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TOPICAL REVIEW

Feasibility assessment of climate change adaptation options across Africa: an evidence-based review

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Supplementary material for this article is available online

Abstract

Considering the feasibility and effectiveness of adaptation options is essential for guiding responses to climate change that reduce risk. Here, we assessed the feasibility of adaptation options for the African context. Using the Global Adaptation Mapping Initiative, a stocktake of adaptation-related responses to climate change from the peer-reviewed literature in 2013–2020, we found 827 records of adaptation actions in Africa. We categorised and evaluated 24 adaptation options and for each option, six dimensions of feasibility were considered: economic, environmental, social, institutional, technological, and evidence of effectiveness. Over half (51%) of all adaptation actions were reported in the food sector where sustainable water management (SWM) was the most reported option. The fewest actions were reported for cities (5%). The majority of actions (53%) were recorded in just six countries: Ghana, Ethiopia, Kenya, Tanzania, Nigeria and South Africa. Encouragingly, effectiveness was assessed as medium or high for 95% of adaptation options. However, no options had high feasibility on any other dimension. Technological and institutional factors present major barriers to implementation. Crop management, SWM, sustainable agricultural practices, agroforestry, livelihood diversification, ecosystem governance and planning, health governance and planning, infrastructure and built environment, all had moderate feasibility across three or more dimensions. Human migration has low feasibility but high potential for risk reduction. Major knowledge gaps exist for environmental feasibility, for assessing adaptation limits at increasing levels of climate hazard, for economic trade-offs and synergies, and for Central and Northern Africa. Our results highlight sectors where enablers for adaptation can be increased. Future assessments can apply the method established here to extend findings to other national and local levels.

1. Introduction

African governments increasingly recognize the urgent need for evidence-based climate change adaptation options (Babatunde 2019, Damptey and Zakieldeen 2020). African faces above global-average increases in exposure to climate hazards and has many communities and ecosystems among the most vulnerable to climate change (Schleussner *et al* 2018, Sylla *et al* 2018, Ahmadalipour *et al* 2019, IPCC 2019a, 2019b, Rao *et al* 2020). Climate variability and change, especially extreme events, have already negatively impacted economic growth, food production, water security and human health in multiple African countries (Diffenbaugh and Burke 2019, IPCC 2019a, WMO 2021). These current impacts and future risks highlight the need for information on the feasibility of a broad range of adaptation options across multiple sectors to enable climate change adaptation planning.

Policymakers in Africa also face the growing challenge of allocating scarce resources among climate change mitigation and adaptation options, and balancing the co-benefits and trade-offs for other development challenges. Africa's response, therefore, requires adaptation options that are both feasible and effective at reducing climate change risks. Previous work has emphasized the need for relatively low-cost, low-regrets adaptation options that reduce risk, avoid maladaptation, and have multiple benefits for development (IPCC 2014).

A synthesis of existing adaptation knowledge in Africa is particularly needed to inform the continent's adaptation choices for the future, and enable more effective risk management. Even as the literature on climate change adaptation has grown during the last decade (Haunschild *et al* 2016, Minx *et al* 2017), there has been no systematic assessment of the feasibility of adaptation options for Africa hence drawing out lessons for climate action remains a challenge. This knowledge gap has been attributed to multiple factors, including: locally specific evidence, inconsistent monitoring and metrics for measuring adaptation outcomes and effectiveness, and incomplete temporal and spatial data for some aspects of feasibility (e.g. costs) (Ford *et al* 2013, Klein *et al* 2014, van Valkengoed and Steg 2019). Furthermore, although recent evaluation frameworks for adaptation have been developed (Owen 2020, Singh *et al* 2020), overlap in the framings of adaptation feasibility and adaptation effectiveness have resulted in uncertainty in their interpretation. At the global scale, the Intergovernmental Panel on Climate Change (IPCC) has assessed the feasibility of select adaptation options in the context of global warming of 1.5 °C (2018b), but this global aggregation makes it difficult to draw relevant insights for specific regions. African decision-makers and practitioners need feasibility assessments that are tailored to the African context, and researchers require better understanding of where knowledge gaps persist.

We therefore conducted a multidimensional feasibility assessment of adaptation options applicable to the African region to inform further research, policy and practice. We identified 24 groups of adaptation options, mapped research on these options across Africa, and assessed the feasibility and evidence for risk reduction associated with each adaptation option.

2. Methodology

2.1. Definition and framing of 'adaptation' and 'feasibility'

Definitions of climate change adaptation keep evolving (Ford *et al* 2013, Berrang-Ford *et al* 2015, 2019, Ford and King 2015, Araos *et al* 2016). The IPCC frames *adaptation* of human systems as the 'process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities' (2019a). We adopt this IPCC definition of adaptation. It is important to note that many adaptation responses mentioned in the literature and considered for our study are also used to address developmental support issues and planning activities in Africa. Explanation of each adaptation option's relation to climate hazards and risk reduction is given in table S5 in the supplementary material to show how climate drives each response (available online at stacks.iop.org/ERL/16/073004mmedia).

No single adaptation strategy exists to meet climate change adaptation needs across Africa, and not all adaptation responses are sustainable (Mbow *et al* 2014). Responses to climate change can have unintended consequences or maladaptive outcomes (Barnett and O'Neill 2010, O'Hare *et al* 2016, Atteridge and Remling 2018, Torabi *et al* 2018, Schipper 2020), and together with the multidimensional nature of determinants of climate change risk requires that the effect of adaptation options across social, economic, and environmental domains are considered (Chambwera and Anderson 2011, Colding *et al* 2020, Revi *et al* 2020). Feasibility assessments need to go beyond unidimensional appraisals of discrete options to consider the interconnections, synergies and trade-offs of an option across different sectors (Thornton and Comberti 2017). Furthermore, there is a point at which adaptive actions cannot secure an actor's objectives or system needs from risks beyond certain tolerance levels (IPCC 2019a). These points serve as either hard limits (where no adaptive actions are possible to avoid intolerable risks), or soft limits to adaptation (where current adaptation options are insufficient to avoid intolerable risks) (IPCC 2019b).

The IPCC (2018b) defines *feasibility* of adaptation options as 'the degree to which climate goals and response options are considered possible and/or desirable'. Feasibility assessment is a systematic plan, evaluation and assessment of the sustainability of such options, taking into consideration factors such as technical and organizational aspects and financial implications (Singh *et al* 2020). A feasibility assessment aims to influence decisions or a course of action by identifying the risks, merits and demerits of projects (Mcdonnell *et al* 2018, Jewell and Cherp 2020).

In climate adaptation literature, several conceptual framings like adaptation effectiveness, and barriers and enablers to adaptation, overlap with feasibility (Singh *et al* 2020). Assessment of effectiveness generally evaluates how successful an adaptation response is at reducing risk based on specified outcomes. There has also been increased focus on the barriers and enablers of different adaptation options (Diiro *et al* 2016, Oberlack 2017, Spires and Shackleton 2018, Chanza *et al* 2019). A *barrier* refers to a factor that hinders or blocks the implementation of an adaptation response (Biesbroek *et al* 2013). A focus on barriers highlights factors that influence adaptive capacity, the resources

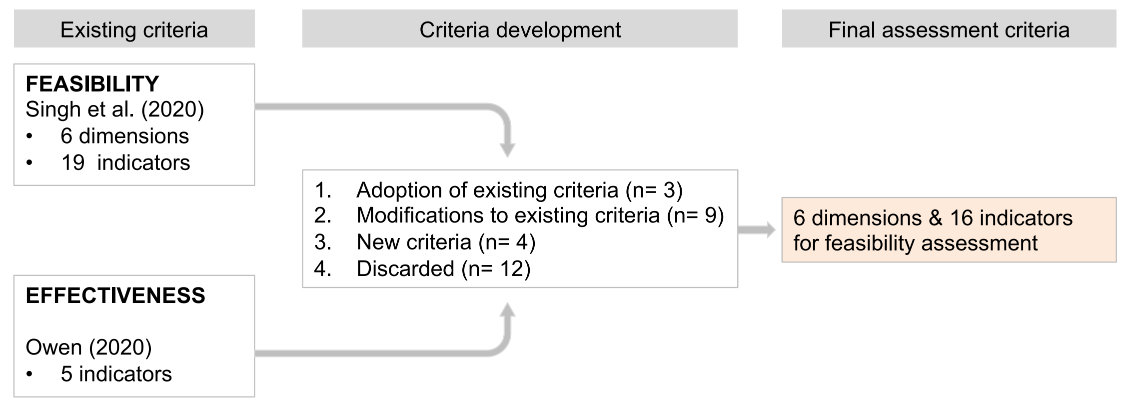

Figure 1. Process of assessment framework selection and development of assessment criteria.

required for adaption, and why some groups or individuals adapt while others do not (Nyanga *et al* 2011, Ludi *et al* 2012). However, such 'barriers' approaches neglect enabling conditions for the implementation of adaptation options (Biesbroek *et al* 2015, Ford *et al* 2017). Further, it can be misleading to consider the multiple forms of barriers and enablers as separated pieces while in practice, none of them operate in isolation, and their interaction shapes the overall conditions affecting adaptation (Lehmann *et al* 2015, Few *et al* 2017). Implementation of adaptation responses continues to remain a challenge in Africa, with actual progress reported to be slow (Kurukulasuriya *et al* 2006, Ndamani and Watanabe 2015).

