (2021) note that *"this model has acted as an essential source of finance for the needy to*

generate income", demonstrating how collective action can generate economic and social sustainability (Thottadi and Singh, 2024).

In Yunnan province, China, 37.7% of households coped with drought by digging or sharing wells and ponds with relatives, friends and neighbours, demonstrating **the importance of social networks in securing water access during climate shocks**. In Shanxi province, 85.1% of farmers adopted soil conservation technology, a low-cost and efficient strategy for reducing exposure to soil erosion and drought impacts. These collective and networked responses helped reduce the community's sensitivity to drought (J. Chen, Zhong and Sun, 2022).

In Nigeria and Ghana, social networks played a critical role in reducing sensitivity exposure to flood impacts. During recent flood events, communities relied on mutual support systems, including providing labour, financial assistance, and material aid from family and friends, to secure shelter and resources. These informal networks enabled rapid redistribution of goods and labour, minimising displacement and economic losses and reducing exposure (Wagner et al., 2021).

Reduced exposure

Social capital and collective action can help to reduce communities' exposure to climate-related risks such as flooding, although reduced exposure is mentioned less in the literature than reduced sensitivity and increased adaptive capacity.

Mzimela and Moyo (2023), for example, describe how in the aftermath of the 2018 Kerala floods, community members coordinated efforts to bring people to safety and provide necessary supplies. This collective action, underpinned by social support and community embeddedness, was crucial in reducing exposure and building resilience to the disaster. The study emphasises that higher levels of collective efficacy within a community are positively correlated with support for adaptation policies and proactive behaviours to reduce exposure to hazards.

Increased adaptive capacity

Social capital, consisting of the networks, relationships, trust, and shared norms within communities, has demonstrated impacts on increasing adaptive capacity across multiple contexts. Social capital helps farmers to access information, share knowledge and coordinate efforts, all of which contribute to their ability to adapt to climate variability and change. This is seen in studies such as those by Thottadi and Singh (2024), Mzimela and Moyo (2023) and Nyoni et al. (2024). In Cuba, for example, social capital manifested through the National Association of Small Farmers (ANAP) facilitated significant agricultural transformation:

> *"Through effort from the Cuban National Association of Small Farmers (Asociación Nacional de Agricultores Pequeños, ANAP) using farmer-to-farmer transfer of knowledge, over 200,000 farm families moved from convention agriculture to agroecological farming"* (Dagunga et al., 2023).

Collective efficacy, a form of social capital that reflects community members' shared belief in their collective ability to address challenges, has been particularly effective in responding to water scarcity and flood events.

> *"In the aftermath of the 2019 Kerala (India) floods, Panigrahi and Suar (XXXX) report that the community coordinated efforts to bring people to safety during the flood and*

> *provided them with necessary supplies. The collective effort strengthened the capacity to survive, and CE was one of the attributes (together with social support and community embeddedness) that mediated the adverse effects, thereby facilitating flood resilience"* (Mzimela and Moyo, 2023).

Higher levels of CE were positively correlated with greater support for water conservation policies in India, even when these policies placed financial burdens on individuals, demonstrating how social capital can enable communities to accept short-term costs for long-term resilience.

Reduced poverty

Social capital can play a crucial role in poverty reduction through risk mitigation and by expanding access to resources, information, and economic opportunities. In one study, social networks are mentioned as a risk-averse strategy for poor households, minimising exposure to potential losses and shocks (Etana et al., 2022). Poor households often use informal networks, based on reciprocity with neighbours, friends or extended family, to share resources, labour, and information during times of stress or crisis. This suggests that social capital can potentially contribute to reducing poverty by providing safety nets and support systems during times of stress, although it is not always reliable. Furthermore, the study notes that availability of labour, as well as economic resources, were important to participate in, and benefit from, reciprocal social support networks and diversification of livelihood strategies. Thottadi and Singh (2024) also show that VSL schemes, as discussed above, help with risk mitigation, which can reduce poverty. In addition, the study notes the positive effects of CSA on food security and nutritional security.

In China, social networks function as crucial economic buffers during times of stress:

> *"Under the social and cultural background of China, local networks and social relations can be used as social capital that can provide effective resource and non-resource income channels for farmers when they are threatened, allowing them to build a stable and balanced diversified livelihood model"* (Fan et al., 2022).

Reduced GHGs

Social capital and collective action can help to bridge adaptation and mitigation goals, facilitating the adoption of practices with GHG reduction potential, such as CSA and soil management, through knowledge sharing and information dissemination. This review highlights six key mechanisms through which social capital and collective action enable adaptation interventions with GHG emission reduction co-benefits, all relating to agriculture and land use. Some examples are provided below.

In South Asia, collective action through farmer cooperatives and women's self-help groups enabled widespread adoption of zero-tillage practices and climate-resilient seeds (Naveen et al., 2024). These practices reduced methane emissions from rice-wheat systems by 33–40% compared to conventional tillage, equivalent to 7,653 kg CO_2 eq./ha/year. Institutional support from local governments and NGOs strengthened social networks, providing access to climate information via ICT tools (e.g., SMS-based weather alerts) and subsidised machinery. For instance, laser land levelling – a water-efficient technique promoted through community workshops – reduced groundwater extraction, lowering energy use and associated emissions. In Ethiopia, communal forest associations implemented rotational grazing and agroforestry, restoring 12,000 hectares of degraded land (Etana et al., 2022). Satellite data showed a 20%

decline in deforestation rates, avoiding approximately 4.8 Mt CO_2 emissions annually. Trust-based resource-sharing agreements and traditional leadership structures were critical to success.

One study documents how village-level water user associations in China's Heihe River Basin collectively adopted alternating wetting and drying (AWD) irrigation for rice cultivation (J. Chen, Zhong and Sun, 2022). By coordinating planting schedules and water-sharing agreements, these groups reduced methane emissions by 30–50% compared to continuous flooding. However, the study also noted unintended consequences: drip irrigation systems in arid regions increased GHG emissions by 135% due to energy-intensive groundwater pumping, underscoring the need for context-specific collective planning.

Evidence of negative outcomes

For the most part, social capital and collective action emerge as critical components of climate adaptation across diverse contexts, operating through community networks, institutional linkages, and knowledge-sharing mechanisms. However, maladaptation risks arise when social capital and collective action are exclusionary, reinforce inequalities, or prioritise short-term gains over long-term resilience.

Social capital, for example, can perpetuate inequalities when networks exclude vulnerable populations. In Burkina Faso, women were often excluded from agricultural associations, limiting their access to climate information and resources (Dagunga et al., 2023). In Bangladesh, centralised government strategies eroded trust when they sidelined community-based adaptation approaches, reducing buy-in and effectiveness (Rijal et al., 2022). Social capital in hierarchical structures can also entrench inequities. In Kenya and Malawi, one study documented how crop insurance schemes favoured wealthier farmers with stronger social ties to institutions, exacerbating income disparities (Rahmani and Sharifi, 2025).

Findings were similar for collective action. Zimbabwe's VSL groups, for example, occasionally prioritised wealthier households, leaving the extreme poor without safety nets during droughts and deepening vulnerability among marginalised groups (Thottadi and Singh, 2024). Externally imposed collective action frameworks can also undermine local social capital. In Bangladesh, centralised government strategies disrupted community-based adaptation approaches, eroding trust in collective action (Rijal et al., 2022). Farmers reverted to individual coping strategies, reducing the effectiveness of flood risk management. In Nepal, in the same study, externally driven policies disrupted traditional resource-sharing norms, fracturing community cohesion and reducing the legitimacy of collective adaptation efforts.

