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TOPICAL REVIEW

The (Co)Benefits Portal—an evidence-based and climate policy-relevant tool for decision-making

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Keywords: climate change, (co)benefits, trade-offs, adaptation, mitigation, decision-support tool, policy relevance

Supplementary material for this article is available online

Abstract

From improving health outcomes and health inequalities to ensuring energy and income security, the mitigation of and adaptation to climate change has extensive and diverse benefits. This paper describes a systematic evidence synthesis of climate action (co)benefits and trade-offs as well as the development of a decision-support tool that enables policy makers to explore that evidence-base. The term '(co)benefit' is used deliberately to encompass both the direct benefits of averted impacts due to climate change as well as the indirect or ancillary benefits resulting from mitigation and adaptation interventions. We conducted a systematic search of the peer-reviewed literature in the IPCC 6th Assessment Report, Web of Science, and the Lancet Countdown on Health and Climate Change Reports. Our search strategy prioritised synthesised evidence (e.g. reviews, assessments) excluding primary studies and single case-studies. Data were extracted from 74 distinct records meeting our inclusion criteria and a total of 1785 rows of evidence were analysed. Scientific and technical teams then worked together to develop a tool interface that underwent iterative testing among a small group of potential users. The resulting (Co)Benefits Portal presents an assessment of the available scientific evidence of health, ecosystem, economic, energy, and socio-cultural (co)benefits and trade-offs associated with 40 different mitigation and adaptation actions for both global and regional scales. We then apply the (Co)Benefits Portal into a UK context, in combination with national policy documents and departmental guidance, to connect evidence about relevant climate interventions and reveal cross-sectoral policy implications that are essential for optimising opportunities and avoiding risks. We discuss how evidence-based tools can be developed to bridge critical climate adaptation and mitigation research, policy, and decision-making gaps.

1. Introduction

From improving health outcomes and health inequalities to ensuring energy and income security, the mitigation of and adaptation to climate change has extensive and diverse benefits. For example, in addition to reducing the immediate risks and impacts of extreme weather events, nature-based solutions have been shown to improve mental health outcomes, food and water security, reduce air quality related illnesses and vector-borne diseases, as well as provide ecosystem services, employment, income diversification, and cultural services through education, recreation, tourism, and research [1–3]. Despite the complexities of measuring these impacts, evidence quantifying the magnitude of (co)benefits is emerging.

Clayton *et al* [4] analysed regional differences in fine particulate matter ($PM_{2.5}$) concentrations and ozone (O_3) reductions across Europe due to climate mitigation policies, as well as key sectors, like agriculture, where mitigation actions will have the greatest impact at reducing emissions. Reddington *et al* [5] estimated future reductions in $PM_{2.5}$-attributed mortality associated with a combination of decarbonisation and air pollution controls, as well as the inequities of those benefits globally across socio-economic groups and geographic regions [5]. While policies and measures to mitigate nitrogen pollution from croplands, such as crop rotation, optimal irrigation, tillage, and nitrogen credit systems, have been shown to have a global societal net economic benefit in terms of human health, crop yield, and ecosystems [6]. To this point, there is also clear and emerging evidence of the potential trade-offs associated with climate policy and measures. For example, urban planning and land use interventions can both mediate or exacerbate spatial inequities by triggering climate gentrification and affecting already vulnerable and socio-economically disadvantaged groups (e.g. [2, 7–9]). While mitigation policies and measures that require the use of land, such as reforestation and bioenergy, can increase demand on agroeconomic systems leading to higher food prices and potential food insecurity [10]. Evidence of these trade-offs and (co)benefits related to climate policy and measures is emerging and imperative for strengthening decision-making.

There is enormous complexity built into making decisions about mitigation and adaptation policy and measures. For example, the solution spaces and the system transitions necessary for responding to the impacts of climate change involve numerous, diverse, and sometimes conflicting, goals. The sometimes discordant priorities, such as between mitigation and development or between agriculture and biodiversity, can present challenges to decision-makers and choices that are sometimes at odds with each other. For example, adaptation options like hard coastal grey infrastructure protect against sea level rise and reduce the risk of coastal erosion and flooding, however, they can, at times, conflict with mitigation goals and may also lead to negative ecological impacts that can undermine ecosystem health [11–14]. Nature-based adaptation options, like watershed ecosystem management, can affect greenhouse gas (GHG) emissions and facilitate an interplay between mitigation and adaptation interventions. Land-based mitigation measures, such as producing bioenergy crops and biochar, can increase the demand for land, elevate food prices, prevent access to markets, negatively impact on the livelihoods of smallholder farmers and food security of subsistence-based communities [12, 15]. The nature, magnitude, and distribution of trade-offs and (co)benefits will vary across local, regional, and global contexts—disproportionately affecting the most vulnerable and disadvantaged (e.g. [2, 12]). A contextualised and equity-based understanding of the broad scale and cross-sectoral impact of climate policy and measures will be essential to avoid unnecessary trade-offs [15–18] and harness worthwhile benefits—be they direct or indirect, anticipated or unanticipated.

Under continued climate warming, the range of options, in particular for adaptation, may become more limited [8, 19–21]—bringing an urgency to how we synthesise and communicate evidence to inform effective and equitable actions as well as avoid perverse trade-offs. Critical to this process is understanding how evidence synthesis methodologies and outputs can meaningfully connect with decision-makers and-support tools that effectively communicate action imperatives, policy entry points, and catalyse decisions [22–24]. For example, to implement and evaluate adaptation and mitigation options, decision-makers require the support of evidence and evidence-based tools that are reflective of the adaptive, complex, innovative, and political needs of decision-making [22, 25, 26]. As well, developing evidence-based, actionable, policy-relevant tools requires going beyond a single 'disciplinary-focused' approach to synthesis towards integrating evidence, as well as communities of research and practice, across disciplinary divides [27, 28]. Framing these challenges as opportunities, robust evidence synthesis approaches can enable a more nuanced understanding of an evidence base as it relates to decision-making [29–31].

This paper describes an evidence synthesis of climate action (co)benefits as well as the development of a decision-support tool that enables policy makers to explore that evidence-base. First, we present the methods underpinning the development of a global and regional assessment of (co)benefits and trade-offs for 40 different adaptation and mitigation actions, which led to the development of the (Co)Benefits Portal [32]. Then, we demonstrate how the (Co)Benefits Portal, in combination with national policy documents and departmental guidance, can be applied to a national policy context to connect evidence about relevant climate interventions and reveal cross-sectoral policy implications that are essential for optimising opportunities and avoiding risks. Lastly, we discuss how evidence-based tools can be developed to bridge climate adaptation and mitigation research, policy, and decision-making.

2. Methods

Following the ROSES (Reporting standards for systematic evidence syntheses) approach to systematic evidence synthesis [33], we assessed the available scientific evidence of (co)benefits and trade-offs for a range of adaptation and mitigation intervention options.

2.1. Search strategy

Three key sources of evidence were used: a Web of Science database search, hand-searching of available IPCC reports (6th assessment cycle) [34–36], and the Lancet Countdown on Health and Climate Change Reports [1, 37–39] as well as the Lancet 2009 (volume 374, issue 9705) [40–45]. There is no standard and widely accepted definition of '(co)benefit', and a wide range of terms are often used interchangeably. For this assessment, we apply the term (co)benefits to include both the direct benefits of averted impacts due to climate change, as well as the indirect (incidental) benefits of mitigation and adaptation strategies. 'Trade-offs' include both the direct (not averted) impacts, as well as the indirect, new, or unanticipated emerging risks that arise from different adaptation and mitigation scenarios. Trade-offs thus represent negative outcomes, while (co)benefits reflect positive outcomes, regardless of whether they are planned, unanticipated, direct, or incidental. Following an *a priori* scoping review using key articles and review of keywords used in the literature, relevant search terms were developed (table 1). The database search conducted in Web of Science focussed on impact pathways and associated interventions for heat, air quality, and flooding.