We developed an integrated approach to adaptation feasibility assessment for this study by adapting the effectiveness approach developed by (Owen 2020) and the barrier approach of Singh *et al* (2020). A barriers approach was considered because there is established literature on barriers to adaptation within the region (Bryan *et al* 2018, Guodaar *et al* 2018, Aheeyar *et al* 2019, Davies *et al* 2019). Also, since resources like funding and expertise for development are basic requirements for the implementation of adaptation responses, policymakers and adaptation practitioners can easily relate and understand barriers and enablers to such factors. Our main data source, the Global Adaptation Mapping Initiative (GAMI), provides a broad coverage of existing adaptation actions and can be used to identify factors limiting their increased use. Furthermore, an effectiveness approach was considered because *effectiveness*, as modified from Owen (2020), evaluates multiple indicators including an adaptation option's ability to reduce climate risk and environmental impacts, and enhance social relations, economic co-benefits and other inclusive institutional approaches (UNISDR 2011, 2015, 2017, Hunde 2012).

2.2. Research design

The feasibility assessment followed a multi-stage process. First, informed by sectors identified to be particularly at risk from climate change (IPCC 2014, 2019a), we identified priority sectors and adaptation options to be considered for the study. We focussed on six sectors: food, fibre and other ecosystem products; health, well-being, and communities; ecosystems (terrestrial, freshwater, ocean and coastal); water and sanitation; cities, settlements, and key infrastructure; and economy, poverty and livelihoods. We used these sectors because they align with the sectoral framing agreed by the IPCC for governments globally based on their vulnerability and exposure to climate change, as well as the stated sectoral adaptation priorities for African governments (Aylett 2015, England *et al* 2018a, 2018b). Adaptation options within each sector were identified iteratively through a review process that grouped adaptation options according to Singh *et al* (2020) and the IPCC Special Report on Global Warming of 1.5 °C (2018a), and an extensive desk review to identify standard adaptation options implemented in Africa with specific examples. Through consultations with key experts, we further clustered observed adaptation actions into 24 categories of adaptation options across the six sectors based on their relatively low regrets, relevance to climate risk reduction and multiple developmental benefits applicable in Africa. For example, options related to both indigenous and scientific knowledge for weather forecasting were classified together as climate information services under the food sector (see table S1 in supplementary material for detailed list of adaptation option categories by sector, as well as the corresponding specific examples of actions within each category).

Second, we developed an adaptation feasibility framework through extension of the feasibility assessment framework of Singh *et al* (2020) and the adaptation effectiveness of Owen (2020) (figure 1). Singh *et al* (2020) developed five outcomes/goals for measuring the feasibility of adaptation options considering six dimensions (economic, technological, institutional, sociocultural, geophysical, and environmental) and 19 indicators facilitating adaption. We changed the 'geophysical' dimension used by Singh *et al* (2020) into an indicator as part of the broader environmental dimension (including geophysical and biological). Next, we modified the indicators and guiding questions to more specifically apply to the African context (table 1). For instance, due to the limited econometric studies on adaptation in Africa, the 'employment and productivity potential' indicator from the global-level study was modified to become 'economic co-benefit' in this study, with the guiding question modified from '*How many people can be employed or how much can a system's productivity increase under the option?*' (Singh *et al* 2020), to '*Does the option increase employment or increase a system's productivity under the option?*'.

We introduced effectiveness as a new dimension ('evidence of effectiveness') to the Singh *et al* (2020) feasibility framework. Specifically, for each adaptation option we assessed the five indicators of effectiveness proposed by Owen (2020) based on the capacity of the adaptation response to (a) reduce risk to climate change impacts; (b) enhance social relationships and community well-being; (c) improve environmental quality; (d) increase income and access to economic resources; and (e) strengthen institutional connections. We called Owen's first indicator as 'effectiveness', measured as potential for risk reduction. Indicators 2–4 were included in the modified indicators on co-benefits in social, environmental and economic dimensions. We applied the same assessment scoring protocol of Singh *et al* (2020) to the indicators in the effectiveness dimension. We included a new assessment question on the 'acceptable hazard threshold' as part of effectiveness to identify levels of climate hazards at which adaptation options are understood to no longer be effective. A similar approach to modifying assessment questions was followed for all the remaining indicators (see table 1).

Knowledge gaps identified in previous assessments highlight the need for feasibility assessment to consider trade-offs between socioeconomic and environmental adaptation options in Africa, including trade-offs with mitigation goals (Niang *et al* 2014, Noble *et al* 2014). While developing our framework, we added new indicators for adaptation feasibility for the African context specifically targeted at 'environmental trade-offs' (including for reducing greenhouse gas emissions), 'social trade-offs', and 'financial/economic feasibility' (table 1). These indicators were added due to their relevance to Africa for instance, 'financial/economic feasibility' is considered a new indicator because financial factors are widely reported as constraints to the planning and implementation of adaptation options in Africa, and yet this was not included in the global study by Singh *et al* (2020). A similar reasoning was used during the selection and modification of the remaining new indicators. We suggest these new indicators may also be useful for assessments in other regions. Our final framework has a total of six dimensions and 16 indicators (figure 1; table 1).

2.3. Criteria for article selection

The GAMI provides a stocktake of human adaptation-related responses to climate-related changes that have been documented in the peer-reviewed literature globally between July 2013 and January 2020 (Berrang-Ford *et al* 2020). It used bibliographic databases including Scopus, PubMed, Web of Science Core Collection, and Google Scholar (Berrang-Ford *et al* 2020). GAMI recorded if actions could (or were) directly reducing risk, exposure, and/or vulnerability to climate change. It excluded non-empirical (that is, theoretical and conceptual) and non-peer reviewed literature on adaptation, as well as autonomous or evolutionary adaptation in natural systems. It identified 518 articles reporting adaptation actions in Africa (Lesnikowski *et al* 2020, Fischer *et al* 2020).

The breadth of GAMI's stocktake is unmatched in terms of quantity of articles identified, screened and coded, highlighting its potential value to capture the breadth of the literature on adaptation (Lesnikowski *et al* 2020, Fischer *et al* 2020). After Asia (34%), Africa recorded the second highest number of adaptation articles identified by GAMI, accounting for 32% of the total GAMI database (Berrang-Ford *et al* in review). However, there is publication bias in the GAMI database, particularly based on language (dominance of English-language publications), and it is typically difficult to distinguish whether absence of adaptation reporting reflects lack of adaptation activities or lack of reporting in the peer-reviewed literature (Biesbroek *et al* 2018, Berrang-Ford *et al* 2019). Nevertheless, the focus on peer-reviewed literature aligns with the assessment needs of the IPCC, making these findings easily translatable for such expert-driven processes.