Focusing on short-term gains over long-term resilience can undermine the effectiveness of social capital and collective action. In West Africa, mutual support networks after a flooding event focused on temporary relocation and resource sharing but failed to invest in long-term infrastructure (e.g., flood barriers) (Watkins and Collins, 2024). This perpetuated cycles of vulnerability. In Mozambique, Colombia and China, farmers also delayed adopting land use practices until they observed success in trusted networks (Snilsveit et al., 2019). This "wait-and-see" approach slowed the implementation of critical adaptations.

Adaptation interventions seeking to draw on social capital and collective action should therefore look to integrate marginalised voices, strengthen local governance, and balance immediate needs with long-term planning.

Equity considerations

Social capital and collective action disproportionately benefit certain groups while excluding others, often reinforcing existing inequalities. Marginalised groups (women, elderly people, ethnic minorities)

face systemic exclusion from social capital networks due to cultural norms, poverty, or lack of representation, while wealthier households often co-opt collective action initiatives, diverting resources away from the most vulnerable (Dagunga et al., 2023; Thottadi and Singh, 2024; Rijal et al., 2022).

In Burkina Faso, for example, women were systematically excluded from agricultural associations managing climate-resilient practices, limiting their access to adaptation resources and decision-making power (Dagunga et al., 2023). Nyoni et al. (2024) similarly mention that women are among the underserved groups who may be excluded from accessing CIS, implying that social capital interventions need to be more inclusive of women.

Etana et al. (2022) mention that informal networks based on reciprocity may exclude the most vulnerable households (e.g., female-headed households) who were unable to invest (e.g., labour and economic resources) in social networks. Zimbabwe's VSL model, for example, often prioritised wealthier households during droughts, leaving women-headed households and the extreme poor without safety nets (Thottadi and Singh, 2024). In Zimbabwe, elderly populations were also excluded from participatory decision making, reducing their access to adaptation resources (Dagunga et al., 2023).

Several studies focus on smallholder farmers and how social capital can influence their access to information, technologies, and support systems (Thottadi and Singh, 2024; Mzimela and Moyo, 2023; Nyoni et al., 2024; Li, Ma and Zhu, 2024). This implies that smallholder farmers, in general, can benefit significantly from interventions that leverage social capital. However, wealthier farmers typically benefit the most from social capital and collective action. In Niger, for example, farmers connected to agricultural associations gained access to climate information, markets, and policy insights, enhancing their adaptive capacity (Fan et al., 2022). Brazil's PNAE programme also linked smallholders to school feeding markets, but benefits skewed toward those with pre-existing social networks and land access (Brambilla et al., 2022).

Implications for practice

The evidence demonstrates that social capital can be a critical enabler of effective climate adaptation, particularly for increasing adaptive capacity and reducing both sensitivity and poverty. While direct links to GHG emissions reduction are less evident in the data examined, the transition to sustainable agricultural practices facilitated by social networks likely has mitigation co-benefits.

These findings suggest that adaptation interventions should explicitly incorporate strategies to identify, leverage and strengthen existing social capital within communities to enhance effectiveness and sustainability of outcomes. They also indicate that locally led approaches that seek to build on and enhance existing knowledge and networks need to be a key part of the adaptation process. However, social capital can be a double-edged sword, enabling adaptation through collective action and knowledge sharing but risking exclusion if not deliberately managed. Its potential is maximised when paired with equitable institutions, inclusive governance, and targeted resource allocation. Future interventions should prioritise building bridges between informal community systems and formal structures to address systemic vulnerabilities.

FCDO should therefore seek to embed participatory, inclusive approaches into the design and delivery of adaptation projects while addressing structural inequalities to maximise benefits. This might include:

- Prioritising participatory design, building trust and strengthening social networks as part of project design

- Engaging “sustainability champions” to bridge formal and informal knowledge systems
- Seeking to establish institutions that enable collective efficacy, for example agricultural unions/associations and producer cooperatives with greater bargaining power
- Addressing inclusion gaps, potentially by supporting and drawing on the knowledge of community-based organisations with the legitimacy and capacity to influence deeper social drivers of exclusion, and/or combining social capital building with economic support to enable participation
- Integrating formal and informal institutions, for example supporting farmers and cooperative groups while helping them to develop equitable governance structures.

5 Findings on cost effectiveness

Only nine studies provide explicit data on cost effectiveness. This is in line with expectations of looking for this level of cost information at the systematic review level rather than in primary studies. The limited available data indicate varying cost effectiveness across several different intervention types, with nature-based solutions (NbS) showing more favourable cost-benefit ratios in some contexts, while water infrastructure interventions often have high implementation costs with variable benefits. Due to the very small sample size, however, this analysis is limited, unreliable and should be used with caution.

Nature-based solutions: NbS demonstrate significant cost effectiveness in certain contexts, particularly for coastal protection. In Bangladesh, for example, villages protected by mangroves experienced approximately half the monetary loss from flood and wind damage during extreme weather events (around £1,025 per household) compared to unprotected villages (Smith et al., 2021). The same study found that a 100-metre strip of healthy mangroves can reduce storm surge velocity by up to 92%, significantly reducing embankment maintenance costs (Smith et al., 2021). However, NbS interventions also face important cost-related challenges, including challenges relating to implementation and ongoing maintenance. Low-cost hybrid approaches have emerged as promising alternatives. For example, Indonesia has implemented hybrid NbS infrastructure combining natural elements with engineering techniques, including permeable bamboo dams (T-Dams) for shoreline stabilisation. These represent good examples of low-cost, community-managed solutions, although permeable bamboo dams can also degrade within three to seven years, requiring resources for maintenance and repair (Villamayor-Tomas et al., 2024).

Agricultural adaptation strategies show varying degrees of cost effectiveness depending on implementation approaches and contextual factors. Results of a meta-analysis on income suggests that agroforestry interventions lead to *"a small, positive impact on income, with moderately high heterogeneity in the results"* (Castle et al., 2021). Positive income effects typically stem from either increased yields providing additional income or incentive payments offsetting costs associated with decreased yields. However, opportunity costs can be significant – in rural Xinjiang, China, for example, farmers experienced negative income effects because the additional time spent managing agroforestry systems reduced off-farm income opportunities (Castle et al., 2021).

A study focused on integrated soil fertility management in Ethiopia highlights this approach as *"the best-bet and most feasible option which could provide a more holistic, lower cost, and sustainable climate-smart solution"* in Ethiopia. Despite its potential cost effectiveness, however, adoption remains limited due to implementation and dissemination challenges (Abegaz et al., 2024). Overall, CSA practices often require substantial upfront investments in sustainable approaches like organic inputs, crop diversification, and agroforestry. These initial costs, coupled with delayed benefits, can create significant barriers, particularly for small-scale farmers lacking access to credit or financial resources.