Titles and abstracts were screened against a set of inclusion criteria to identify relevant documents. Documents were included if they were indexed in English and published between January 2014 and December 2021, and presented a global or regional assessment of (co)benefits or trade-offs of climate change intervention options with documented outcome measures relevant to extreme heat, flooding, and/or air quality improvement. Documents were included only if they presented synthesised evidence (e.g. reviews, assessments); primary studies and single case-studies were excluded. Both adaptation and mitigation interventions were included. Documents in the academic peer-reviewed and policy literature were included. Sources meeting these criteria, or those where it was not possible to clearly ascertain whether they met these criteria from title and abstract alone, were included for full-text review. Sources meeting all criteria with enough detail of (co)benefits and/or trade-offs and associated intervention options were included in the assessment. The outlines of IPCC assessment reports and the Lancet Countdown on Health and Climate Change Reports were screened against the same inclusion criteria to identify relevant chapters and sections of the reports. (Co)benefit and trade-off search terms were also used to search the text of chapters and supplementary materials (table 1). Different from our Web of Science database search strategy, there was no restriction regarding specific impact pathways and associated intervention options and all relevant evidence related to (co)benefits and trade-offs were included. A total of 74 documents were identified through this process and included in the assessment (figure 1). A summary of included documents can be found in the supplementary material (table S2).

Table 1. Examples of search terms and pathways used for compiling search strings in each database.

(Co)benefit terms	'Co-benefit' or 'mutual benefit' or 'ancillary benefit' or 'side benefit' or 'collateral benefit' or 'synergy' or 'externality' or 'co-priority' or 'associate benefit'
Trade-off terms	'Trade-off' or 'ancillary impact' or 'co-effect' or 'adverse side-effect' or 'co-impact' or 'cost'
Example pathway (heat)	'Heat protection' or 'heat impact' or 'heat effect' or 'urban heat island effect' or 'heat surveillance' or 'heat monitoring and response' or 'heat stress' or 'extreme heat' or 'heat wave' or 'heat exposure' or 'heat vulnerability'
Example pathway (air quality)	'Air quality improvement' or 'air pollution control' or 'air quality monitoring' or 'air quality index' or 'pollutant exposure'
Example pathway (flooding)	'Flood protection' or 'flood planning' or 'flood management' or 'flood surveillance' or 'flood-prone' or 'flood vulnerability' or 'flood exposure' or 'flood zone' or flood area' or 'flood risk' or 'flood impact' or 'flooding' or 'flash flood' or 'surface water flood' or 'river flood'

2.2. Data extraction and analysis

A typology and online extraction platform were developed to extract and analyse evidence from relevant documents. Based on a scoping review, five

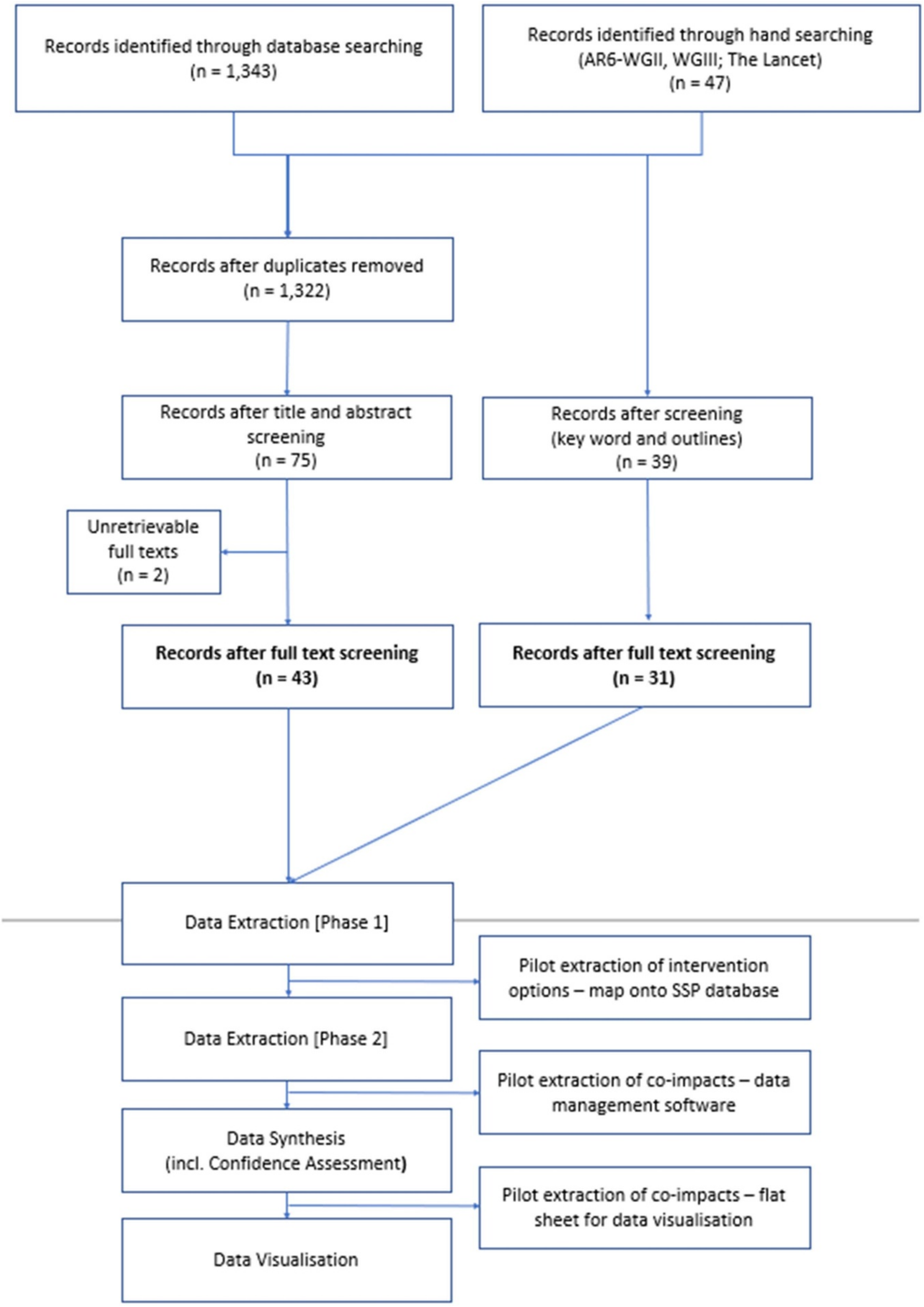

Figure 1. Reporting standards for systematic evidence syntheses (ROSES) flow diagram for systematic reviews [33] modified to include data extraction and synthesis process.

categories of impact were identified *a priori* to data extraction: health, energy, economic, ecosystem, and socio-cultural (table 2). Following a scoping review and pilot data extraction using SR1.5 [34] and a sub-section of retrieved literature sources, 40 specific interventions were identified, categorised into 18 intervention groups, which are further classified within 4 transition categories based on IPCC AR6 transitions: energy systems; land, oceans, and ecosystems; infrastructure and urban systems; and overarching adaptation actions (figure 2) (table S1 in supplementary material).

Table 2. Operational definitions and examples of each (co)impact category used in the assessment.

Category	Operational definition	Examples
Economic	(Co)benefits and trade-offs related to economic services, systems, and infrastructure. Includes references to consumption, investment, employment, productivity, affordability, and trade.	Economic gains, cost savings, lower emission control costs, reduced/returned investments, minimised economic losses and damages, employment opportunities, strengthened financial infrastructures of low-income populations, improved economic and livelihood resilience, government subsidies, changes to tax revenue, opening/closure of industries and businesses
Ecosystem	(Co)benefits and trade-offs related to the functioning and quality of ecological systems and the environment more broadly. Includes references to ecosystem services, biodiversity, and carbon sequestration.	Improved ecosystem services, increased biodiversity, carbon sequestration, ecosystem-driven changes to water and/or air and/or soil quality
Energy	(Co)benefits and trade-offs related to the production, conversion, distribution, and use of energy. Includes references to access, availability, quality, acceptance, efficiency, and reliability of energy.	Improved access to renewable energy, improved access to renewable fuel sources, reduced/increased energy consumption
Health	(Co)benefits and trade-offs related to individual and population health as well as health systems, services, and infrastructure. Includes references to outcomes and determinants of physical, mental, psychological, spiritual, emotional health and wellbeing.	Avoided premature mortality, disease specific morbidity, losses of life years, thermal comfort, increased recreation and activity, water security, food security, air quality related health outcomes
Social-cultural	(Co)benefits and trade-offs related to societal and cultural systems and institutions. Includes references to identity, heritage, ceremony, spirituality, worldview, as well as governance.	Changes to social capital, improved adaptation capacity, loss of solidarity within communities, exacerbated conflicts among different groups, improved social resilience, improved standard of living, social and cultural acceptability of interventions