2.4. Data extraction

We segregated the 518 articles from GAMI's database according to the six priority sectors we focus on in this study, mapped articles to the 24 categories of adaptation options we identified and screened for relevance to these options. This process resulted in the exclusion of 80 studies. Studies were excluded if: they did not fit into any of the 24 categories of adaptation options considered, did not contain explicit information on specific options mentioned, or when evidence of the variables/indicators considered was inadequate. 438 studies were considered for the final assessment. Using the set of guiding questions for each indicator, each adaptation option was assessed along the feasibility and risk reduction dimensions as shown in table 1. During the assessment, the guiding questions were contextualized to each adaptation option. The literature reviewed was used to extract

Table 1. Feasibility dimensions, their associated indicators and questions guiding the indicator-level assessment. Status of indicators is given as existing from previous studies, modified, or new to this study.

Dimension	Adaptation indicator	Guiding questions	Supporting references	Status of indicator
Economic	Micro-economic viability	What are the economic costs and trade-offs of the option?	Dalton *et al* (2015), Singh *et al* (2020)	Existing
	Financial/economic feasibility	Is the financial/economic potential (related to lack of financial resources, economic structures, and economic mobility) for the adaptation option a constraint? OR Are there known economic barriers?	Makate *et al* (2019)	New
	Economic co-benefits	Does the option increase employment or increase a system's productivity under the option?	Pandey *et al* (2016), Owen (2020), Singh *et al* (2020)	Modified
Environmental (biological and geophysical)	Ecological/land use change co-benefits	Does the option enhance supporting, regulating or provisioning ecosystem services or biodiversity in any way? OR Does the option enhance carbon stocks? (e.g. through forest restoration)	Wamsler *et al* (2016), Berbés-Blázquez *et al* (2017), Owen (2020), Singh *et al* (2020)	Modified
	Environmental trade-offs	Does the adaptation option give negative interactions with other environmental goals, such as biodiversity conservation or increase greenhouse gas emissions?	Harvey *et al* (2014), Mbow *et al* (2014), Locatelli *et al* (2015), Loucks and van Beek (2017)	New
	Bio-geophysical feasibility	Is the biological/ecological and physical potential (related to ecological and geological context, as well as current climate conditions such as temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind, physical elevation and topography) for the adaptation option a constraint?	Adoho and Wodon (2014), Barnett *et al* (2015), Brown and Sonwa (2015), Gross-Camp *et al* (2015), Amamou *et al* (2018), Harmanny and Malek (2019), Singh *et al* (2020)	Modified
Social	Regional scope	Are different geographical areas in Africa included in the option? OR Is the project already being scaled or could it be scaled to multiple regions in Africa?	Tschakert *et al* (2017), Singh *et al* (2020)	Modified
	Socio-cultural/ human acceptability	Is there public resistance to the option? OR Does the option typically find acceptance within existing socio-cultural norms, utilise diverse knowledge systems including indigenous and local knowledge? OR Is the sociocultural/human capacity potential (related to social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support/ individual, organizational, and societal capabilities to set and achieve adaptation objectives over time) for the adaptation option a constraint?	Biesbroek *et al* (2014), (2015), Ford and King (2015), Singh *et al* (2020), Tschakert *et al* (2017)	Existing
	Social inclusiveness	To what extent does the option reduce inequalities (of gender, income, indigenous groups, migrants, among others)—within and/or between countries—(or make them worse)? OR	Sovacool *et al* (2015), Tschakert *et al* (2017), Benveniste *et al* (2020), Singh *et al* (2020)	Modified

(Continued.)

Table 1. (Continued.)

Dimension	Adaptation indicator	Guiding questions	Supporting references	Status of indicator
		Is this option accessible particularly to vulnerable groups?		
	Social co-benefits	Are there social co-benefits, such as health, education, peace, food security, energy access, water and sanitation, to be had from the option (positive interactions or synergies with other policy goals)?	Wiederkehr *et al* (2018), Owen (2020), Singh *et al* (2020)	Modified
	Social trade-offs	Does the option have negative interactions with other social development goals, such as health, education, peace, food security, energy access, water and sanitation?	Lipper *et al* (2014), Arakelyan *et al* (2017)	New
Institutional	Enabling conditions	Would current 'conditions' (political, human capacity, legal) allow the implementation of the option? OR Is the option administratively supported? OR Are human resources and conditions to support implementation of the adaptation option clearly identified? OR What are the conditions needed to be in place for this option to be more effective?	Biesbroek *et al* (2013), Eisenack *et al* (2014), Ford and King (2015), Gupta (2016), Singh *et al* (2020)	Modified
	Governance, Institutions and Policy feasibility	Is the Governance, Institutions and Policy potential (related to existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity) for the adaptation option a constraint? OR Are there known legal and regulatory barriers? OR Is there a specific limiting factor to the increased use (scaling) of this option? OR Is the option politically acceptable? Does the option reflect stakeholder perceptions about the meaning and purpose of adaptation? OR Are policy goals and targets for the option explicitly articulated; monitoring and evaluation protocols are set up to track implementation; and transparent reporting mechanisms are in place to synthesize progress and gaps?	Mcevoy *et al* (2013), Ford and King (2015), Hjerpe *et al* (2015), Sovacool *et al* (2015), Henstra (2016), Biesbroek and Lesnikowski (2018), Singh *et al* (2020)	Modified
Technological	Technical resource availability	Are the technology and associated human administrative resources needed for an adaptation option available? Are the technological potential (related to Information /Awareness/Technology/physical resources) needed for an adaptation option a constraint?	Thornton and Herrero (2015), van Vliet *et al* (2016), Singh *et al* (2020)	Existing
Potential effectiveness/risk reduction	Risk reduction potential	Is there any evidence (implicitly or explicitly) provided that this adaptation option successfully reduces risk? OR	Owen (2020), Alfieri *et al* (2016)	Modified

(Continued.)

Table 1. (Continued.)

Dimension	Adaptation indicator	Guiding questions	Supporting references	Status of indicator
		Does the option reduce the risk/impact exposure to a hazard? OR To what degree can the option reduce the likelihood and/or consequences of risks? OR Is there any evidence of Disaster Risk Reduction? OR Is this option addressing a 'large' spectrum of hazards?		
	Acceptable hazard threshold	Is there a level of hazard at which this option is no longer effective?	Owen (2020), Hoegh-Guldberg *et al* (2018), Wong *et al* (2014), Hsiang *et al* (2013)	New

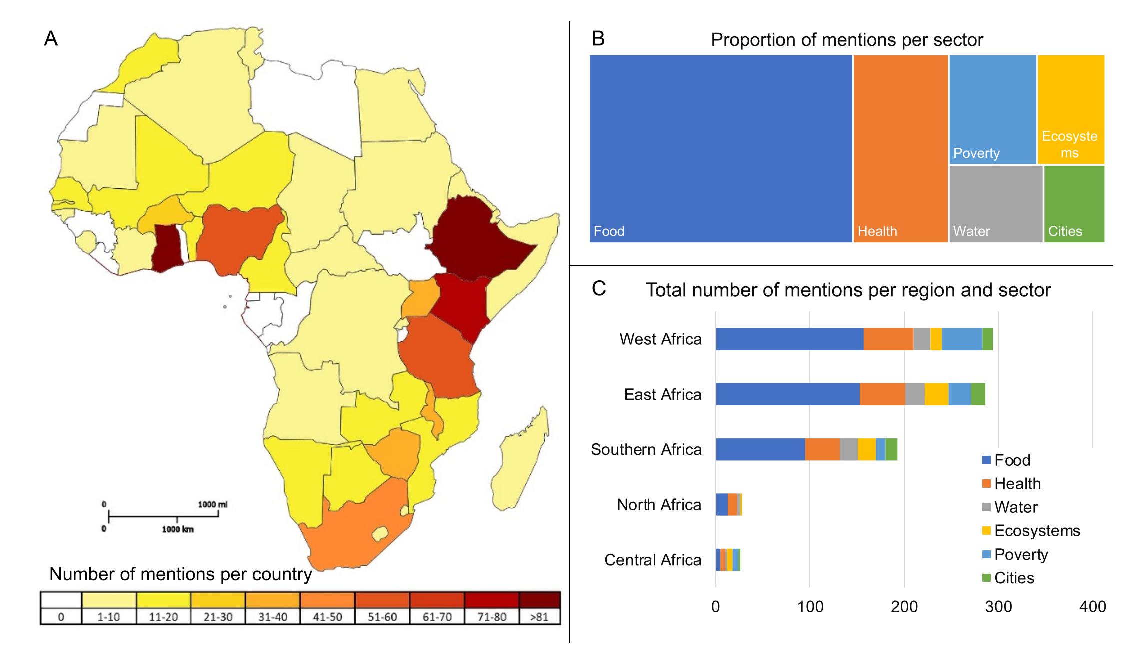

Figure 2. Mapping the number of adaptation actions recorded in the literature by country, region and sector. (A) Regional map showing which countries feature the most published mentions of adaptation actions. (B) Proportion of adaptation mentions in each sector. (C) Distribution of adaptation mentions by African region, illustrating the dominance of adaptation in specific sectors and regions. Sectors are food, fibre and other ecosystem products; health, wellbeing and communities; economy, poverty, and livelihoods; terrestrial, freshwater, ocean and coastal ecosystems; water and sanitation; and cities, settlements and key infrastructure.

statements that showed whether an indicator hinders or is a barrier to the feasibility of an adaptation option or not. See table S4 in supplementary material for an example of how options were specifically assessed. To ensure transparency and reduce bias in the assessment process, outcomes from the assessment were thoroughly discussed among the team members. Figure 2 depicts country-level representation of all the adaptation options identified, and how different sectoral adaptations feature in different African regions.