Technology-based interventions: Findings indicate complex cost-effectiveness considerations for technological adaptation approaches. A groundbreaking IoT smart irrigation system implemented in Kenya, for example, demonstrated *"substantial crop yield improvements, significant water conservation, substantial cost reductions, and enhanced climate resilience"* but required significant initial investments and comprehensive technical training. Factors potentially limiting the cost effectiveness of technology-based solutions, particularly in Sub-Saharan Africa, include the need for constant upgrades, limited infrastructure hampering deployment and preventing scaling, and high acquisition and maintenance costs

(Wanyama et al., 2024). This study notes that traditional skills and labour practices may be lower-cost, more environmentally sustainable, and effective enough when combined with other interventions.

Autonomous and community-based adaptations: Low-tech, autonomous adaptations can demonstrate strong cost effectiveness. In relation to agriculture, for example, soil and water conservation measures, traditional irrigation methods, minimum tillage, and mulching are identified as cost-effective ways of reducing crop loss and increasing crop yields which can have a positive effect on farmer incomes (Guja and Bedeke, 2024, Thottadi and Singh, 2024). Community-based approaches can also offer cost-effective solutions through resource sharing. In Yunnan province, China, 37.7% of households coped with drought by digging or sharing wells and ponds with relatives, friends and neighbours. In Shanxi province, 85.1% of farmers adopted soil conservation technology, a low-cost and efficient strategy for reducing exposure to soil erosion and drought impacts (J. Chen, Zhong and Sun, 2022).

Built infrastructure: Ogie, Adam and Perez (2020) highlight concerns about the cost effectiveness of flood defence approaches, noting that high-cost flood defence construction faces significant limitations due to design constraints (e.g., 100-year flood planning) and may not remain effective in the long term given constantly increasing flood risks. The same study also notes how structural measures failed to protect Manila from flooding caused by typhoon Ondoy in 2009, as they were designed using only 10-year and 30-year discharge return periods for the drainage works and flood protection works, respectively (Ogie, Adam and Perez, 2020).

Implications for practice

Based on a very limited dataset, we found that cost effectiveness varies across adaptation intervention types. However, the following summary points should be considered with caution given the low number of studies that discuss cost effectiveness, which increases heterogeneity challenges and increases the risk of bias.

- Nature-based solutions potentially offer strong long-term benefits but face implementation and maintenance challenges.
- Agricultural interventions show promising returns but often require significant initial investments.
- Technology-based approaches demonstrate high potential but face substantial barriers in resource-constrained settings.
- The most consistently cost-effective approaches appear to be autonomous adaptations, community-based solutions, and traditional practices that leverage existing knowledge and social networks, but even these require supportive financing mechanisms and appropriate governance frameworks to achieve optimal outcomes.
- Contextual factors, implementation quality, and proper targeting can significantly influence the cost effectiveness of any adaptation intervention.

6 Conclusions

6.1 Summary

This rapid umbrella review examines the effectiveness of climate change adaptation interventions in low- and middle-income countries, drawing on 109 systematic reviews published since 2019. The evidence demonstrates that adaptation interventions are taking place across multiple sectors and geographies, with the agricultural sector featuring prominently. Most studies report positive outcomes, although findings on effectiveness vary across contexts and intervention types. The evidence indicates that adaptation interventions are more effective when they combine multiple approaches rather than implementing single strategies in isolation; particularly in agriculture and coastal risk reduction. Interventions that integrate local knowledge with scientific innovations tend to be more sustainable and contextually appropriate.

The review also highlights significant methodological challenges in measuring adaptation effectiveness. Heterogeneity in how outcomes are defined and measured makes cross-comparison difficult, with different studies emphasising social, ecological, or (more rarely) financial dimensions of effectiveness. Limited longitudinal data further complicate our assessment of long-term sustainability and the transformative potential of different adaptation interventions.

6.2 Which interventions have been most effective in leading to a) reduced exposure, b) reduced sensitivity, and c) increased adaptive capacity?

The evidence shows that well-designed interventions can successfully reduce exposure to climate hazards, decrease sensitivity to impacts, and enhance adaptive capacity among vulnerable populations. Below, we summarise our findings from *Sections 4.4.1 to 4.4.10* by outcome type.

Our summary assessment of effectiveness across interventions is limited by the same methodological challenges encountered in each of the findings sections. The heterogeneity in how outcomes are described and measured, as well as the heterogeneity both across and within intervention types, make it difficult to make accurate and definitive comparative assessments.

Our summary below is therefore not an ordinal ranking of different intervention types based on a common interpretation of adaptation effectiveness. Rather, it is a synthesis of our findings above, drawing out which interventions are most often linked with achieving certain outcomes. In addition to frequency, we have taken into account our assessments of the quality of the studies containing these findings, as well as qualitative assessment of the evidence base (including whether there is consensus of findings across studies, how wide and deep the evidence base is, and whether similar findings are reported across a range of contexts).

As such, the interventions linked to outcome types below should be seen as a starting point to help the reader interpret the more detailed evidence above. For more detail, the reader is advised to refer to the individual findings sections.

Interventions that have been most effective in ***reducing exposure*** to climate hazards include:

- **Nature-based solutions and agroforestry**, where interventions create physical buffers against climate extremes, particularly in coastal and hilly regions. There is evidence, for example, that NbS reduce exposure to some of the risks in coastal regions, reducing intensity of tidal surges, and

having quantifiable damage reduction values. On farms, agroforestry protects crops from heat stress as well as flood risk in some cases, reducing the magnitude or severity of the risks. NbS are highly context-specific, and each context needs careful consideration to avoid potential maladaptive outcomes.

- **Early warning systems and climate information services** have shown effectiveness in reducing exposure by enabling proactive risk management and evacuation before climate hazards strike, notably in Southeast Asian contexts where storms are a particular challenge.

Interventions that have been most effective for ***reducing sensitivity*** to climate hazards include:

- **Agroforestry and climate-smart agriculture techniques**, particularly those that enhance soil moisture retention and soil health, such as conservation agriculture, mulching, and integrated soil fertility management. However, these benefits may be limited by the scale of climate risks. In urban contexts, appropriate urban planning such as integration of trees or microforests leads to reduced heat island effects and heat stress.
- **Diversification** emerges as a powerful strategy across multiple contexts. Interventions that promote diverse crop varieties and mixed farming systems, for example, have demonstrated faster productive recovery compared to monoculture approaches (e.g., Dobhal et al., 2024). Pastoralists diversifying their herds with drought-tolerant livestock species has also proven effective. More broadly, combinations of adaptation interventions are often described as more likely to have positive outcomes.
- **Water-efficient irrigation systems** have been shown to maintain productivity during drought periods, with evidence of positive economic returns and reduced poverty levels (e.g., Ategeka et al., 2024). The combination of water management with crop production technologies is particularly effective at reducing sensitivity to drought. As with all irrigation systems, there is a risk of negative environmental impact if increased water demand (as a result of the intervention) goes on to exacerbate water scarcity issues. Again, understanding the context is key.

Interventions that have been most effective for building ***increased adaptive capacity*** to climate hazards include:

- **Knowledge building and information dissemination**, such as climate information services and extension programmes that incorporate local knowledge, have successfully enhanced farmers' decision-making abilities. CIS, for example, reduces sensitivity by enabling livelihood decisions such as planting times or seed selection that enable continued activities despite climate threats. When digital technologies are made accessible, they significantly improve access to climate information and agricultural advisories. There is significant evidence, therefore, that CIS must be accompanied by consideration of accessibility, timeliness, and localisation of information provided. Similarly, CSA interventions are more likely to be effective when combined with extension services, training, and continued information provision.
- **Income diversification and financial inclusion** can create the conditions for additional income streams and improve access to financial resources. These are often associated together as some access to additional funds is needed to diversify income streams. The provision of credit is not without risks, given climate variability and other risks that can threaten the ability to repay on time. Diversification is effective because alternative income sources may be less exposed or

sensitive to certain climate risks. This may take the form of generating income in new locations, or seeking income from sources not affected by dominant climate risks.