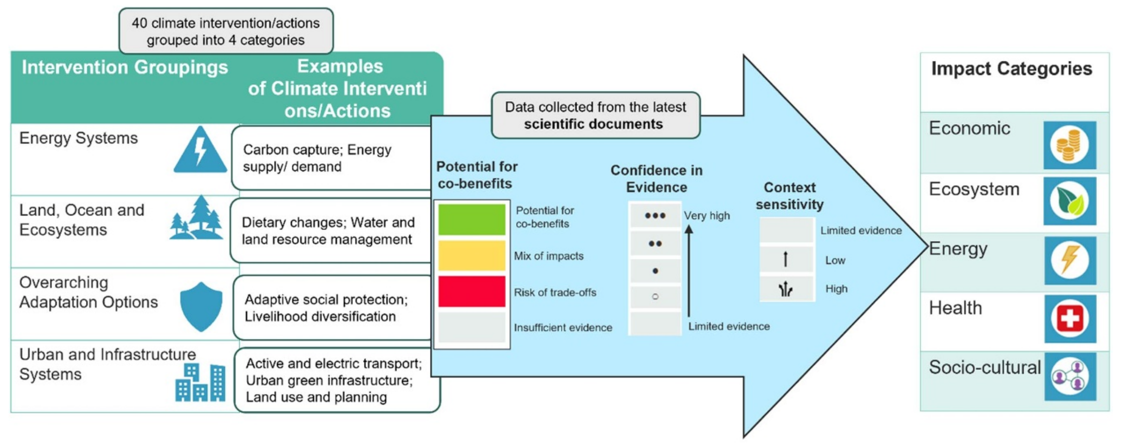

Figure 2. Overview of the categorisation and analysis of adaptation and mitigation interventions and impact categories.

Data extraction was undertaken using the online platform, SysRev. Data were extracted from 74 documents, producing a total of 1785 rows of evidence. The resulting data were used to construct evidence matrices to identify evidence of high potential for trade-offs or (co)benefits. Where possible, data were aggregated into six regional datasets (Africa, Asia, Europe, North America, Oceania, and South & Central America) consistent with the IPCC WGII continental regions. Data that were relevant across multiple regions or at a global scale were synthesised in a global dataset. The six regional datasets of Africa,

Table 3. Components, questions, and levels used in the confidence assessment.

Component	*Questions*	*Levels*
Agreement	What is the level of agreement between different lines of evidence?	High, medium, low
Robustness—source type	What type of literature is this source? (e.g. Scientific peer-reviewed literature may provide more confidence as a source of evidence compared to grey literature, however, this is only one aspect of evidence quality and validity. e.g. Indigenous knowledge may provide strong validity on other key aspects like relevance and context).	—
Robustness—methodological rigour	Are methods sufficient to answer the research question? Are there any major sources of bias in the data collection, analysis, or interpretation of results?	No or very minor, minor, moderate, serious
Robustness—adequacy	Did the record contain sufficient and adequate data (quantity and/or richness) for you to feel confident answering the research question?	No or very minor, minor, moderate, serious
Robustness—relevance	Are the findings of this record relevant to a particular context only (e.g. a particular region, population, or context)? If so, what is the context within which these findings are valid/relevant?	Direct, indirect, partial, uncertain
Context sensitivity	Are particular interventions more likely to be effective, feasible, or just in some contexts but not others? Is there a high likelihood that some interventions will result in a significant re-distribution of risks?	High, low, unknown/limited evidence

Asia, Europe, North America, Oceania, and South & Central America are heterogeneous in their geographical range, resolution, and socio-economic context. For example, one regional database can encompass evidence relating to nature-based solutions for grasslands, peatlands, coastal and marine ecosystems, while another regional database contains evidence for high as well as low-and middle-income contexts and countries.

2.3. Confidence assessment and context sensitivity

The data extraction process was complemented using an adapted GRADE-CerQual approach [30] to assess the confidence in evidence for all (co)benefit and trade-off results. The assessment of confidence includes three components: agreement, robustness [46, 47], and context sensitivity (table 3). *Agreement* considers how contradictory or consistent the body of evidence is for each (co)impact—intervention option association. *Robustness* considers the type of source, methodological rigour/limitations, adequacy, and relevance of underlying evidence. *Context sensitivity* considers how different contexts may affect the risk of trade-off and/or the opportunity of (co)benefit for a particular intervention option-with a focus on implications for effectiveness and feasibility ('success') as well as equity [18]. Assessments of agreement, robustness, and context sensitivity are combined to generate an overall level of confidence for each (co)impact—intervention option association (table 4). An example of a complete justification statement for **Medium confidence**: 'There is medium agreement that affordable low-meat, low animal products, plant-rich diets have health (co)benefits in relevant population groups and that (co)benefits do not apply consistently to all regions and populations. There is medium robustness of evidence supporting this finding due to changes in the relevance of association depending on the population group (e.g. children, LMICs, HDI) and considerable heterogeneity in study designs, definitions, and data sources. There is evidence of context sensitivity'. To ensure inter-reviewer reliability and consistency, two members of the author team independently assessed the individual and collective components of confidence for each (co)-impact—intervention association as well as each contributing record using explicit assessment criteria [48–52]. The assessment process includes making critical judgments and justifications based on the evidence to highlight the seriousness of concerns regarding each component that may reduce confidence in the overall finding. As such, discussions amongst author team members to resolve conflicts and explain justifications were an important part of the assessment process. For example, conflicts arose due to variations in the level of concern (i.e. no or very minor, minor, moderate, or serious) within a given component or between components. Conflicts were

Table 4. Matrix used to guide final assessment of confidence in the evidence (adapted from IPCC uncertainty guidance [46, 47]).

Medium confidence [High agreement; limited robustness]	**High confidence** [High agreement; medium robustness]	**Very high confidence** [High agreement; high robustness]
Low confidence [Medium agreement; limited robustness]	**Medium confidence** [Medium agreement; medium robustness]	**High confidence** [Medium agreement; high robustness]
Very low confidence/limited or no evidence [Low agreement; limited robustness] [Insufficient evidence]	**Low confidence** [Low agreement; medium robustness]	**Medium confidence** [Low agreement; high robustness]

then resolved through explanations about decreased confidence (i.e. risk of bias, imprecision, inconsistency) as well as ensuring judgements were framed in relation to overall findings. When capturing variation within components, the decision was made to reflect the highest level of concern. When capturing variation between components, the decision was made to lower the level of overall confidence for each component where 'serious' concerns had been identified.

2.4. Decision-support tool: development and user testing

The (Co)Benefits Portal was developed iteratively between the scientific team generating the results and a technical team working on the tool. User testing was conducted with a small group of potential users outside of the project. Users were conveniently identified as known contacts of the author team and purposefully chosen to give a spread of different policy focus areas as well as representation from across UK government departments with a climate change remit. The external users included scientific specialists on climate and impacts, communication specialists, as well as climate, health, and environment policy analysts. User feedback was then used to refine the (Co)Benefits Portal prototype.

2.5. Decision-support tool: national application and user experience

We then explored how the (Co)Benefits Portal could be applied as a practical tool to support national policymaker engagement with the scientific evidence base in decision making processes. We conducted a targeted review of UK policy and strategy documents [53–56] to identify references to adaptation and mitigation interventions the corresponded with the (Co)Benefits Portal's European regional dataset. A comprehensive visual of UK policy-relevant interventions was then developed. Visuals for specific climate intervention examples were produced based on conversations with government officials and researchers from the Department for Energy Security and Net Zero, UK Health Security Agency, and Department for Environment, Food and Rural Affairs, which focused on meaningfully capturing relevant information contained within the (Co)Benefits Portal about the potential (co)benefits and trade-offs they can create in the UK.

3. Results

The (Co)Benefits Portal presents the results of an evidence synthesis and confidence assessment about which adaptation and mitigation interventions have beneficial or negative impacts to health, environment, economy, energy, and society. Specifically, the (Co)Benefits Portal can support decisions by identifying where there is: a positive and/or negative impact associated with a climate intervention; clear and high confidence in the contributing evidence; contextual and nuanced evidence for implementation; as well as gaps and low confidence in the contributing evidence. When applied in a policy context, the (Co)Benefits Portal provides an overview of how interventions can impact other policy areas, and where it is important to work across policy areas so as to optimise benefits and avoid negative impacts. When applied to local adaptation and mitigation policy, the (Co)Benefits Portal indicates where there is a need for a greater understanding of the local context and the range of outcomes that an intervention may have given that specific context. The results highlighted here first present examples from the global and regional level evidence syntheses before scaling down to focus on a national policy level application of the tool and evidence base.