2.5. Data analysis

The evidence generated for each of the 24 adaptation options was mapped onto the indicators. For an adaptation option to be assessed for a specific indicator, two or more papers were required. Indicators were then given a score of A, B or C based on whether they potentially block the feasibility of an option (A), have some effect on the feasibility of an option (B), or do not pose barriers to the feasibility of an option (C). Options with less supporting literature were marked as 'No Evidence' (NE, no papers as evidence to support indicator), 'Limited Evidence' (LE, fewer than two papers), or 'Not Applicable' (NA, no relevance of the indicator to the option). The score for effective indicators (number of indicators less the number of 'NAs') was averaged to calculate feasibility for each dimension, following Singh *et al* (2020). Using the mean score for the indicators, the dimensions were assessed as: low feasibility/significant barriers (score < 1.5); medium feasibility with moderate barriers (score of 1.6–2.5); high feasibility/low barriers (score > 2.6). 'Evidence of effectiveness' was also scored 'low', 'medium' or 'high' when an option showed low quantity of evidence for effectiveness/potential to reduce risk, some quantity of evidence for effectiveness/mixed potential to reduce risk or significant quantity of evidence for effectiveness/high risk reduction potential. Details of the scoring and assessment process can be found in the supplementary material (section SI 3).

2.6. Limitations

Other sources of data that were not included, such as grey literature from NGOs or international development organisations (FAO 2012, 2016), potentially contain valuable information on adaptation options. However, including such literature would make assessment of important aspects of effectiveness, such as risk reduction, problematic due to potential inconsistencies, undisclosed interests and non-empirical claims of effectiveness common to non-peer reviewed literature (Piggott-McKellar *et al* 2019). Additionally, although we sought consensus on external information from individual experts regarding the development of our framework, our approach lacked a structured expert-elicitation process due to time constraints. This may have provided valuable insight and facilitated a more robust and systematic process to reduce bias on the outcome of the assessment. Expert elicitation should be considered in future studies, to enhance reproducibility, comparability and credibility of our approach. Also, for assessment purposes, indicators or dimensions were weighted equally (combining indicators into dimension level feasibility), while in practice some might be more important, considering the diversity of a community's values and aspirations (Colding *et al* 2020). Rankings and comparisons across different sets of evidence are guided by a set of specified questions, however, this process also includes subjective interpretation. This is a common transparency challenge for feasibility assessments (Singh *et al* 2020). Another limitation, as indicated in Singh *et al* (2020), is the clustering of adaptation actions into groups of options resulted in feasibility assessment at the level of the 24 groups whereas feasibility of individual adaptation actions may vary in specific local contexts. It is important to note that the dimensions used in the feasibility assessment are dynamic and could change over time and space, influencing how options are prioritize. Although our framework could be modified to highlight these dynamics, we did not report changes over temporal scales. We also acknowledge that the current approach for feasibility/effectiveness assessment considers only climate-related stressors, while in practice communities deal with both climatic and non-climatic challenges. The integration of non-climatic factors may modify the trend of the assessment. Future studies could aim to address these highlighted limitations in their assessments.

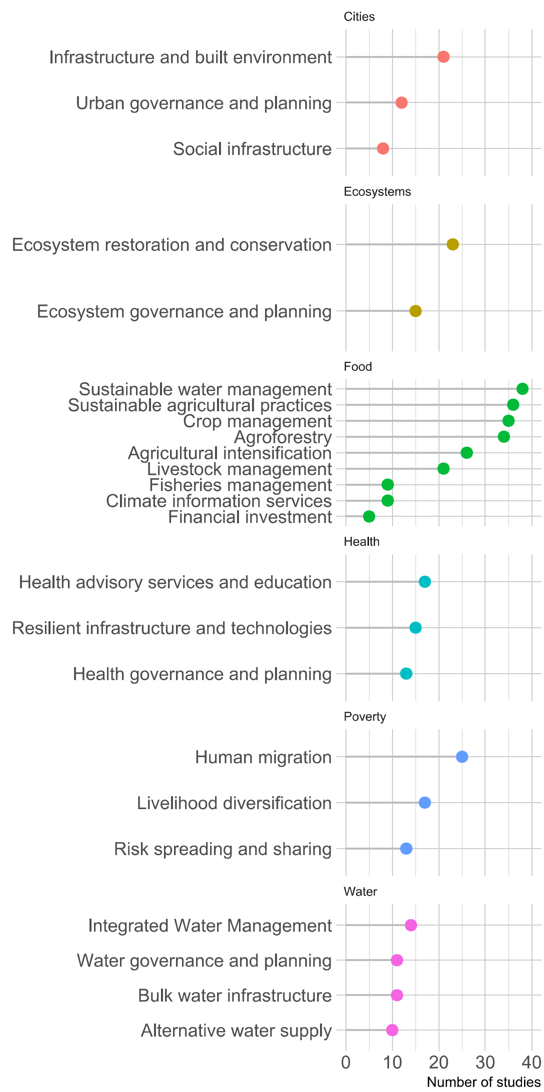

Figure 3. Number of studies on climate change adaptation options across six sectors in Africa.

3. Results

3.1. Summary of studies

Four hundred and thirty-eight articles were reviewed in this study. About half of the studies were from the food sector (49%), followed by economics and poverty (13%), water (11%), health (10%), cities (9%), and ecosystems (8%). A large number of studies focused on sustainable water management (SWM) (38 articles), sustainable agricultural practices (35 articles), crop management (35 articles) and agroforestry (34 articles), while financial investment, social infrastructure, climate information services and fisheries management all had fewer than ten studies (figure 3).

3.2. Adaptation options recorded in the literature: evidence base

Beyond a count of studies on adaptation, the feasibility assessment concentrated on the recorded adaptation strategies and actions empirically observed within those studies. Individual studies frequently reported multiple adaptation actions, resulting in 827 adaptation responses from the 438 studies. The food sector had by far the greatest numbers of reported adaptation actions (51% of all reported actions), especially in Ethiopia (6.8%) and Ghana (9.8%) (table 2). The single most widely reported category of adaptation options was SWM for food production (14.4%) (table 2). Specific adaptation strategies falling within this category included: rainwater harvesting for irrigation, watershed restoration, efficient irrigation through water conservation (e.g. drip or sprinkler irrigation), less water intensive cropping, and pit digging.

Health was the sector with the second highest number of reported adaptation actions (18.5%). Resilient infrastructure and technologies was the most frequently reported adaptation category for health (8.5%), including: water and sanitation infrastructure, robust non-conventional technology in all sectors to prevent contamination and pollution of water, improved water, sanitation and hygiene (WASH), and improved health infrastructure. Reported health adaptations are concentrated most in East and West Africa, with Kenya and Ghana having 1.7% and 1.5% of reported actions, respectively.

The water and ecosystem sector had a similar number of reported adaptation strategies (7.6%). Integrated water management (IWM) was most frequently cited (4.4%), with IWM approaches including subnational financing, demand management (e.g. through subsidies, taxes like water tariffs and financial penalties, sustainable water technologies and services). Ecosystem governance and planning (EGP), and conservation and restoration had similar numbers of records.