- **Community-based adaptation approaches** that build social networks and facilitate resource sharing have enhanced collective adaptive capacity. Village savings and loans organisations in Zimbabwe, for example, provide financial security during climate-related crises (e.g., Thottadi and Singh, 2024).
- **Bottom-up and participatory approaches** that engage communities from the outset and integrate local knowledge systems have demonstrated greater effectiveness and sustainability; for instance, by engaging communities and indigenous knowledge in early warning systems and climate forecasting, rather that only focusing on data driven CIS. These approaches empower marginalised communities to participate in adaptation planning and implementation. Participatory approaches also have the benefit of enabling participants in the process to understand more about climate risks affecting their area, the types of interventions available, while also being able to direct an intervention towards critical priorities. Bottom-up approaches that also delegate decision making and delivery to communities can increase effectiveness by designing more locally appropriate interventions, which are more likely to be sustained as they have community buy-in. Since participation is both an enabler of effective adaptation, but requires some investment to ensure it is done well, we include it here as a contributor to adaptive capacity.

6.3 Knowledge and evidence gaps

Despite a growing body of evidence on adaptation effectiveness, significant knowledge gaps remain that warrant further research. To further support FCDO in prioritising its adaptation programming under ICF 4, we highlight the following areas for continued/further research:

1. **Long-term effectiveness and sustainability:** Most studies assess short- to medium-term outcomes, with limited longitudinal evidence on the durability of adaptation benefits. Research tracking interventions over extended periods would provide crucial insights on sustainability and transformation potential. This would also enable better identification and analysis of interventions that move beyond incremental changes to address structural vulnerabilities and enable transformative adaptation.
2. **Public and private goods:** Studies offer little analysis of how the public or private nature of adaptation investment and adaptation benefits might influence the effectiveness of an intervention. A study on the appropriateness of public or private goods in different contexts may further help to direct the nature of funding for interventions in specific locations.
3. **Cost effectiveness and value for money:** Few studies provide robust cost-benefit analyses or comparative assessments of different adaptation approaches, limiting evidence for optimal resource allocation. Focused research on the cost effectiveness of adaptation interventions would complement the findings in this study.
4. **Urban adaptation:** The evidence base is stronger for rural and agricultural settings than for urban contexts, indicating a need for more research on effective urban adaptation interventions. This might include sectors such as health, education and urban infrastructure.
5. **Integration of indigenous and scientific knowledge:** While several studies acknowledge the value of indigenous knowledge, more research is needed on effective models for integrating traditional

and scientific approaches to adaptation, including how this can be best supported and/or funded by external stakeholders.

6. **Maladaptation risks:** Further research could examine the conditions under which well-intended adaptation interventions may lead to negative outcomes or exacerbate vulnerabilities for certain groups. This could be linked to a study on the limits to adaptation that explores the thresholds beyond which current adaptation strategies become ineffective, particularly in highly vulnerable contexts.

Annex 1: Detailed search terms and summary of steps taken to search each database

The review team created a bespoke set of search terms for each database (Scopus and Web of Science), based on character limits and search functions. Our search and screening strategy for each database is set out below. Search terms were created in collaboration with FCDO and are detailed in the research protocol.

Scopus

Scopus - WoS translated

(((TITLE-ABS-KEY ("climat* change" OR "global warming" OR "climat* variability" OR "climat* hazard" OR "weather variability" OR "sea-level*" OR "sea level" OR "extreme event*" OR "heat wave*" OR "extreme weather" OR "natural hazard" OR (climate AND fire) OR flood* OR drought OR hurricane OR storm OR cyclone OR mudslide* OR landslide* OR "rainfall variability" OR "natural disaster*" OR "precipitation variability" OR "temperature variability" OR "water scarcity" OR "Heat Adaptation" OR "heat-adaptation" OR "extreme heat"))) AND (((TITLE-ABS-KEY ("systematic review" OR "meta-analysis" OR "meta-regression" OR "Research synthesis" OR "Evidence synthesis" OR "meta synthesis" OR "analytical review" OR "rapid review" OR "scoping review" OR "Systematic integrated literature review" OR "Systematic literature review" OR "Systematic review approaches" OR "narrative review" OR "evidence gap map" OR "Umbrella review*" OR "overview stud*" OR "landscape review*" OR "effectiveness review" OR "systematic review* of systematic review*"))) AND (((TITLE-ABS-KEY (household* OR farm* OR communit* OR village* OR institution* OR office* OR home* OR district* OR disab* OR youth* OR parish* OR cooperative* OR rural* OR city OR cities OR town* OR school* OR women OR children OR company OR companies OR SME OR enterprise OR factory OR factories OR building* OR infrastructur* OR municipalit* OR smallholder*)))) AND (((TITLE-ABS-KEY ("adapt* to" "climate change adaptation" OR "adapt* to climat*" OR "adaptive capacity" OR "adapt* strateg*" OR "adapt* intervention*" OR vulnerab* OR resilie* OR "coping with climat*" OR "coping with weather" OR "cope with climat*" OR "cope with weather" OR "coping with extreme" OR "cope with extreme" OR "disaster risk reduction" OR (disaster AND reduction) OR (human AND adaptation) OR (climate OR risk AND mitigation) OR "risk management" OR preparedness OR "livelihood diversification" OR "early warning" OR "risk reduction" OR "reduc* risk*" OR "ecosystem-based" OR "nature-based" OR mainstreaming OR (Climate AND integration) OR governance OR "ecosystem-based adaptation" OR "community-based adaptation" OR "climate information services")))) AND (((TITLE-ABS-KEY (agricultur* OR forest* OR water* OR land* OR societ* OR social OR health OR industr* OR energ* OR fish* OR *econom* OR livelihood OR income OR develop* OR sustainab* OR financ* OR "private sector" OR (regenerative AND agriculture) OR agroforestry OR

193 hits

Web of Science

Final WoS search strings, adapted from Deval:

#1 TS= ("climat* change" OR "global warming" OR "climat* variability" OR "climat* hazard" OR "weather variability" OR "sea-level*" OR "sea level" OR "extreme event*" OR "heat wave*" OR "extreme weather" OR "natural hazard" OR (climate AND fire) OR flood* OR drought OR hurricane OR storm OR cyclone OR mudslide* OR landslide* OR "rainfall variability" OR "natural disaster*" OR "precipitation variability" OR "temperature variability" OR "water scarcity" OR "Heat Adaptation" OR "heat-adaptation" OR "extreme heat")

#2 TS= ("systematic review" OR "meta-analysis" OR "meta-regression" OR "Research synthesis" OR "Evidence synthesis" OR "meta synthesis" OR "analytical review" OR "rapid review" OR "scoping review" OR "Systematic integrated literature review" OR "Systematic literature review" OR "Systematic review approaches" OR "narrative review" OR "evidence gap map" OR "Umbrella review*" OR "overview stud*" OR "landscape review*" OR "effectiveness review" OR "systematic review* of systematic review*")