3.1. Assessment of (co)benefits and trade-offs

3.1.1. Win–win (co)benefits

Our global and regional assessments of (co)benefits and trade-offs identified several examples of where evidence indicated opportunities for win–win outcomes across multiple impact categories—health, ecosystem, economic, societal, energy (figure 3). For example, increases in energy efficiency and reliability in Europe demonstrated (co)benefits to health via reductions in air pollution attributed annual excess deaths, non-accidental and non-violent mortality, annual lung cancer cases [57], cardiovascular disease, acute and chronic respiratory disease, as well

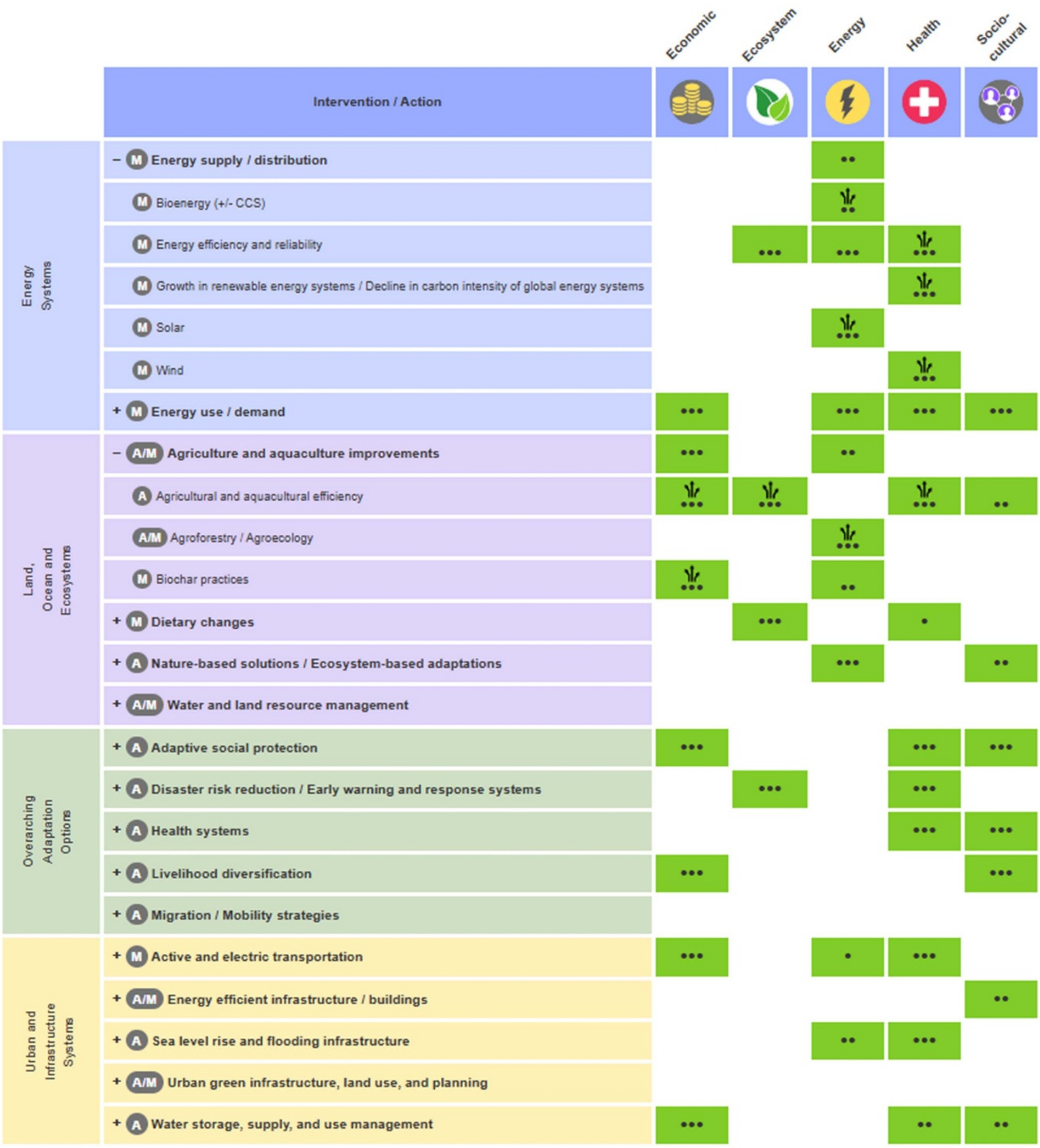

Figure 3. An overview of climate adaptation and mitigation interventions with evidence of opportunity for win–win (co)benefits, taken from the (Co)Benefits Portal global dataset. Examples of specific action areas for 'energy supply' and 'agriculture and aquaculture improvements' are expanded.

as winter/cold-related deaths [45]. In addition to offering energy (co)benefits by reducing energy use and increasing energy security, actions that improved energy efficiency and reliability also offered ecosystem (co)benefits via improved air quality and reduced water resource extraction and use [58–60]. Improving agricultural efficiency contributes to both adaptation as well as mitigation goals and provides numerous (co)benefits to health, ecosystem, economy, and society. Various climate-smart and conservation approaches to agriculture are capable of improving productivity and crop yields, increasing net income, increasing efficient use of natural and agricultural resources, as well as reducing GHG emissions. Reducing agricultural run-off and pesticide use in agriculture leads to reductions in chemical exposure as well as water-borne and food-borne diseases and has win–win (co)benefits when it comes to reducing pressures on the wider health, social, and economic systems. Figure 3 presents a visual summary of the synthesised evidence supporting these examples of win–win (co)benefits using the (Co)Benefits Portal global dataset.

3.1.2. Trade-offs

Our assessment also highlighted mitigation and adaptation options where evidence supported the potential for trade-off (figure 4). Examples of interventions where evidence indicated the potential risk of trade-offs included renewable energy technologies

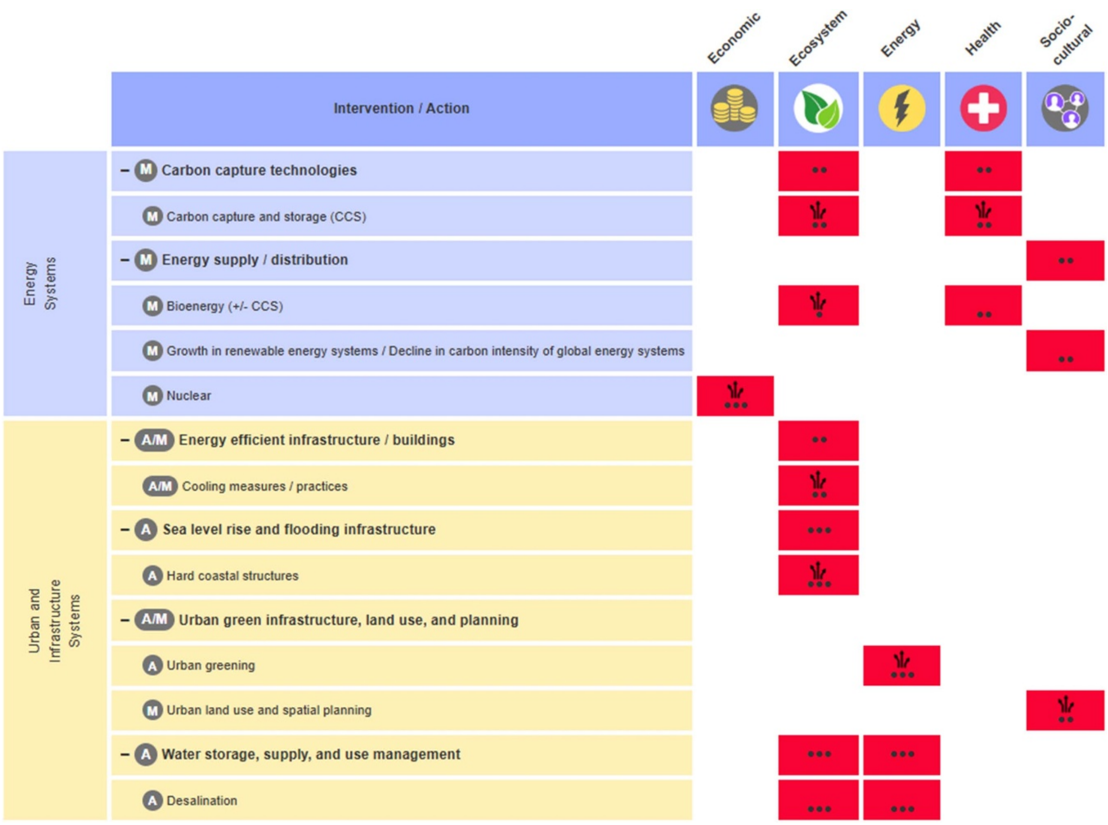

Figure 4. An overview of climate adaptation and mitigation interventions with evidence of risk of trade-offs, taken from the (Co)Benefits Portal regional European dataset. Specific action areas under each intervention are expanded.