The economy/poverty sector recorded the next highest number of observed adaptation actions, with human migration as the most cited strategy (7.5%), including temporary seasonal and permanent migration, as well as refugee resettlement, with Ghana and Ethiopia the most frequently cited countries.

The cities sector had the fewest adaptation strategies reported (5% for all reported actions). Urban governance and planning dominated this sector (2.5%). Examples of specific strategies for this adaptation category included: integrating risk management into urban planning; strong coordination of climate change adaptation and flood risk management at a city level, urban land use planning; establishing partnerships with the formal and informal sectors to improve governance; use of tools such as property taxes to drive the implementation of spatial plans that enhance adaptive capacity, and vertical integration with other spheres of governments.

Ghana was the country most cited (14.8%) in adaptation studies in Africa, followed by Ethiopia (9.8%), Kenya (9.1%), Tanzania (6.8%), Nigeria (6.5%), South Africa (5.8%), Zimbabwe (4.4%), Uganda (4.1%), and Malawi (3.9%). Most of the reported adaptation strategies were from West and East Africa, followed by Southern Africa, with Central and North Africa mentioned least (table 2 and figure 1). There were also country-level concentrations of specific adaptation options. Kenya has the highest number of reported water-related adaptation responses (more than double the average). Kenya, Ghana and Nigeria lead for health responses. Ghana dominates both poverty and food sector adaptation responses, although Ethiopia, Kenya, Tanzania and Nigeria all have over 50 observed food sector responses. In contrast, ecosystem-related responses are generally evenly distributed across regions. Only three countries have five or more observed adaptation responses in cities: South Africa, Tanzania and Kenya.

3.3. Summary of multidimensional feasibility assessment

Fifteen of the 24 categories of adaptation options showed medium potential for reducing risk (table 3). A further eight categories of adaptation options showed high potential for risk reduction in the African context, including: urban governance and planning, and infrastructure and built environment (Cities), bulk water infrastructure (Water), EGP (Ecosystem), human migration (Poverty), agroforestry, agricultural intensification and financial investment (Food). All categories of adaptation options, except human migration, demonstrated moderate feasibility in at least one other feasibility dimension in addition to effectiveness (table 3). Crop management, SWM, sustainable agricultural practices, agroforestry, livelihood diversification, EGP, and infrastructure and built environment, showed moderate feasibility across three or more dimensions. Human migration had low feasibility but high potential for risk reduction. No options demonstrated high feasibility in the economic, environmental, social, institutional or technological dimensions. The highest amount of evidence for the assessment was within the food sector (agroforestry, sustainable agricultural practices, agricultural intensification, SWM and crop management). The remaining options had medium or low evidence supporting assessment.

Overall, technological barriers were the most frequent factor limiting the implementation of adaptation options in Africa, with 22 out of 24 options assessed as having low technological feasibility. High institutional barriers were another major concern, with two-thirds of the assessed options having low institutional feasibility. Adaptation options for

Table 2. Frequency of observed adaptation actions reported in the literature by sector and region of Africa.

Sector	Adaptation option	Central Africa				East Africa												North Africa				
		Cameroon	Central African Rep	Chad	DRC	Djibouti	Eritrea	Ethiopia	Kenya	Madagascar	Mauritius	Rwanda	Seychelles	Somalia	Sudan	Tanzania	Uganda	Algeria	Egypt	Mauritania	Morocco	Tunisia
Cities	Urban governance and planning	2						2	3							3	1					
	Social infrastructure								1							2	1					
	Infrastructure and build environment								1							1						
	Total	*2*						*2*	*5*							*6*	*2*					
Water	Alternative water supply								2							1						
	Bulk water infrastructure		1					1	4													
	IWM			1				1	4			1				3	1				1	
	Water governance and planning							1								2					2	
	Total		*1*	*1*				*3*	*10*			*1*				*6*	*1*				*3*	
Ecosystems	Ecosystem restoration and conservation	2	1		1		1	2	3		1	1	1		1	1	1		1			
	Ecosystem governance and planning	2					1	2	1		1	1	1		1	1	4		1			
	Total	*4*	*1*		*1*		*2*	*4*	*4*		*2*	*2*	*2*		*2*	*2*	*5*		*2*			
Health	Health governance and planning	1					1	1	5	1	1	2	1		1	2	3		2		2	
	Health advisory services and education						1		3		1	1	1		1		1		2			
	Resilient infrastructure and technologies	2		2		1	1	6	6					1	1	4	1		1	1	1	1
	Total	*3*		*2*		*1*	*3*	*7*	*14*	*1*	*2*	*3*	*2*	*1*	*3*	*6*	*5*		*5*	*1*	*3*	*1*
Poverty	Risk spreading and sharing	1					1	1								1						
	Human migration	1	1	2				8	5							4	1					
	Livelihood diversification				1										1	1	1					
	Total	*2*	*1*	*2*	*1*		*1*	*9*	*5*						*1*	*6*	*2*					
Food	Agroforestry	1						3	4	1		2				5	5					
	Sustainable agricultural practice							9	4							4	2					
	Agricultural intensification	2						6	5	1						8	3					
	SWM	1						17	10	2						10	5	1	1		4	3
	Climate information services																					
	Financial investment							1														
	Crop management	1						11	5							3	1				2	
	Livestock management						1	6	6		1	1	1		1		2		1			
	Fisheries management							3	3								1		1			
	Total	*5*					*1*	*56*	*37*	*4*	*1*	*3*	*1*		*1*	*30*	*19*	*1*	*3*		*6*	*3*
Grand total		16	3	5	2	1	7	81	75	5	5	9	5	1	7	56	34	1	10	1	12	4

Sector	Adaptation option	Southern Africa										West Africa												Grand total
		Angola	Botswana	Lesotho	Malawi	Mozambique	Namibia	South Africa	Swaziland	Zambia	Zimbabwe	Benin	Burkina Faso	Cape Verde	Cote d'Ivoire	Gambia	Ghana	Guinea-Bissau	Mali	Niger	Nigeria	Senegal	Sierra Leone	
Cities	Urban governance and planning				1			2									2				2	3		21
	Social infrastructure					1		2														1		8
	Infrastructure and build environment	1				2	1	3					1				1				1			12
	Total	*1*			*1*	*3*	*1*	*7*					*1*				*3*				*3*	*4*		*41*
Water	Alternative water supply										1						1							5
	Bulk water infrastructure								1							1	1							9
	IWM		1		1		2	4			4	2	2			2	2		1	2	1	1		37
	Water governance and planning		1		1		1			2							1			1				12
	Total		*2*		*2*		*3*	*4*	*1*	*2*	*5*	*2*	*2*			*3*	*5*		*1*	*3*	*1*	*1*		*63*
Ecosystems	Ecosystem restoration and conservation		2	1	1		1	1	1	1	1					1	1	1			1		1	31
	Ecosystem governance and planning		1	1	1	1	1	2	1	1	1					1	2	1		1	1		1	33
	Total		*3*	*2*	*2*	*1*	*2*	*3*	*2*	*2*	*2*					*2*	*3*	*2*		*1*	*2*		*2*	*64*
Health	Health governance and planning		1	1	3	1	1	2	1	3	2	1			1	2	3	1	1	1	2		1	51
	Health advisory services and education		1	1	4		1	2	1	1	2					1	3	1			2		1	32
	Resilient infrastructure and technologies	1	1			1	1	2			3	2	5	1	1	3	6		3	3	6	2		70
	Total	*1*	*3*	*2*	*7*	*2*	*3*	*6*	*2*	*4*	*7*	*3*	*5*	*1*	*2*	*6*	*12*	*2*	*4*	*4*	*10*	*2*	*2*	*153*
Poverty	Risk spreading and sharing				1			1								1	5				2	1		15
	Human migration		1		1		1	2			3	4	2			2	13		3	2	4	2		62
	Livelihood diversification											1										1		6
	Total		*1*		*2*		*1*	*3*			*3*	*5*	*2*			*3*	*18*		*3*	*2*	*6*	*4*		*83*
Food	Agroforestry							1			2	1	4		2		10		1	1	3	1		47
	Sustainable agricultural practice				2	1		1		1	1	1	1				10		1	2	2	1		43
	Agricultural intensification		1		1	1		3		2	3	1	3				13			1	9			63
	SWM		2		5	2		7		2	7	2	4		1		20		2	2	8	1		119
	Climate information services		1		2	1		2		1							1		1		1	1		11
	Financial investment							2									2							5
	Crop management		2		3	1	1	4		1	2	2	2		1		13				1			56
	Livestock management		2	1	3	1	1	3	1	3	2	1				1	6	1			4		1	51
	Fisheries management				2	2		2		2	2						6				4			28
	Total		*8*	*1*	*18*	*9*	*2*	*25*	*1*	*12*	*19*	*8*	*14*		*4*	*1*	*81*	*1*	*5*	*6*	*32*	*4*	*1*	*423*
Grand total		2	17	5	32	15	12	48	6	20	36	18	24	1	6	15	122	5	13	16	54	15	5	827

Table 3. Feasibility assessment of 24 adaptation options in Africa. Higher feasibility (that is, no or low implementation barriers) are presented in darker shades, moderate shading shows medium feasibility (presence of some barriers/mixed evidence) and lighter shading represents low feasibility (presence of multiple implementation barriers). The same shading is used to show high, medium or low effectiveness (that is, potential for risk reduction), as well as amount of evidence supporting the assessment of the option across all dimensions.

