Global Environmental Change 76 (2022) 102575

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Evaluating the benefits of national adaptation to reduce climate risks and contribute to the Sustainable Development Goals

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ARTICLE INFO

Keywords:
Sustainable Development Goals (SDGs)
National adaptation assessments
Climate risk analysis
Spatial SDG indicator translation
Participatory methods

ABSTRACT

Scaling up national climate adaptation under the Paris Agreement is critical not only to reduce risk, but also to contribute to a nation's development. Traditional adaptation assessments are aimed at evaluating adaptation to cost-effectively reduce risk and do not capture the far-reaching benefits of adaptation in the context of development and the global Sustainable Development Goals (SDGs). By grounding adaptation planning in an SDG vision, we propose and demonstrate a methodological process that for the first time allows national decision-makers to: i) quantify the adaptation that is needed to safeguard SDG target progress, and ii) evaluate strategies of stakeholder-driven adaptation options to meet those needs whilst delivering additional SDG target co-benefits. This methodological process is spatially applied to a national adaptation assessment in Ghana. In the face of the country's risk from floods and landslides, this analysis identifies which energy and transport assets to prioritise in order to make the greatest contribution to safeguarding development progress. Three strategies ('built', 'nature-based', 'combined SDG strategy') were formulated through a multi-stakeholder partnership involving government, the private sector, and academia as a means to protect Ghana's prioritised assets against climate risk. Evaluating these adaptation strategies in terms of their ability to deliver on SDG targets, we find that the combined SDG strategy maximises SDG co-benefits across 116 targets. The proposed methodological process for integrating SDG targets in adaptation assessments is transferable to other climate-vulnerable nations, and can provide decision-makers with spatially-explicit evidence for implementing sustainable adaptation in alignment with the global agendas.

1. Introduction

The impacts of climate change already severely threaten societal development, affecting the most vulnerable countries and populations (Gomez-Echeverri, 2018; Liu et al., 2015; Masson-Delmotte et al., 2018). As a global response, 197 governments have committed to a global adaptation goal and to engage in national adaptation planning under the Paris Agreement on Climate Change (Magnan and Ribera, 2016; Morgan et al., 2019). To help decision-makers inform national adaptation planning, evidence on whether and where to adapt is required. Such evidence is often derived by evaluating the benefits of adaptation to cost-effectively reduce climate risk (Jafino et al., 2021). Yet, thinking about adaptation purely in terms of risk reduction can underestimate the wider significance of adaptation for achieving a nation's development objectives and the 169 targets of the global Sustainable Development Goals (SDGs) (Schipper et al., 2016; Reichstein et al., 2021). Despite numerous calls to integrate adaptation and sustainable development (Fuso Nerini et al., 2019; Fuldauer et al., 2022; Zhenmin and Espinosa, 2019), national adaptation plans under the Paris Agreement are seldom articulated in terms of their contribution to the SDGs. To maximise synergies between the achievement of the Paris Agreement and the SDGs, it is therefore critical to evaluate national adaptation with respect to *both* reducing climate risk *and* contributing to the SDGs.

In this paper, we focus on biophysical adaptation assessments, acknowledging the importance of social, financial, institutional and private sector engagement adaptation. Biophysical adaptation assessments are typically structured around two main phases: I) adaptation needs, which refer to the physical assets or locations requiring actions in response to climate risks; and II) adaptation options, which are comprised of the array of physical measures to address these needs

Abbreviations: SDGs, Sustainable Development Goals; NDC, Nationally Determined Contributions.

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https://doi.org/10.1016/j.gloenvcha.2022.102575
Received 25 September 2021; Received in revised form 15 May 2022; Accepted 1 August 2022
Available online 18 August 2022

(Noble et al., 2015). The high spatial granularity of such two-phase assessments is useful to help decision-makers identify combinations of assets and adaptation options that cost-effectively and robustly reduce climate risk (Ward et al., 2017; Koks et al., 2019; Thacker et al., 2017b; Kheradmand et al., 2018). Yet, in its current form, the range of sustainability benefits of adaptation, such as protecting development progress towards energy access or contributing to biodiversity (Jafino et al., 2021), are not adequately represented in either of these two phases.