that occupy land, such as bioenergy, which can create socio-cultural, health, and ecosystem trade-offs through the displacement of pastoral land use by vulnerable communities, acting as a 'spatial injustice' upon their livelihoods and well-being ([7, 58, 61]). Carbon capture and storage (CCS) was shown to negatively impact on health and ecosystems through the deterioration of local air quality as well as the over-extraction and pollution of freshwater resources [62, 63]. Figure 4 presents a visual summary of the synthesised evidence supporting these examples of trade-offs using the (Co)Benefits Portal regional European dataset.

3.1.3. Mix of (co)benefits and trade-offs

For a majority of interventions (36/40), the evidence supported a mix of (co)benefits and trade-offs in at least one (co)benefit or trade-off category (figure 5). For example, while urban green infrastructure options have substantive evidence for health, socio-cultural, ecosystem, economic, and energy (co)benefits, there is also the potential for trade-offs with (co)benefits being highly context sensitive. Urban greening actions, such as increasing tree cover and vegetated open spaces, are considered both mitigation measures—sequestering and storing carbon—as well as adaptation measures—reducing the exposure of people to higher ambient temperatures in cities, influence thermal comfort, impact water availability, and control air and noise pollution [7, 64, 65]. The mechanisms by which trees regulate air pollution are complex and may affect the concentration of pollutants in a way that has mixed net effects on health. For example, potential health trade-offs of urban green spaces can include respiratory conditions occurring due to enhanced ground-level ozone formation [66] or increases in allergic responses due to pollen or risks of exposure to harmful microorganisms that can cause pathogenic infection or antibiotic resistance [65]. However, the (co)benefits that urban greening can have on reducing vulnerability due to heat stress and food insecurity are particularly relevant for low-income households and neighbourhoods with public access to urban green spaces reducing health inequalities more generally [2, 7, 64, 67]. Evidence suggests that equity considerations of how (co)benefits are differentially accessed and awarded are critical during the early planning, implementation, as well as evaluation phases of such mitigation actions.

Hard coastal infrastructure is another example of an adaptation intervention with mixed (co)benefits and trade-offs. Infrastructure-based options are more viable for wealthier communities, and less so for highly developed areas with poorer communities who are far more susceptible to potential economic and

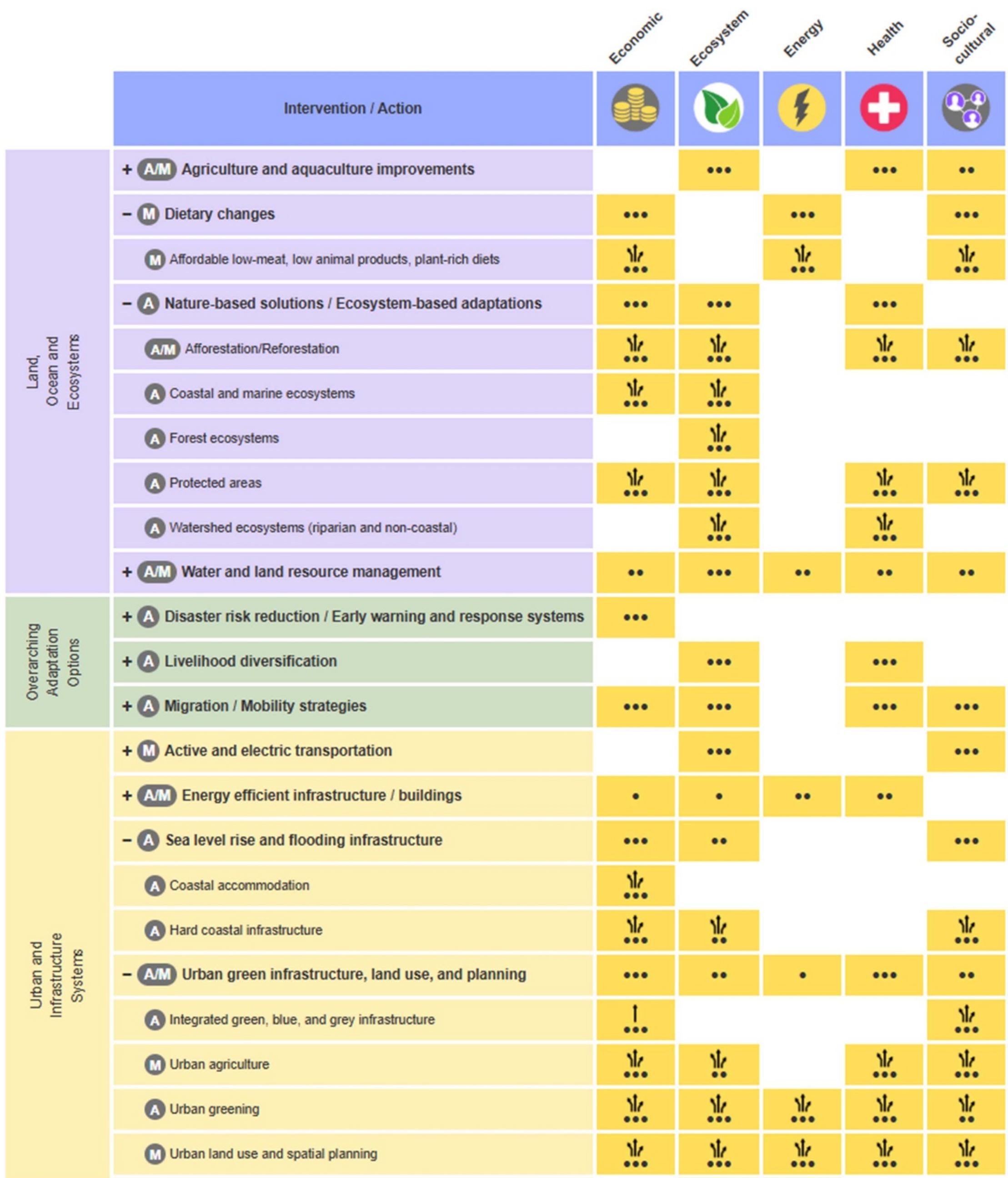

Figure 5. An overview of climate adaptation and mitigation interventions with evidence of mixed (co)benefits and trade-offs, taken from the (Co)Benefits Portal global dataset. Examples of specific action areas for 'urban green infrastructure, land use, and planning', 'sea level rise and flooding infrastructure', 'nature-based solutions', and 'dietary changes' are expanded.

socio-cultural trade-offs that come from being locked into engineered responses. For example, ecosystem trade-offs of hard coastal infrastructure (e.g. reduced water quality and erosion acceleration) often require that infrastructure is designed to lower levels of effectiveness for coastal defence than is technically feasible making them less cost-effective than other ecosystem-based adaptation options. Furthermore, while coastal defence structures can be ecologically engineered to enhance biodiversity and ecosystem functioning, those options will not provide the same ecosystem services as nature-based and integrated (soft eco-engineering) approaches used in restored and natural habitats. Therefore, the combined consideration of long-term economic, socio-cultural, and ecosystem impacts of diverse, and perhaps hybrid, coastal adaptation options is needed for optimising opportunities and avoiding risks.

Afforestation and reforestation are climate actions that can contribute to both mitigation (i.e. sequestering carbon) and adaptation processes (i.e. reducing the impacts of floods and landslides). While there are numerous and apparent ecosystem (co)benefits, including water resource regulation, air quality improvement, microclimate regulation, soil erosion protection, and nutrient cycling, the nature of these (co)impacts can also be highly context sensitive. Factors like the rate and scale of deployment, previous land use and biomass use, the type of trees being planted (e.g. native, non-native, monocultures), and climate (e.g. arid, semi-arid, humid) may influence whether afforestation and reforestation result in (co)benefits or trade-offs [3, 9, 13, 15, 59, 62, 68].