		Feasibility dimension						
Sector	**Adaptation option**	**Economic**	**Environmental**	**Social**	**Institutional**	**Technological**	**Effectiveness**	**Evidence**
Cities, settlements, and key infrastructure	Urban governance and planning	Low	Insufficient literature	Medium	Medium	Low	Medium	Medium
	Social infrastructure	Low	NA	Medium	Insufficient literature	Low	High	Low
	Infrastructure and built environment	Medium	Insufficient literature	Medium	Medium	Low	High	Medium
Water and sanitation	Alternative water supply	Medium	Insufficient literature	Medium	Low	Low	Medium	Low
	Bulk water infrastructure	Medium	Insufficient literature	Medium	Low	Low	High	Low
	IWM	Medium	Insufficient literature	Medium	Low	Low	Medium	Medium
	Water governance and planning	Low	Insufficient literature	Medium	Low	Low	Medium	Medium
Terrestrial, freshwater, ocean and coastal ecosystems	Ecosystem restoration and conservation	Medium	Medium	Low	Low	Low	Medium	Medium
	EGP	Medium	Insufficient literature	Low	Medium	Medium	High	Medium
Health, well-being, and communities	Health governance and planning	Insufficient literature	Insufficient literature	Medium	Medium	Medium	Medium	Medium
	Health advisory services and education	Insufficient literature	Insufficient literature	Medium	Medium	Low	Medium	Low
	Resilient infrastructure and technologies	Insufficient literature	Insufficient literature	Medium	Low	Low	Medium	Medium
Poverty, livelihoods, and sustainable development	Risk spreading and sharing	Low	Insufficient literature	Medium	Low	Low	Medium	Low
	Human migration	Low	Insufficient literature	Low	Low	Low	High	Medium
	Livelihood diversification	Medium	Insufficient literature	Medium	Medium	Low	Insufficient literature	Low
Food fibre and other eco system products	Agroforestry	Medium	Medium	Medium	Low	Low	High	High
	Sustainable agricultural practices	Medium	Medium	Medium	Low	Low	Medium	High
	Agricultural intensification	Medium	Low	Medium	Low	Low	High	High
	SWM (conservation and efficiency)	Medium	Low	Medium	Medium	Low	Medium	High
	Climate information services	Insufficient literature	Insufficient literature	Insufficient literature	Low	Low	Medium	Low
	Financial investment	Medium	Insufficient literature	Low	Low	Low	High	Low
	Crop management	Medium	Medium	Medium	Low	Low	Medium	High
	Livestock management	Medium	Insufficient literature	Medium	Low	Low	Medium	Medium
	Fisheries management	Insufficient literature	Low	Medium	Low	Low	Medium	Medium

High
Medium
Low
Insufficient literature
NA—Dimension not applicable to option

ecosystem and health governance and planning were an exception in both of these cases, with only moderate barriers. Feasibility was higher for the social dimension of adaptation responses, with moderate feasibility for most options, and only 17% of the adaptation options having low feasibility in relation to the social dimension. Four options (17%) showed moderate environmental feasibility and three (12%) had low feasibility, but there was insufficient evidence to assess environmental feasibility for 67% of the adaptation options—the largest evidence gap for any of the dimensions. Lastly, most options (58%) had moderate economic feasibility, with 21% of options each having low feasibility or insufficient literature for assessment.

4. Discussion

4.1. Feasibility of adaptation options in Africa

We assessed feasibility and effectiveness for 24 categories of climate change adaptation responses in Africa. Encouragingly, we found high potential for risk reduction for eight options and medium potential for 15 options. However, feasibility was only moderate or low for every option across the other five dimensions of feasibility. Comparing all dimensions considered for this study (table 3), the feasibility of adaptation options in Africa is most limited by technical factors, followed by institutional arrangements, then economic implications and social conditions. We note feasibility is context specific because local contextual factors, such as values, norms, development patterns and resource limitations play a key role in feasibility of particular options (Biesbroek *et al* 2013, Singh *et al* 2020), and we discuss differences in feasibility between countries for specific adaptation options (see section 4.2). Nevertheless, our results present a broad synthesis of feasibility for climate-related adaptation options across multiple sectors in Africa highlighting knowledge gaps on environmental feasibility and widespread institutional and technological barriers.

Apart from two adaptation options (EGP, and health governance and planning), the technological feasibility of adaptation options across Africa was low (table 3). This is related to factors including lack of information (such as evidence from scientific findings, weather information, on available technologies), lack of efficient technology (hardware, software, technology applications), lack of awareness, and inadequacy of physical resources such as infrastructure needed for the implementation of adaptation options. For example, limited generation of information on available technologies limits the dissemination of adaptation to local communities (Dumenu and Obeng 2016), and a further barrier to uptake is lack of awareness of the technological aspects of adaptation options and access to efficient technology (Amare *et al* 2019). Technological barriers in terms of adequacy of infrastructure were identified in North and West Africa in our assessment. For example, lack of adequate irrigation infrastructure led to maladaptive water practices (Magnan *et al* 2016, Antwi-Agyei *et al* 2018). The low technological feasibility of adaptation options across Africa highlights the need to ensure technological aspects of adaptation options are considered during adaptation policy planning and barriers to accessing technology are removed.

Institutional feasibility was also low for 67% of reported adaptation options (table 3). This finding extends the assessment of Niang *et al* (2014), which identified limited collaborative governance and poor engagement of civil society as a limitation in national adaptation policies in Africa. Institutional aspects include legal and regulatory issues such as governance and policy or local rules and stakeholder engagement affecting adaptation. It also involves enabling conditions for implementation, whether current political, human capacity, and legal conditions allow for the implementation of the option. Although more countries across Africa are developing climate change laws with subsequent mainstreaming of adaptation into policies and planning (Aylett 2015, England *et al* 2018b), legislative and policy frameworks for adaptation are commonly fragmented, and most cities do not have local government-led adaptation policy (Aylett 2015, Rumble 2019a, 2019b). These realities in institutional and political spheres act as barriers to adaptation implementation but are rarely taken into account in adaptation processes (Mukheibir and Ziervogel 2007, Pasquini and Cowling 2015, Shackleton *et al* 2015, Ebi and Otmani del Barrio 2017, Sonwa *et al* 2017).

There were reported co-benefits and trade-offs with the implementation of some options. These co-benefits and trade-offs were identified for mitigation actions (carbon sequestration related to the environment). Options such as agroforestry, agricultural intensification, crop management and SWM (food sector), ecosystem restoration and conservation, and IWM had synergies with and/or trade-offs with mitigation. For example, agroforestry practices have the potential to reduce greenhouse gas fluxes (Kimaro *et al* 2016, Rosenstock *et al* 2016), but were reported to cause high mortality rate among cocoa plants planted among shade trees (Abdulai *et al* 2018). IWM also improves environmental sustainability by lessening need for use of fuel, which increases carbon dioxide sequestration (Dobson *et al* 2015), but some activities such as expansion of farmlands were reported to erode natural resource base and hence were not sustainable in the long run (Wiederkehr *et al* 2018).