#3 TS= (household* OR farm* OR communit* OR village* OR institution* OR office* OR home* OR district* OR disab* OR youth* OR parish* OR cooperative* OR rural* OR city OR cities OR town* OR school* OR women OR children OR company OR companies OR SME OR enterprise OR factory OR factories OR building* OR infrastructur* OR municipalit* OR smallholder*)

#4 TS= ("adapt* to" "climate change adaptation" OR "adapt* to climat*" OR "adaptive capacity" OR "adapt* strateg*" OR "adapt* intervention*" OR vulnerab* OR resilie* OR "coping with climat*" OR "coping with weather" OR "cope with climat*" OR "cope with weather" OR "coping with extreme" OR "cope with extreme" OR "disaster risk reduction" OR (disaster AND reduction) OR (human AND adaptation) OR (climate OR risk AND mitigation) OR "risk management" OR preparedness OR "livelihood diversification" OR "early warning" OR "risk reduction" OR "reduc* risk*" OR "ecosystem-based" OR "nature-based" OR mainstreaming OR (Climate AND integration) OR governance OR "ecosystem-based adaptation" OR "community-based adaptation" OR "climate information services")

#5 TS= (agricultur* OR forest* OR water* OR land* OR societ* OR social OR health OR industr* OR energ* OR fish* OR *econom* OR livelihood OR income OR develop* OR sustainab* OR financ* OR "private sector" OR (regenerative AND agriculture) OR agroforestry OR environmental OR (ecosystem AND governance) OR (livelihood AND diversification))

#6 #1 AND #2 AND #3 AND #4 AND #5

Add timeframe: 1 Jan 2019 to date

2,856 hits

Annex 2: World Bank LMIC classifications

Based on the World Bank's current classification by income

Afghanistan	Malawi
Albania	Malaysia
Algeria	Maldives
Angola	Mali
Argentina	Marshall Islands
Armenia	Mauritania
Azerbaijan	Mauritius
Bangladesh	Mexico
Belarus	Micronesia
Belize	Moldova
Benin	Mongolia
Bhutan	Montenegro
Bolivia	Montserrat
Bosnia and Herzegovina	Morocco
Botswana	Mozambique
Brazil	Myanmar
Burkina Faso	Namibia
Burundi	Nauru
Cabo Verde	Nepal
Cambodia	Nicaragua
Cameroon	Niger
Central African Republic	Nigeria
Chad	Niue
China (People's Republic of)	North Macedonia
Colombia	Pakistan
Comoros	Palau
Congo	Panama
Costa Rica	Papua New Guinea

Côte d’Ivoire	Paraguay
Cuba	Peru
Democratic People’s Republic of Korea	Philippines
Democratic Republic of the Congo	Rwanda
Djibouti	Saint Helena
Dominica	Saint Lucia
Dominican Republic	Saint Vincent and the Grenadines
Ecuador	Samoa
Egypt	São Tomé and Principe
El Salvador	Senegal
Equatorial Guinea	Serbia
Eritrea	Sierra Leone
Eswatini	Solomon Islands
Ethiopia	Somalia
Fiji	South Africa
Gabon	South Sudan
Gambia	Sri Lanka
Georgia	Sudan
Ghana	Suriname
Grenada	Syrian Arab Republic
Guatemala	Tajikistan
Guinea	Tanzania
Guinea-Bissau	Thailand
Guyana	Timor-Leste
Haiti	Togo
Honduras	Tokelau
India	Tonga
Indonesia	Tunisia
Iran	Türkiye
Iraq	Turkmenistan
Jamaica	Tuvalu

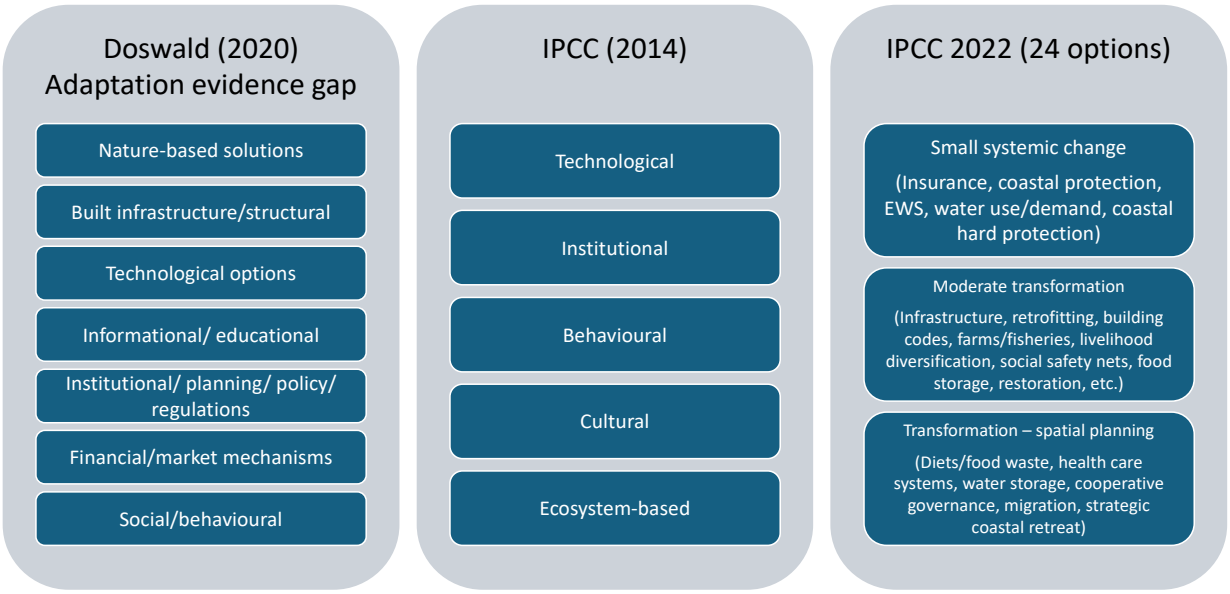
Jordan	Uganda
Kazakhstan	Ukraine
Kenya	Uzbekistan
Kiribati	Vanuatu
Kosovo	Venezuela
Kyrgyzstan	Viet Nam
Lao People’s Democratic Republic	Wallis and Futuna
Lebanon	West Bank and Gaza Strip
Lesotho	Yemen
Liberia	Zambia
Libya	Zimbabwe
Madagascar	

Annex 3. Analytical framing for the study

The study team carried out a rapid (non-exhaustive) review of options for coding, categorising and organising evidence emerging from academic databases and grey literature. Due to the wide-ranging nature of climate adaptation in practice and as an academic field, numerous categorisations and definitions are possible. Frameworks were mainly explored in two categories: 1. Intervention typologies and 2. Outcome framing. Sectoral categorisations (i.e., health, water, infrastructure) were also considered but were excluded due to growing recognition of adaptation as a systemic and holistic challenge that needs corresponding holistic assessments.