Another example of interventions that may be beneficial in one context and have trade-offs in another are mitigation actions associated with dietary changes. While these have the potential to provide health, energy, and ecosystem (co)benefits, such as such as reduced premature deaths due to excess red meat consumption and other dietary risk factors, the evidence supporting such (co)benefits is highly context sensitive and does not apply consistently to all regions and populations. For example, a decrease in the intake of animal products can potentially have adverse effects on childhood growth and development, particularly in low-income countries [1]. It is, therefore, recommended that in these contexts dietary changes are made safely to ensure nutritional requirements are met and to prioritise the elimination of hunger in vulnerable populations. Figure 5 presents a visual summary of the synthesised evidence supporting these examples of mixed (co)benefits and trade-offs using the (Co)Benefits Portal global dataset.

3.2. National policy review and illustrated examples

We use the UK as a policy context to demonstrate how the (Co)Benefits Portal could generate insights for national-level policy assessment. Results of the policy review connected evidence from the regional European assessment of (co)benefits and trade-offs in the (Co)Benefits Portal with 24 relevant climate adaptation and mitigation interventions referenced in UK climate policy (figure 6). Interventions evidencing win–win opportunities include: active and electric transport; early warning and response systems; watershed ecosystems adaptation; agriculture and aquaculture efficiency; energy efficiency and reliability. Interventions with the potential for trade-offs include: CCS; bioenergy. Interventions with a mix of evidence of (co)benefit and trade-off include: urban greening; afforestation and reforestation; hard coastal infrastructure; growth in renewables. We also present the findings from co-produced outputs of UK-relevant climate interventions. We include examples of implementing interventions to achieve both specific sectoral goals (figures 7 and 8) as well as wider climate ambitions (figure 9)—illustrating the associated impacts on a range of other policy areas (i.e. win–win opportunities and mix of benefits and trade-offs).

Win–win opportunities—Within a UK policy context, there is very high to high confidence that active and electric transport have clear health, sociocultural, and ecosystem (co)benefits (figures 6 and 7). Shared clean vehicles, clean affordable public transportation, and accessible active modes of transportation contribute to more equitable societies and higher mobility, accessibility, and wellbeing for all. For example, higher mode sharing of active transport is associated with more equal gender representation in cycling [1]. However, the evidence suggests that without careful consideration of sociocultural context, including existing inequalities, in the implementation of active and electric transport interventions that these (co)benefits may not be equitably distributed within and between populations (e.g. [1, 64]). This would suggest that equity considerations of how (co)benefits are differentially accessed

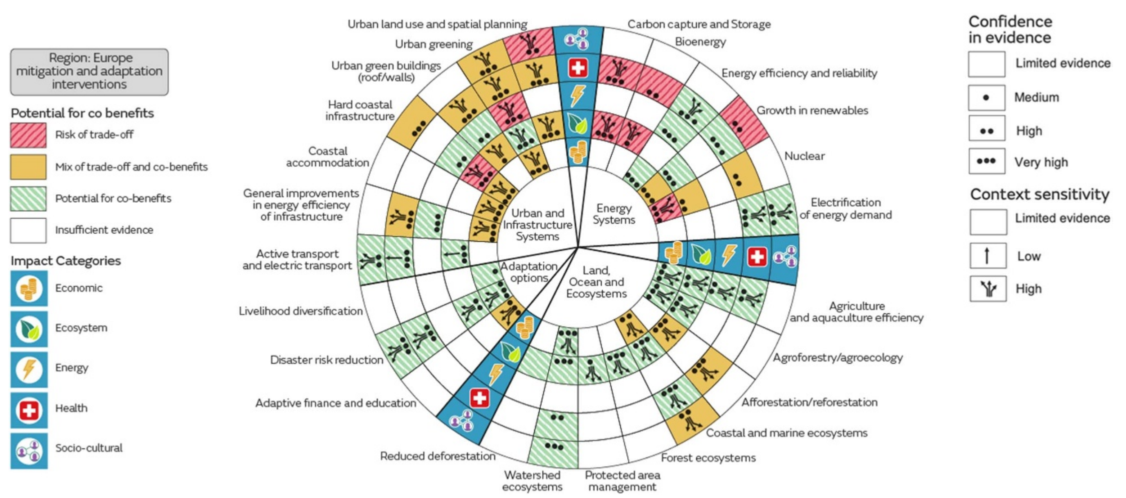

Figure 6. (Co)benefits and trade-offs of UK-relevant climate mitigation and adaptation interventions with levels of confidence in the underlying evidence.

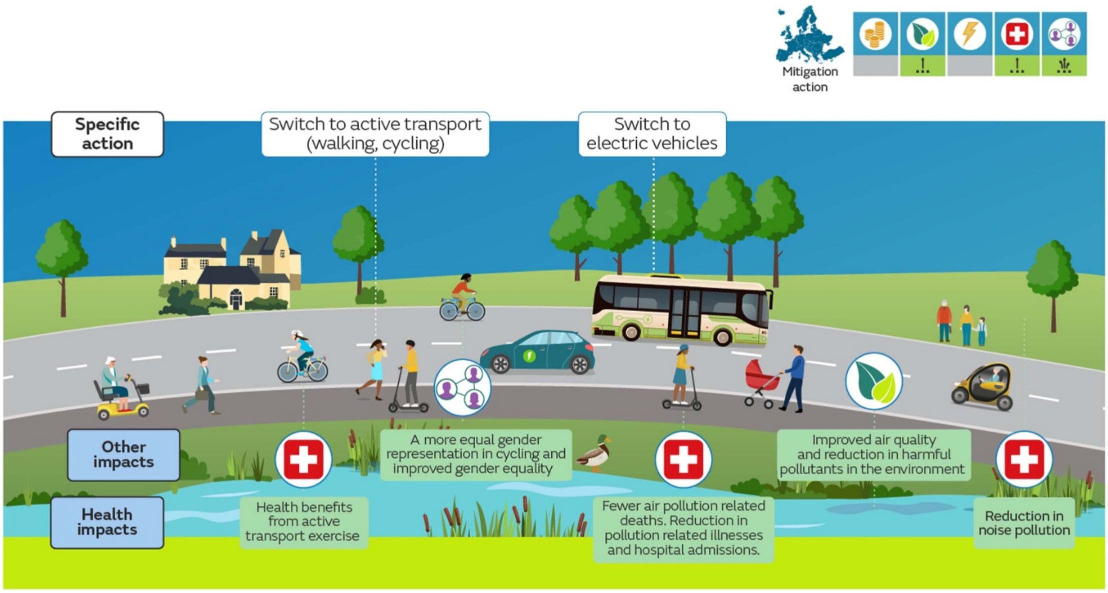

Figure 7. Win–win (co)benefits of active and electric transport.

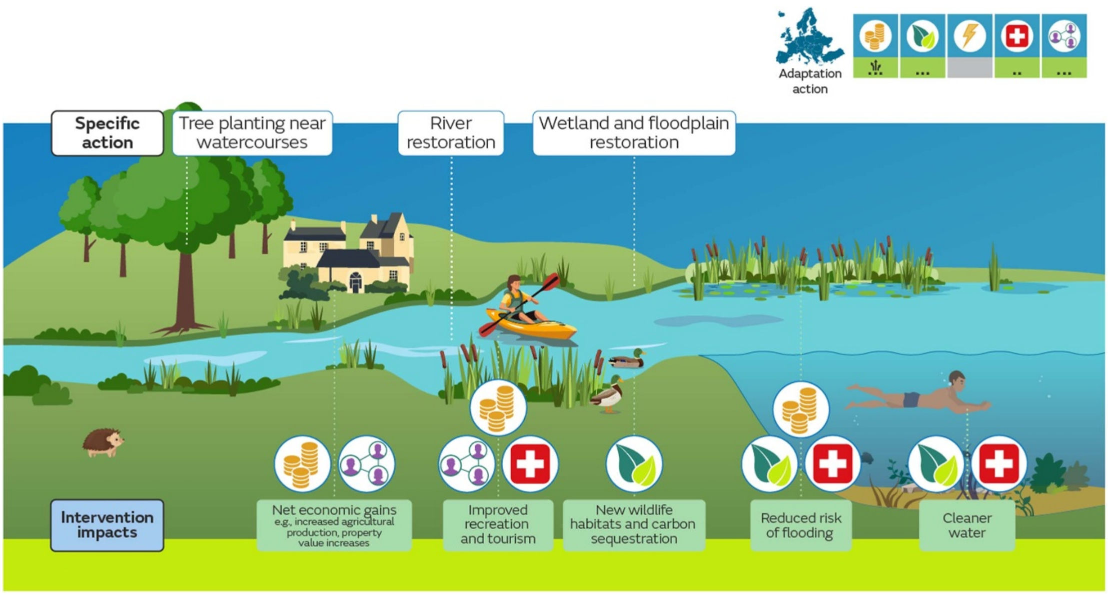

Figure 8. Win–win (co)benefits of watershed ecosystem adaptation.

and awarded are critical during the early planning, implementation, as well as evaluation phases of such mitigation actions.