There were multiple positive economic and social impacts of adaptation implementation. Implementation of adaptation options generally increased employment and/or a system's productivity (economic co-benefits). For example, SWM practices within the food sector have demonstrated potential for improving food security by increasing crop productivity, as well as increasing economic returns and managing water deficiency (Leese and Meisch 2015, Blanchard *et al* 2017). Positive interactions or synergies with social policy goals were observed with the implementation of adaptation options across all sectors. Adaptation of urban areas to floods through constructing embankments (infrastructure and built environment) has been reported to promote development and reduce risks of disease outbreaks such as cholera (Campion and Venzke 2013).

However, some adaptation options also presented trade-offs with other goals. For example, water in shallow areas as an alternative water source has been reported to mar the local scenery and also generate health problems, as they become breeding grounds for mosquitoes and other disease vectors (Takken and Lindsay 2019). Although temporary relocation to respond to climate-induced conflict from water as an IWM option improved households' immediate resilience, it disturbed livelihood strategies (Hooli 2016). Migration's withdrawal of labour from farm enterprises can result in a cycle of poor land husbandry and declining yields, which may increase food insecurity (Kidane *et al* 2019). Highlighting identification of such co-benefits and trade-offs related to implementation of adaptation options across multiple social, environmental and economic goals can guide eliminating or minimizing negative effects whilst improving the positive outcomes. It may also guide investment in options toward win–win solutions.

4.2. Feasibility of specific adaptation options

In this section, we examine how the feasibility assessment can be used to inform prioritization and implementation for the most frequently reported adaptation option in each of five sectors in Africa: SWM (food systems), human migration (economy/poverty), resilient infrastructure and technologies (health), IWM (water), and EGP (ecosystems).

4.2.1. Sustainable water management (SWM)

SWM is critical for all sectors, particularly the food sector in Africa, as it contributes to improving food security (Megdal *et al* 2017, Ahmadi *et al* 2020).

Specific strategies under SWM may include rainwater harvesting for irrigation, watershed restoration, efficient irrigation through water conservation (e.g. through drip or sprinkler irrigation), and less water intensive cropping and pit digging (Antwi-Agyei *et al* 2014, Sarr *et al* 2015, Douxchamps *et al* 2016, Bedeke *et al* 2019). The assessment shows that while SWM has medium feasibility economically, environmentally and socially, the institutional and technical feasibility is low. For instance, irrigation farming is considered to pose major financial constraints on farmers with regards to its operational cost (Dube *et al* 2016, 2018, Dube and Nhamo 2018). Implementation of SWM requires more labour and capital, and this can hinder farmers' ability to adapt because of limiting factors such as access to credit/savings or labour shortages (Bryan *et al* 2009, Shikuku *et al* 2017, García de Jalón *et al* 2018, Ologeh *et al* 2018). In Africa, farmers have limited skills in managing large-scale irrigation infrastructure. Most of these infrastructures constructed reportedly fail because of the lack of or poor maintenance (Amede 2015).

Yet, there is currently medium (that is, mixed) evidence of sustained risk reduction in observed SWM practices. Broader benefits have been shown by some strategies within SWM, such as rainwater harvesting for irrigation, which was shown in Ethiopia to reduce poverty levels by approximately 22% and provide a buffer against production risks from increasing rainfall variability (Gebregziabher *et al* 2016). However, weak local institutions hinder adaptation in the food sector where small-scale irrigation plays an important role in adapting to climate change. Access for farmers and especially marginalized groups remains limited (Amede 2015). One impact study concluded that inefficient irrigation may not be able to reduce the negative effect of future climate changes on crops (Muchuru and Nhamo 2019). As an adaptation response that relies on water resources, other trade-offs from its implementation may include water level reduction and nutrient leaching (Harrod *et al* 2018).

4.2.2. Human migration

In response to shocks or stressors associated with climate change, such as droughts or floods, poor infrastructural development and lack of jobs, some people migrate (Okpara *et al* 2016, Boas *et al* 2019, Borderon *et al* 2019, Negev *et al* 2019, Hoffmann *et al* 2020, Rao *et al* 2020). In general, the effectiveness dimension of feasibility for migration was high. Although the assessment shows that across economic, social, institutional and technological dimensions, implementing human migration—be it temporary, seasonal, or permanent migration—has low feasibility. There is LE available in the literature about the environmental impacts of this option. Migration can lead to increased income (Antwi-Agyei *et al* 2018) and studies positively related risk reduction and household food security status to migration that provided an opportunity to earn income (Antwi-Agyei *et al* 2018, Samuel *et al* 2019). However, at the local level, it can also undermine household resources and social services, decrease work force at places of origin, and can negatively affect broader developmental outcomes such as health (Cattaneo and Peri 2015a, 2015b, Peer 2015, Gemenne and Blocher 2017, Chersich *et al* 2018, Negev *et al* 2019). Limited financial and technical support for migration commonly restricts the extent to which migration can make a meaningful contribution to resilience (Djalante *et al* 2013, Trabacchi and Mazza 2015, Sanni *et al* 2019). An alternative strategy like temporary relocation, could be more feasible, but would require complementary investment in raising awareness and programs that provide early-warning systems to temporarily relocate (Musyoki *et al* 2016).

4.2.3. Resilient infrastructure and technologies

Resilient infrastructure and technologies under the health sector consist of strategies such as improving housing to limit heat and exposure (Egbue *et al* 2017, Stringer *et al* 2020), water and sanitation infrastructure (Ruiters and Matji 2015, Hallegatte *et al* 2019), robust non-conventional technology to prevent contamination, improved WASH (Hallegatte *et al* 2019, Houéménou *et al* 2020). Overall, there is LE on the economic and environmental feasibility of resilient infrastructure and technologies for health. Infrastructure construction is expensive and could cost millions of dollars (Okaka and Odhiambo 2019a, 2019b), resulting in inadequate availability for use (Choko *et al* 2019). The institutional and technological feasibility associated with resilient infrastructure and technologies is also considered low. Technologies alone are unlikely sufficient to cope with climate challenges (Mapfumo *et al* 2017) and, within the institutional dimension, complexities with accessing land from people with title deeds to land (land holdings) have been highlighted as hindering implementation of resilient infrastructure and technologies, making it difficult to invest in strategies for drought and/or flood management (Gbegbelegbe *et al* 2018).

On the effectiveness of resilient infrastructure and technologies, the rehabilitation and restructuring of suitable drainage and waste disposal systems eliminates elements of complex disease systems (vectors) (Kahime *et al* 2017). Most of the adaptation measures implemented to cope with health risks may be considered reactive or mere stopgap measures, and would do little to reduce long-term vulnerability (Okaka and Odhiambo 2019a, 2019b).

4.2.4. Integrated water management (IWM)

IWM is crucial to address water insecurity caused by either drought or floods (Allan *et al* 2013, Cameron and Katzschner 2017). Specific strategies included subnational financing (Cameron and Katzschner

2017, Ding et al 2019), demand management through subsidies, rates and taxes (Simpson et al 2019b, Ouweneel et al 2020), and sustainable water technologies (Muller 2019, Nhamo and Agyepong 2019, Simpson et al 2019a, 2020). Although IWM had medium feasibility along economic and social dimensions, it showed low feasibility for most African cities due to technical and institutional restrictions. An example of this institutional barrier being overcome in Uganda is local water infrastructure projects adopted by the National Slum Dwellers Federation that saved communities from paying exploitative prices for water during the dry season (Dobson et al 2015). Conversely, in Namibia, despite the collective and organizing capacities of the urban poor, there is lack of government attention to such local or informal adaptation responses, which is compounded by limited financial and technical support for their activities (Hooli 2016). This limits the extent to which meaningful contribution to urban resilience could be made through IWM alone. Further, IWM does not commonly integrate disaster risk reduction (Kiunsi 2013, Nahayo et al 2017) and there is currently insufficient evidence to evaluate its environmental feasibility.