Intervention typologies:

Figure 10: Intervention typologies explored under the study

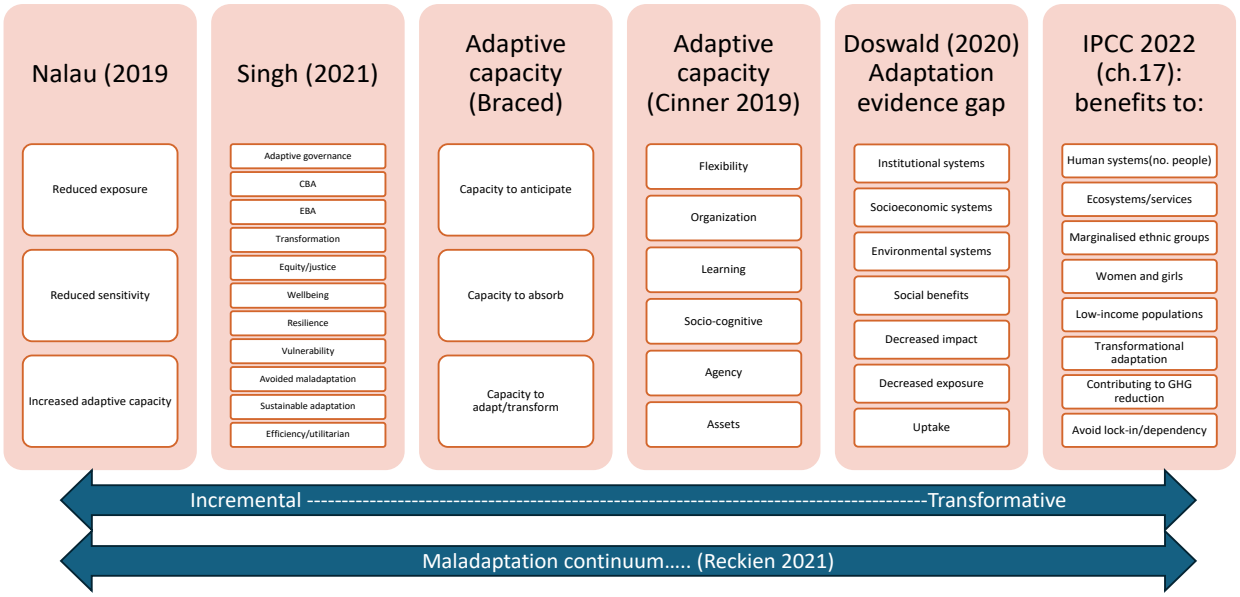


Index: This is the selected category for the systematic review process.

The diagram above illustrates a comparison of intervention typologies across different frameworks. A study commissioned by the Green Climate Fund (GCF) in 2020 – Doswald (2020) – explores the evidence gaps across the adaptation literature landscape and introduces seven categories of intervention that can cover institutional and capacity-building interventions alongside technology, infrastructure or nature-based activities. The IPCC (2014) framework categorises adaptation strategies into five broader groups. The 2022 IPCC report extends these categories and offers 24 specific adaptation options as a way of presenting their contribution to systemic or transformative change. Doswald's (2020) typology is comprehensive without being overly complicated or tied to particular interventions; we therefore selected this as a typology for the study.

Outcome framing:

Figure 11: Outcome framing explored under the study



Effective adaptation outcomes can be defined in multiple ways – for example, minimally as reduced vulnerability or reduced exposure to shock/stress and maximally as transformed governance structures or more equitable communities. It can also be assessed at different levels – for example, at individual, household, institutional or country level. The diagram above synthesises various approaches to framing adaptation outcomes, drawing on multiple academic sources to present an understanding of adaptation effectiveness.

Singh (2021), reviewing a wide range of adaptation literature, points out that the framing chosen usually reflects the ideological leanings of the writer, and picks out 11 characterisations of adaptation objectives. Adaptive capacity is a broad term referring to a system's ability to adjust in various ways to climate risks. It can be a direct intended outcome of an adaptation intervention or a co-benefit of a wide variety of adaptation or broader development interventions. Adaptive capacity can consist of multiple factors likely to vary across contexts – from psychological factors, such as the confidence to make decisions, to economic factors, such as savings and productivity, through to education or political inclusion. Cinner (2019) and FCDO's BRACED programme both introduced approaches to categorising this capacity, with Cinner more applicable at the household or individual level. The IPCC 2022 approach frames outcomes in terms of their benefits to specific groups or ecosystems, or in terms of reduced GHG emissions and avoidance of lock-in effects. Given the breadth of the review, a simpler framing, that of Nalau (2019), is more helpful. This picks out outcomes of reduced exposure and sensitivity to climate risk while recognising that efforts to achieve these outcomes will have adaptive capacity co-benefits that are essential to track. Adaptation benefits can also be assessed for their contribution to transformative adaptation processes and outcomes – i.e., through addressing structural barriers to adaptation. These outcomes form the foundation of successful adaptation interventions, and these benefits are open and shaped by context. Screening of systematic reviews will be able to identify these benefits and their likelihood of occurring.

Across all interventions, in assessing their effectiveness, it is essential to consider the continuum from incremental through to transformative interventions, and the risk of maladaptive outcomes that deepen or create vulnerability for already vulnerable people or groups. In screening evidence for adaptation effectiveness, the study team will be guided by the outcomes and intervention types mentioned above,

but not limited by them. Adjustments to create more appropriate categorisations will be considered if these are inadequate.