There is agreement and medium to high robustness of evidence that watershed ecosystem adaptation has win–win (co)benefits for health, society, economy, and ecosystem (figures 6 and 8). These benefits include cleaner water, enhanced public safety, improved recreational space, creation of new wildlife habitats, increased amenity value, and reduced flood risk [69–71]. Evidence also indicates that the economic (co)benefits of watershed ecosystem adaptation will vary depending on the context and specific action taken. For example, the economic (co)benefits of low-cost flood risk reduction due to river restoration and upstream forest restoration compared to the high-cost development of green ways in floodplains, which provide economic (co)benefits of both avoided flooding as well as increasing property and amenity value [69, 70]. Given the context sensitivity, the comparison of costs and (co)benefits are likely to affect political and public support during the planning and implementation phases of adaptation.

Mix of (co)benefits and trade-offs—There is very high confidence that growth in renewable energy systems in a UK/European context has (co)benefits to

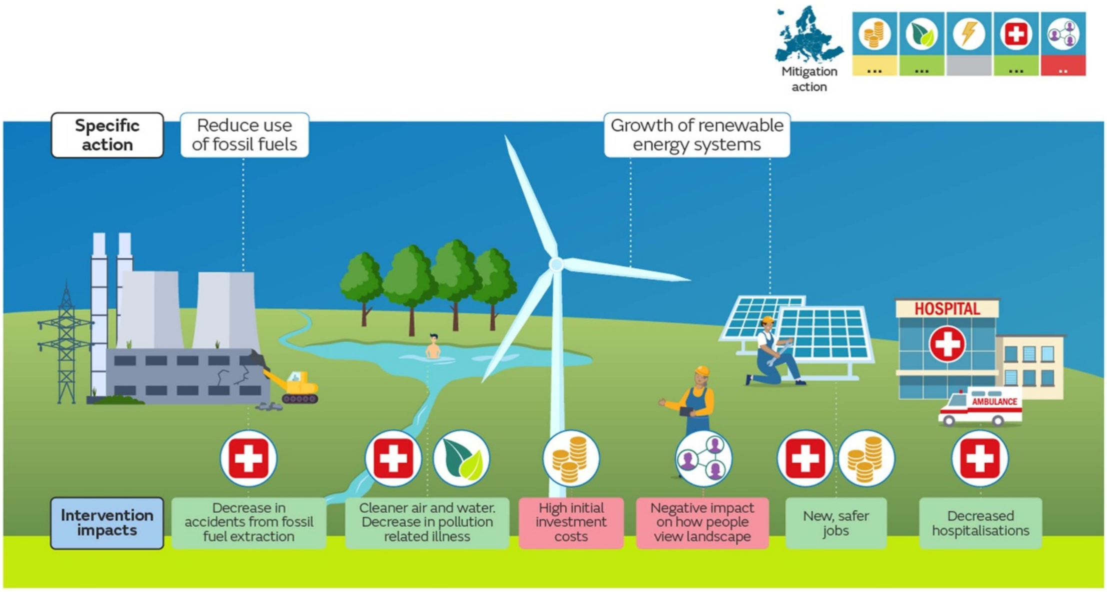

Figure 9. (Co)benefits and trade-offs of declining carbon intensity and growing renewable energy systems.

both health and ecosystem (figures 6 and 9). These benefits include improvements in air and water quality, as well as reductions in pollution-related deaths and diseases, prevention of hospital admissions and emergency department visits, and reductions in the number of sick-days. There is also high confidence that growth in renewable energy systems has a mix of economic (co)benefits and trade-offs. For example, the initial investment and capital required to access novel renewable energy technologies may create economic barriers to entry and increase fuel poverty (e.g. [45]). While economic (co)benefits include employment opportunities, safer jobs, as well as economic gains from numerous of the health (co)benefits previously indicated (e.g. [1]). There is high agreement in the literature and medium robustness of evidence that growth in renewable energy technologies can have socio-cultural trade-offs including negatively impacting on how communities view and relate to landscapes and their surrounding environment (e.g. [72]). The mix of opportunities and risks of mitigation and adaptation actions requires a comprehensive understanding of the cross-sectoral levers in decision-making so as to minimise trade-offs and optimise the health, ecosystem, economic, and socio-cultural (co)benefits.

4. Discussion

Under continued climate warming, our range of options, in particular for adaptation, may become more limited [8, 19, 21]—bringing an urgency to how we synthesise and translate evidence to inform effective and equitable actions as well as avoid perverse trade-offs. In complex cases, where the evidence is not as unambiguous, using a decision-support tool that synthesises the nature, confidence, and context sensitivity of impacts associated with climate mitigation and adaptation interventions can help to: catalyse decisions and initiate actions; implement and evaluate actions; and target evidence gaps for future research. The following section explores what we can learn from applying an evidence-based online decision-making and -support tool into a national climate adaptation and mitigation policy context.

4.1. Leveraging nature, confidence, and context

Minimising trade-offs and optimising (co)benefits requires a comprehensive understanding of the cross-sectoral levers in decision-making processes. The (Co)benefits Portal itself provides a big-picture visualisation of potential win–win (co)benefits for health, ecosystems, society, energy, and economy, where there are risks of trade-offs between them, as well as when (co)benefits and trade-offs cascade across mitigation, adaptation, and Sustainable Development Goals. The co-produced visuals of specific UK-relevant climate interventions (figures 6–9) help to connect the evidence in the (Co)Benefits Portal with specific examples of cross-sectoral policy impacts. This combined consideration of regional and national, short-term and long-term, (co)benefits and trade-offs of mitigation and adaptation options is essential for optimising opportunities and avoiding risks.

Regional datasets, like the European one used to explore and connect evidence with specific UK policy examples, include national-and sub-national level evidence and provide the results of evidence that is synthesised and specific to a region. In many cases, evidence from other regions may still be of relevance and applicable for decision-making in a given context. For example, the (Co)Benefits Portal's Global dataset could also be used to supplement evidence gaps at the regional and national level. When doing so, the (Co)Benefits Portal's confidence assessment can be adjusted to account for changes in the extent to which the body of evidence supporting a regional or global finding is applicable to a specific context and scale—clarifying when the underlying data are of direct, indirect, partial, or unclear relevance [51]. Furthermore, the context sensitivity associated with each intervention impact can also be used to guide decision-makers when supplementing and applying evidence within and across regions. As demonstrated by applying the regional European dataset of the (Co)Benefits Portal to a national policy review, national-level decision-making processes can, and do, benefit from the synthesis and communication of evidence from a diversity of contexts and scales. Due to the heterogeneity of contexts within and across the six regional datasets (Africa, Asia, Europe, North America, Oceania, and South & Central America), assessments of context sensitivity and relevance are essential to communicating and applying the evidence base.

Information about how (co)benefits are differentially accessed and attained is critical during the early planning, implementation, as well as evaluation phases of both adaptation and mitigation actions. In this way, the (Co)Benefits Portal offers contextualised and equity-based considerations for moving from an isolated evidence-base into making decisions that will lead to effective actions. Through deliberate evidence synthesis and assessment methodologies we can develop decision-support tools that emphasise equity concerns and stimulate action needed to address the root causes of underlying climate inequities.