4.2.5. Ecosystem governance and planning (EGP)

Hazards to ecosystems include increasing storms, temperatures, and sea level rise. The assessment shows that there is limited knowledge on environmental barriers to EGP. Institutional capacity and governance are critical for EGP, and the efforts to improve institutional capacity building for ecosystem conservation are key for successful EGP implementation (Du Toit et al 2018). With conflicting modes of governance in Africa, institutional capacity has improved in some countries, for example in South Africa and Senegal (Cartwright et al 2013, Pasquini et al 2013, 2015, Roberts and O'Donoghue 2013, Vedeld et al 2016, Chersich and Wright 2019, Nhamo and Agyepong 2019), while little progress has been made in others (Snorek et al 2014). There is a lack of synergy between national and local institutions in attempts to manage natural resources (Goulden et al 2013). EGP adaptation options in Africa have not adequately focused on enhancing the understanding and acceptability of ecosystem restoration and conservation, so low priority and limited budget allocation is common in this sector. Additionally, funding, staff, and expertise availability frequently constrain EGP activities (Goulden et al 2013, Munji et al 2014). Yet, successful mainstreaming of adaptation strategies into policies and programs as a specific strategy under EGP has been reported in South Africa, where the inclusion of coastal management in the legal framework has helped institutionalize the coordination of coastal management and adaptation (Colenbrander et al 2015, 2018, Rosendo et al 2018). Increasing public environmental education and awareness with ecological financing are important to enhance activities within EGP. Some areas, in Ethiopia, for example, have also adopted a by-law on how to manage the land and build resilience after restoration (Woldearegay et al 2018).

4.3. Gaps in adaptation knowledge

The feasibility assessment exposed substantial gaps both in knowledge and practice for adaptation in Africa. Some feasibility indicators, specifically microeconomic viability and social trade-offs related to adaptation options, had low evidence across most of the adaptation options. There were also limited studies on the environmental feasibility of climate adaptation, especially related to ecological co-benefits and trade-offs.

No studies described the levels of climate hazard at which adaptation options are no longer effective. This is a critical knowledge gap, as knowing the level of hazard at which options are no longer effective can contribute greatly to examining the potential effectiveness of adaptation options and their return on investment. This is crucial for guiding planning and actions towards adaptation implementation, yet we currently know very little of the feasibility of adaptation options in Africa under different global warming levels.

There is also LE on economic trade-offs and co-benefits for different adaptation options in Africa. Such knowledge is important for assessing the viability of different options. There was also low evidence on the sociocultural trade-offs of implementing various adaptation options. Attention has been paid to the effectiveness of equity and social justice aspects of adaptation responses in Africa, including the differential distribution of adaptation benefits and costs (Brooks et al 2005, Madzwamuse 2010). Further exploring social-cultural trade-offs and co-benefits will provide valuable insight for adaptation feasibility.

The spatial and sectoral distribution of recorded adaptation actions varied greatly (figure 2; table 2). More evidence on adaptation is needed from Central and Northern Africa, as well as for African cities. There were also few studies on fisheries management, financial investment, climate information services, alternative water supply and social infrastructure across Africa. Studies on these strategies are still emerging. With the potential to improve climate resilience, application of climate information services, for example, is low in Africa, with limited accessibility and affordability (Ngari et al 2016, Muema et al 2018, Winrock , Diouf et al 2019, Hansen et al 2019, Osumba and Recha 2019, Carr et al 2020, Popoola et al 2020).

There is also little progress on the assessment of specific adaptation strategies. A range of observed adaptation measures are usually combined in a single study, without explicit information about specific options. Studies concentrating on individual adaptation options were scarce in all sectors studied except food and poverty.

Funding in particular is a recurring theme within adaptation literature (Un-Habitat 2014, Lindley *et al* 2015, UNEP 2015, Wisner *et al* 2015a, Gabriel 2016, United Nations Human Settlements Programme 2016, Adenle *et al* 2017, Omari-Motsumi *et al* 2019, Sanni *et al* 2019), yet there is dearth of studies on economic/financial cost of implementing adaptation options, implying an increasing need for information and research (UNEP 2015, Wisner *et al* 2015b, Omari-Motsumi *et al* 2019).

4.4. Future directions for adaptation research and practice

Our study builds upon the framework developed by Singh *et al* (2020) and Owen (2020), through the modification and development of new indicators and dimensions applicable to the African context (table 1). The modifications present regionally relevant indicators, replicable and credible for uptake for other geographical settings under comparable socio-cultural, environmental and political contexts. Combining both the assessment of feasibility and effectiveness, this approach can be a useful guide for practitioners, policy workers in adaptation planning and investments tasked with designing adaptation plans at national and sub-national levels and selecting adaptation options to mitigate climate risks. The stock of adaptation initiatives and knowledge gaps should be explored further.

Adaptation to climate change is dynamic. The feasibility of options could also therefore change over time. This could alter the prioritization of options or have maladaptive implications that are triggered at future global warming levels not considered here. As our evidence based study is informed by human responses to climate change (GAMI), it captured the temporal scale observed in the literature and recorded between 2013 and 2020 but did not focus on future changes over temporal scales. Future empirical and review studies need to consider future climate risk related to the adaptation options in order to advance the empirical base for feasibility assessments to capture these dynamics. Further, future research could also explore studies on the options that are primarily not focused on climate but motivated by development planning and actions to inform development programmes, but which are likely affected by climate change.

The feasibility assessment conducted in this study outlines the complexities in adaptation practice. It guides which dimensions of feasibility require attention and resources to increase an option's practicability. For example, relatively low economic and technological dimensions undermine the feasibility of urban governance and planning. Implementing urban governance and planning therefore requires resources such as funding and the development of better technological capabilities. As such, this approach is able to inform national and sub-national development plans, and enable integrated risk management that increases the feasibility of the option.

Although we explicitly indicated our source of literature, we accept some level of bias in the analysis with under representation of studies from Central and Northern Africa as well as studies on important and emerging options like Climate Information Services and Financial Investment in the food sector. As a literature-based analysis (our analysis relied on evidence solely in the peer-reviewed literature), there was also difficulty in aligning some indicators with variables defined in our dataset (GAMI). We had to download the identified studies to capture information not extracted by GAMI. Including grey literature in a similar analysis in future will help balance the use of peer-reviewed literature that discounts practitioner knowledge in assessment of adaptation (Singh *et al* 2020).

5. Conclusions

Adaptation to climate change is one of the most urgent and important developmental agendas for Africa. Choosing and committing resources for the most feasible adaptation options requires robust evidence for what has been demonstrated to be most effective. Providing the first systematic assessment of the evidence of human adaptation to climate change in Africa, we examined the feasibility of 24 types of adaptation options in the African context. We assessed the economic viability, environmental sustainability, social validity, institutional relevance, technological availability, and their potential for risk reduction the range of options in their applied contexts.

Evidence of feasibility is high for social and built infrastructure in cities, bulk water infrastructure, EGP, migration, and both agricultural intensification and investment. We also found that economic, social and institutional barriers affect the implementation of most adaptation options. Thus, resilient infrastructure and technologies (for water and sanitation infrastructure, for example) requires economic factors (cost—millions of dollars), socio-cultural factors (acceptability) and institutional factors (legal and political support—land holdings). There is need to consider the effect and interaction between multiple dimensions of how an adaptation option works within different economic, social and institutional developmental arrangements. This further reinforces the importance of 'context' as a key consideration regarding the feasibility of an option in adaptation practice, as the feasibility of specific options may differ from community to community across countries. A deep understanding of socio-institutional context therefore matters to design fit-for-purpose strategies.

It is important to note that some adaptation options might show low feasibility (with many barriers) but might still be desirable within a specified local context or for the most sensitive sectors like food, health and water. In such cases, this study serves to guide which dimensions and indicators to consider and address, making the results policy relevant, and guiding decision making on adaptation implementation. It is also important to acknowledge that the feasibility assessment would consider certain flexibility to guide policy and development planning. As adaptation is a dynamic process, where risks change over time, the feasibility assessment may need to be flexible to accommodate uncertainties and possible interactions across spatial and temporal scales.

Serious knowledge gaps concerning adaptation feasibility in Africa persist, particularly for options within health, financial investments and climate services. The feasibility of different options varies greatly over Africa's geography with infrastructural-based options restricted to lower middle and middle-income countries within Southern, Eastern and Western Africa. There is also LE on economic trade-offs and synergies for different adaptation options. There is NE that observed adaptation-related responses included acceptable hazard thresholds making their risk-reduction potential not assessable.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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