Annex 4: Quality appraisal tool

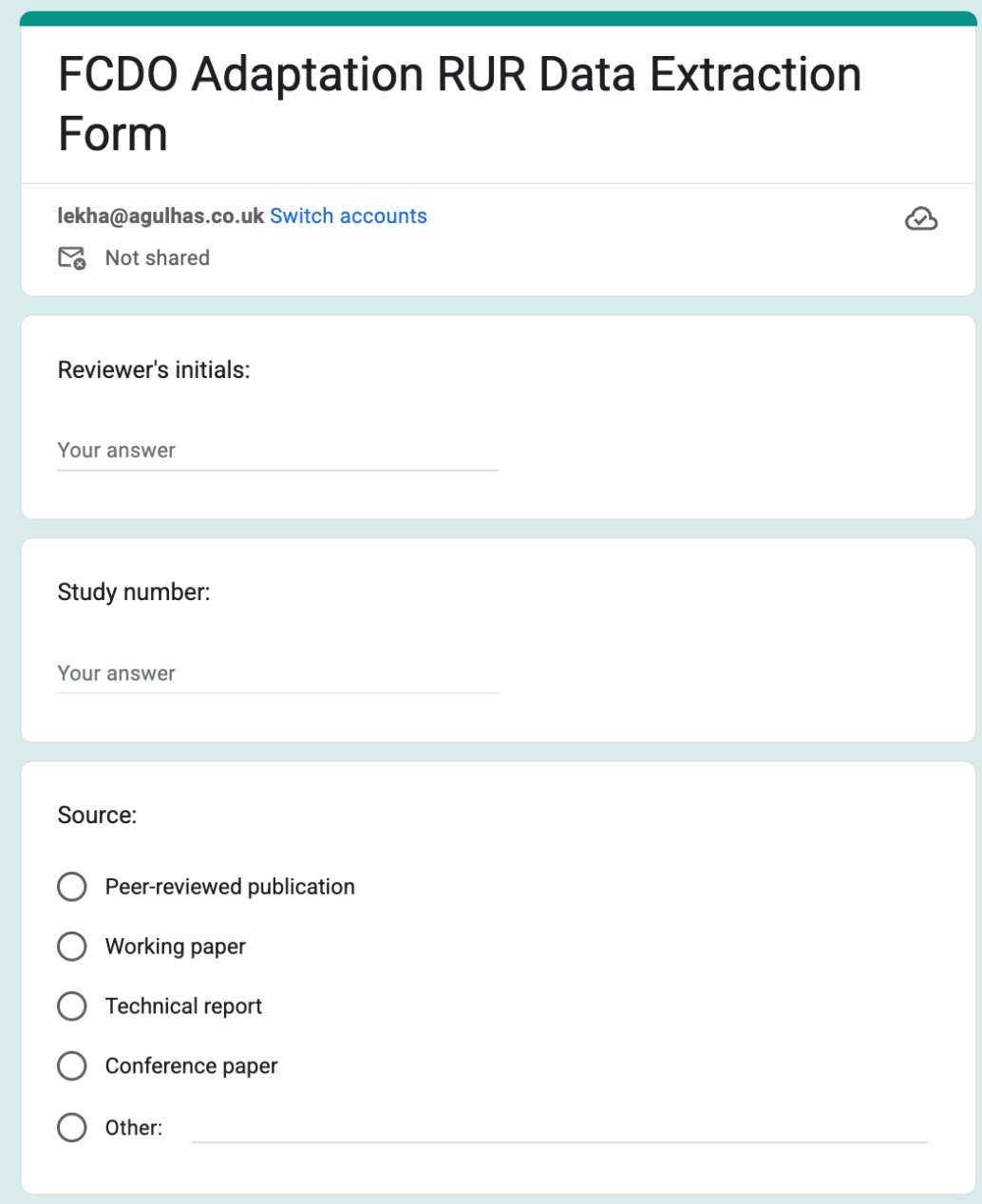
Top-level criterion	1. Cogency	2. Transparency	3. Credibility
Explanation	The report presents a convincing causal argument about the effectiveness of climate change adaptation interventions.	The abstract or a quick full-text scan clearly reveals the methodology used to collect and analyse the data.	The data collection method generates credible data. The methodology to collect results is not only transparent but also credible, thanks to a clear logic of inference (e.g. threats to, especially, internal validity appropriately dealt with). In the SR context, this relates to the synthesis approach taken.
Aspects of criterion	**Theoretically grounded:** The empirical relationship being examined is justified theoretically. E.g., there may be a theory section, a theory of change, a programme theory, or a review of theory literature. Does the theory connect inputs to outcomes; is theoretical grounding literature identified; are underpinning assumptions of the theory discussed; failing that, is there clarity of research questions and confidence that they have been answered sufficiently? **Causal:** The causal argument being made is clearly connected to the type of evidence and the theory presented. E.g., conclusions link findings back to theoretical grounding; evidence collected is relevant to measuring the theory	**Data collection approach and/or sources:** Has grey literature been searched alongside academic databases? Have studies been screened by at least 2 independent reviewers? **Pre-specified eligibility criteria in place?** E.g. PICOS specifying types of studies, participants/ settings/ population, interventions, comparators and outcomes? **Data analysis methodology.** E.g., was an appropriate quality appraisal or risk of bias tool used to assess the quality of the included studies? Have descriptive summary tables been included to report on the key characteristics (in relation to the PICOS) and results of the included studies?	**Transferability:** Generalisability of findings, thanks to sufficient thick description to enable case-to-case transfer. E.g., can the findings be transferred to other geographical contexts, populations and/or other interventions? Were the findings of the relevant studies presented in such a way that the primary review question has been addressed? In case of global studies, at least 50% of included studies need to have focused on LMICs. **Dependability:** Research process is logical, traceable, and clearly documented. Does the review integrate the findings from quantitative and qualitative evidence? Do these integrated findings inform conclusions and implications? If only quantitative or qualitative synthesis tools are used, have these been documented clearly and applied logically?

	presented; backed up link to theory with consultation with content experts in the field		**Confirmability:** Clear demonstration of how conclusions and interpretations were reached. E.g., did the review examine the extent to which specific factors might explain differences in the results of the included studies? How much confidence do you have in the methods used to analyse the findings relative to the primary question addressed in the review?
Grading	YES – the argument is theoretically grounded and potentially causal and convincing → grade "2", continue to 2. PARTIALLY – the argument is causal and convincing but there are some evident gaps in the theoretical justification or logic → grade "1", continue to 2. NO – the argument is not causal and convincing or there are obvious major gaps in theory or logic → grade "0", code as "low quality"	YES – all three aspects are described in the document → grade "2", continue to 3. PARTIALLY – some methodological aspects are described → grade "1", continue to 3. NO – methodology is not described at all → grade "0", code as "low quality".	YES – all three aspects are appropriately dealt with → grade "2" PARTIALLY – some of the aspects are appropriately dealt with, some not → grade "1" NO – none of the aspects are done appropriately dealt with → grade "0"

Decision rule:

A grade of 5 or 6 denotes high confidence
A grade of 3 or 4 denotes medium confidence
A grade of 0, 1 or 2 denotes low confidence.

Annex 5: Data extraction form



FCDO Adaptation RUR Data Extraction Form

lekha@agulhas.co.uk Switch accounts

Not shared

Reviewer's initials:

Your answer

Study number:

Your answer

Source:

- ○ Peer-reviewed publication
- ○ Working paper
- ○ Technical report
- ○ Conference paper
- ○ Other:

Section 1: Context

Country/countries mentioned in the study (where specific interventions / outcomes are detailed)

Your answer

Region(s) included in the study:

- [ ] Sub-Saharan Africa
- [ ] East Asia and Pacific
- [ ] Central Asia and Eastern Europe
- [ ] Latin America and Caribbean
- [ ] South Asia
- [ ] Middle East and North Africa
- [ ] Global

Geography types that apply (if mentioned):

- [ ] Wetland (fresh water)
- [ ] Marine (ocean)
- [ ] Coastal
- [ ] Grassland
- [ ] Shrubland
- [ ] Forest
- [ ] Desert/semi-desert
- [ ] Polar-alpine/Tundra
- [ ] Urban/industrial
- [ ] Not specified
- [ ] Other: _____

If other geography types are included, please list them here:

Your answer

Section 2: Research questions

Is the primary research question clearly stated?

- ◯ Yes
- ◯ No

What is the primary research question of the review?

Your answer

Is/are the secondary research question(s) clearly stated?

- ◯ Yes
- ◯ No

What is/are the secondary research question(s)?

Your answer

Section 3: Interventions

Typology of interventions included in the review

- [ ] Nature-based solutions
- [ ] Built infrastructure/structural
- [ ] Technological options
- [ ] Informational/education
- [ ] Institutional/planning/policy/regulations
- [ ] Financial/market mechanisms
- [ ] Social/behavioural

If other intervention types are included, list them here:

Your answer

Specific activities described as part of the interventions:

Your answer

Scale at which outcomes are described.

- [ ] Household
- [ ] Ecosystem
- [ ] Community (Village, Ward, Gram Panchiyat etc.)
- [ ] Higher level sub-national government (District, Region, Woreda, Zila Parishad)
- [ ] Country
- [ ] International
- [ ] Individual

Social groups targeted:

- [ ] Indigenous groups
- [ ] Extreme poor
- [ ] Women
- [ ] Youth
- [ ] People with disabilities
- [ ] Ethnic or religious minorities

If other social groups are targeted, list them here:

Your answer

Section 4: Enablers and barriers to successful interventions

Factors enabling successful outcomes as a result of the adaptation interventions: These may also be framed as conditions on which the intervention depends.