Gaps in evidence—such as overarching adaptation options (e.g. adaptive financing or livelihood diversification) and land, ocean, and ecosystem options (e.g. forest ecosystem adaptations)—can also be used to highlight where data is needed and resources can be allocated for future research. For example, overarching adaptation options—such as health systems, early warning and response systems, and adaptive social protections—have significant potential for health, economic, and socio-cultural (co)benefits. While these interventions have been classified as having insufficient evidence in our assessment, these gaps may be a result of how supporting evidence is presently considered and reflect an emerging trend towards associating these interventions with climate adaptation options.

4.2. Balancing feasibility, needs, and desires

The evidence assessment underlying the (Co)Benefits Portal does not include all possible evidence on (co)benefits and trade-offs for all possible interventions. For example, the assessment was restricted to scientific records that presented synthesised evidence of (co)benefits and trade-offs—e.g. IPCC AR6 chapters. Articles summarising the outcomes of individual adaptation or mitigation interventions, for example, were excluded. This search strategy and selection criteria were chosen, in part, due to feasibility. The typology of (co)benefit categories, interventions, and intervention groups developed *a priori* to guide the extraction and analysis of evidence influenced our decision to prioritise synthesised evidence (figure 2, table 2, supplementary material). For example, the size and disciplinary diversity of the literature base we were targeting (i.e. five impact categories of (co)benefit and trade-off associated with 40 specific mitigation and adaptation responses relevant to four systems transitions). Furthermore, the timing of our evidence synthesis corresponded with the final government drafts of the IPCC AR6 WGII and WGIII assessment reports. As such we chose to build on the findings of this timely comprehensive scientific assessment process and extend our search using the chapters, each an evidence synthesis in their own right, as another database.

Evidence on the (co)benefits and trade-offs of mitigation and adaptation interventions is still emerging. Many relevant documents do not use standardised terminology or are not clearly indexed, and thus present numerous challenges to developing sensitive and specific search strategies. Furthermore, the diversity of approaches, climate models, policy scenarios, time scales, geographic scales, and assumptions used to quantify the magnitude and distribution of (co)impacts. All of these factors influenced our methodological decisions and supported that a broad cross-sectoral overview of evidence relating to (co)benefits and trade-offs was needed for the initial development of a decision-support tool. Inevitably, our assessment does not capture a large volume of relevant literature, since it is impossible to assess the entire volume of literature on all impacts and interventions. These methodological decisions and limitations speak to a growing challenge of selection bias in evidence syntheses that needs to be articulated when communicating with decision-makers and informing evidence-based policy making [73]. There are limitations and biases possible at every stage of the systematic evidence synthesis process (i.e. identification, screening, appraisal, and synthesis) and we have taken numerous methodological decisions (i.e. *a priori* scoping, systematic search across a suite of resources and databases, confidence assessment) to mitigate the risk of biases and strengthen the reliability and robustness of the evidence base and tool produced [74].

In their current form, the evidence synthesis and the (Co)Benefits Portal do not include evidence on the magnitude of (co)benefits and trade-offs. However, this work does provide a basis for discussions on measuring the magnitude of impacts for relevant adaptation and mitigation interventions—which is still an area of uncertainty. Feedback from potential users, such as government officials, highlighted the desire for information about the magnitude of (co)benefits and trade-offs. The inclusion of evidence on magnitude could allow for the direct comparison of different climate intervention (typically mitigation) options [75], determine optimal decarbonisation rates, allow for the valuation of improved health outcomes [76], and quantify changes in health inequities [5]. However, before being able to generalise about the magnitude of (co)benefits and trade-offs in meaningful ways, we need a strategic and concerted approach, or comprehensive framework, to cumulatively and consistently measure them.

When developing a decision-support tool for climate action, the challenge is understanding the range of information needs—to say trigger cross-sectoral levers that optimise (co)benefits for health, ecosystem, economy, energy, and society—as well as what a decision-support tool can realistically deliver [77]. While introducing evidence related to magnitude may satisfy the information needs of certain decision-makers, it will also introduce trade-offs in terms of other confidence components—i.e. methodological limitations, coherence, adequacy, and relevance [30]. In terms of methodological limitation and agreement, there is no consensus around best-practice for measuring (co)benefits let alone quantifying their magnitude. Methodological complexity and inconsistency of determining the magnitude of impacts associated with interventions can lead to having a coarse resolution of the scale of impact, lack of precision, and loss of sensitivity as well as a preferential assessment of mitigation interventions. Being able to account for contextual factors and equity considerations affecting (co)benefits and trade-offs will be critical for the implementation of climate interventions. Therefore, depending on the level of detailed information desired/needed at different stages of decision-making, the use of the (Co)Benefits Portal in decision-making could be complemented with evidence from magnitude studies. However, the current lack of consistency across methods, scenarios, exposures, temporal scales, and other considerations prevents the syntheses and meta-analyses of such studies, which is what would be required for more significant impact on decision-making across geographic and political scales [78].

4.3. Future directions

There is scope for the (Co)Benefits Portal to evolve and be applied in new directions. For example, the next iteration of the (Co)Benefits Portal will integrate the feedback and needs identified via the initial user testing with policy analysts and decision-makers and focus on: updating the underlying evidence; expanding to include, where possible, evidence related to the magnitude quantification of health (co)benefits and trade-offs (including health equity measures and without disadvantaging evidence related to adaptation options); and tailoring the evidence to national level decision-making priorities. Further ideas include applying the evidence synthesis and confidence assessment underlying the (Co)Benefits Portal to develop indicators for measuring the effectiveness of interventions moving forward. Furthermore, we propose that the updating of our evidence synthesis to inform the next iteration of the (Co)Benefits Portal will include the application of machine learning in an effort to minimise this selection bias and offer a more comprehensive, objective, open, and transparent assessment of an exponentially growing evidence base. Lastly, in addition to available scientific evidence, routinely collected data and novel data-streams, such as remote sensing early warning systems and citizen science surveillance, can be useful for informing sectorally integrated decision-making at different levels [24]. An interesting next step would be to work with policy analysts and decision-makers to understand how the (Co)Benefits Portal can systematically account for, and be complemented by, grey literature and novel data sources as well as discrepancies in the ways different types of information are processed.

The (Co)Benefits Portal will only be effective if used. Despite limited assessments of the effectiveness of decision-support tools, it is necessary to evaluate tools to understand how and why decision-makers use them as well as their limitations [22, 77]. Further still, in addition to a robust and growing evidence base evaluating the (co)benefits of climate policies and measures, there is a dearth of data demonstrating whether/how this evidence base has in turn informed policy-and decision-making processes. For example, as part of the seventh carbon budget, the UK Climate Change Committee presented evidence to the UK government about the quantified (co)benefits of switching to low-carbon heating, electric cars, modal shift, residential insulation, and reducing average meat and dairy consumption—informing national emission reduction targets for 2038–2042. As such, we also recommend that future work focus on understanding better how the benefits of mitigation and adaptation actions play out in practice within national and international policy and political discussions. This would allow tailoring the (Co)Benefits Portal towards particular groups of stakeholders, building wider understanding of the issues involved within the transition to net zero emissions.

5. Conclusion

Regardless of the primary goal of a mitigation or adaptation intervention, there are likely (co)benefits and/or trade-offs in a number of different policy areas to consider. Informed by a systematic evidence synthesis and confidence assessment, The (Co)Benefits Portal [32] presents the available scientific evidence of (co)benefits and trade-offs associated with 40 different mitigation and adaptation actions on a global and regional scale. Our findings demonstrate how iterative and reflective user engagement can play a key part in realising the powerful potential of evidence syntheses and informing the development of tools that support decision-making and enhance decision quality in the face of climate change.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://priestleycentre.shinyapps.io/climatecobenefitsportal [32].

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

BvB: conceptualisation; data curation; analysis; investigation; methodology; visualisation; writing—original draft preparation; writing—review and editing. **LBF**: conceptualisation; funding acquisition; methodology; visualisation; writing—review and editing. **RW**: investigation—national application and user experience; methodology—national application and user experience; validation—national application and user experience; visualisation; writing—review and editing. **DHN**: investigation—national application and user experience; methodology—national application and user experience; validation—national application and user experience; visualisation; writing—review and editing. **ES**: investigation—national application and user experience; methodology—national application and user experience; visualisation; writing—review and editing. **COD**: data curation; methodology; investigation; writing—review and editing. **TJ**: data curation; software; visualisation; writing—review and editing. **PMF**—funding acquisition; writing—review and editing. **SA**: funding acquisition; writing—review and editing. **CR**: writing—review and editing. **JL**: conceptualisation; validation—national application and user experience; writing—review and editing.

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