- [ ] Good governance systems (rule of law, transparency, accountability)
- [ ] Access to finance
- [ ] Access to / incorporation of specific types of knowledge (i.e. technical, scientific, indigenous)
- [ ] Institutional support (i.e. from governments, banks, civil society)
- [ ] Evidence-based research
- [ ] Integrated, holistic approaches (managing climate and non-climate risks together)
- [ ] Prioritisation (focusing on sectors most affected by weather and climate)
- [ ] Flexibile financing and decision making
- [ ] Transparency
- [ ] Technology and innovation
- [ ] Infrastructural development
- [ ] Social protection
- [ ] Legal and policy frameworks
- [ ] Participation of citizens and/or their representatives
- [ ] Mainstreaming climate into existing systems

Please add any additional detail from the paper on enabling factors.

Your answer

Barriers to successful adaptation interventions:

- [ ] Lack of funding
- [ ] Knowledge gaps
- [ ] Poor coordination
- [ ] Limited technical capacity
- [ ] Imbalances in governance
- [ ] Climate change and natural disasters
- [ ] Conflict and humanitarian crises
- [ ] Limited infrastructure
- [ ] Exclusion of target groups from decision making

Please add any additional detail from the paper on barriers.

Your answer

Section 5a: Results and findings - outcomes identified in the study

This section makes a distinction between "intermediate outcomes" and "adaptation outcomes".
Intermediate outcomes are a direct result of an intervention or activity. They are preconditions to adaptation outcomes.
Adaptation outcomes are here defined as reduced exposure, reduced sensitivity or increased adaptive capacity to climate risks.

Are outcomes measured quantitatively?

- ◯ Yes
- ◯ No

Are outcomes measured qualitatively?

- ◯ Yes
- ◯ No

Under which adaptation category are the outcomes described in the paper:

- ☐ Reduced exposure
- ☐ Reduced sensitivity
- ☐ Increased adaptive capacity
- ☐ Reduced poverty
- ☐ Reduced GHG emissions

Describe any intermediate outcomes that followed from interventions or activities that have been the precondition for the adaptation outcome described above.

Your answer

If the study describes adaptation outcomes relating to reduced exposure, summarise them here, including indicators used, any key facts, data, etc. If the study links particular activities to particular activities/interventions, detail this here.
(Exposure = the direct contact people/infrastructure/ecosystems have with climate risks)

Your answer

If the study describes outcomes relating to reduced sensitivity, summarise them here, including any indicators used, key facts, data, etc.: If the study links particular activities to particular activities/interventions, detail this here.
(Sensitivity = extent to which people/infrastructure/ecosystems are affected by climate risk they are exposed to)

Your answer

If the study describes outcomes relating to increased adaptive capacity, summarise them here, including any indicators used, key facts, data, etc.: If the study links particular activities to particular outcomes
(Adaptive capacity = ability to actively anticipate and/or absorb climate risks, and to make informed changes in behavior or investments that adapt to risks).

Your answer

If the study describes adaptation outcomes relating to reduced GHG emissions, summarise them here, including indicators used, any key facts, data. etc. If the study links particular activities to particular activities/interventions, detail this here.

Your answer

If the study describes outcomes relating reduced poverty, summarise them here, including indicators used, key facts, data, etc: If the study links particular activities to particular activities/interventions, detail this here.

Your answer

Length of time over which outcomes are assessed, if mentioned.

Your answer

If applicable, describe any variation across geographical regions.

Your answer

Describe any other relevant findings in the study:

Your answer

If the study details any uncertainties related to interventions or the outcomes produced, detail them here. *Uncertainties are future possible events for which the probability is unknown.*

Your answer

Section 5b: Cost Effectiveness
If the study does not have information in relation to one of these questions, answer "NA".

Does the paper include any cost data?

- ◯ Yes
- ◯ No

If the study mentions costs for intervention/implementation, note the figures and type of cost information here. (e.g. capital costs, total capital and running costs, indirect costs, or any other cost types)

Your answer

Is there quantification of benefits/outcomes (in physical units or monetary terms) in the paper?

- ◯ Yes
- ◯ No

If yes, note the quantification of physical units, benefits or monetary benefits, including the type of benefits reported.

Your answer

Does the study apply a decision support method to rank interventions?

- ◯ Yes
- ◯ No

If yes, what type of method is used, e.g., cost-effectiveness, cost-benefits analysis, multi-criteria analysis, decision making under uncertainty, other

Your answer

If the study applies a decision support method, what is the ranking output, e.g. cost effectiveness [cost per unit reduced], net present value, benefit to cost ratio, economic internal rate of return, financial internal rate of return, etc

Your answer

If the study used cost-benefit analysis, please include the discount rate used.

Your answer

Section 5c: Results and findings - maladaptation and unintended harms

Does the study mention any findings on maladaptation / unintended harms of interventions:

- ◯ Yes
- ◯ No

Describe findings on maladaptation / unintended harms (where possible linking these findings to intervention typologies)

Your answer

Which social groups were most affected by the maladaptation / unintended harms of the intervention

- ☐ Indigenous groups
- ☐ Extreme poor
- ☐ Women
- ☐ Youth
- ☐ People with disabilities
- ☐ Ethnic or religious minorities

Describe any other social groups affected by the maladaptation / unintended harms:

Your answer

Section 5d: Results and findings - mechanisms of change

Mechanisms in refer to the underlying entities, processes, or structures that operate within specific contexts to generate outcomes of interest.
These mechanisms are often intangible and involve changes in participants' cognitive or affective reasoning, attitudes, and choice-making, or in their capacities (e.g., new skills, ideas, information, perspectives, or sources of support). Mechanisms are activated by an intervention, contribute to causing the outcome to occur, and are shaped by the wider context.

What are the key mechanisms that create the changes leading to outcomes (if detailed)

- [ ] Behavioural changes of targeted groups
- [ ] Availability / lack of availability of specific resources
- [ ] Infrastructure improvement / deterioration
- [ ] Environmental factors
- [ ] Institutional processes

Describe the mechanism in more detail

Your answer

Describe the scale of impact each intervention has had in producing the outcomes discussed.

Your answer

Section 5e: Results and findings - measuring adaptation interventions

Detail any "limitations" to the quality of the study that are mentioned in the paper.

Your answer

Does the study refer explicitly to approaches/indicators used to measure the effectiveness of adaptation interventions?

- ○ Yes
- ○ No

If so, which of the following measurement approaches are included:

- ☐ Financial costs and benefits
- ☐ Multi-criteria evaluation
- ☐ Randomly Controlled Trial
- ☐ Surveys
- ☐ Remote sensing
- ☐ Focus groups / Outcome harvesting
- ☐ Panel Study (Longitudinal)
- ☐ Big data
- ☐ Citizen science

Describe any other measurement approaches included:

Your answer

List any specific outcome indicators used

Your answer

Section 6: QA

Does this data extraction form need review by another team member?

- ◯ No - no review necessary
- ◯ Yes - review needed

If review is required, please state why:

Your answer

Additional reflections...

Your answer

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