To maximise synergies between adaptation and the SDGs in Phase I adaptation needs assessments, methods have been developed that adopt a climate-first approach to estimate the range of sustainability dimensions - measured in terms of the number of SDG targets - that can be safeguarded by adapting assets against climate risk (Fuldauer et al., 2021). Whilst such methods provide a broad understanding of the sustainability benefits of adaptation, they do not ground adaptation assessments in a quantified SDG vision. Yet, establishing a vision for SDG achievement at the outset of adaptation needs assessments and thereby adopting a development-first approach is critical to identify assets with the largest potential to safeguard sustainable development.

To account for a broader range of sustainability dimensions in Phase II adaptation option evaluations, feasibility methods have been proposed to evaluate adaptation options across social, environmental, and economic dimensions (Singh et al., 2020; Williams et al., 2021). Yet, methods that evaluate adaptation options across numerous sustainability dimensions remain the exception rather than the norm, and have been particularly called for in the field of nature-based adaptation options (Seddon et al., 2021; Chausson et al., 2020). Nature-based adaptation options, which include ”actions to protect, sustainably manage and restore natural or modified ecosystems” (Cohen-Shacham et al., 2016) have recently gained traction in relation to their ability to provide wider sustainability benefits as compared to built adaptation options such as seawalls or asset fortifications (Malhi et al., 2020; Seddon et al., 2020). To date, the economic costs and benefits of nature-based options alongside built ones have been evaluated (Menéndez et al., 2020; Beck et al., 2018), but methods that account for the contribution of adaptation options to the SDGs are still in their infancy (Gómez Martín et al., 2020; Fuso Nerini et al., 2019) and to our knowledge no method exists that allows evaluating built versus nature-based adaptation options across the broad range of the 169 SDG targets.

Whilst SDGs are not typically considered in national adaptation needs and options assessments, they are widely being recognised as a framework to identify and evaluate sustainable development needs and options (OECD, 2019; Prakash et al., 2017). Increasingly, researchers have used the specificity of the SDG targets to envision a desired sustainability future and quantify the contribution of various investment options to meet desired sustainability target across a range of futures, within and across different sectors of the economy (Adshead et al., 2019; Allen et al., 2019; Allen et al., 2021; Fuldauer et al., 2019). Advancements in SDG quantification enable assessing countries' baselines towards SDG achievement (Schmidt-Traub et al., 2017). More recently, such advancements have also been translated spatially at the sub-national level to better inform decision-making (Xu et al., 2020). Yet, to date, these advancements in national SDG quantification have not been integrated with adaptation needs assessments to reduce climate risk on assets, nor have the 169 SDG targets been used as a basis to evaluate adaptation options.

The goal of this paper is to fill the abovementioned gaps and develop and apply a methodological process that allows national decision-makers to evaluate the total SDG benefit of adapting specific assets or areas against climate risk (see Fig. 1). The total SDG benefit of adaptation is here defined as: I) the quantified benefit of safeguarding a nation's SDG progress by protecting assets against risks from acute climate-change hazards (such as floods or storm surges) and chronic climate-change hazards (such as a drying trend or sea-level rise) and II) the range of SDG target co-benefits of adaptation options to protect these assets. National-scale application of the methodological process enables decision-makers to answer the following two questions: I) where are needs highest for adaptation to safeguard progress on SDGs? (i.e. where and which assets and regions should be prioritised for adaptation to safeguard the largest existing SDG target progress)? and II) how can adaptation options be evaluated in terms of SDG co-benefits? (i.e. which adaptation options should be prioritised to deliver the largest SDG co-benefits)?

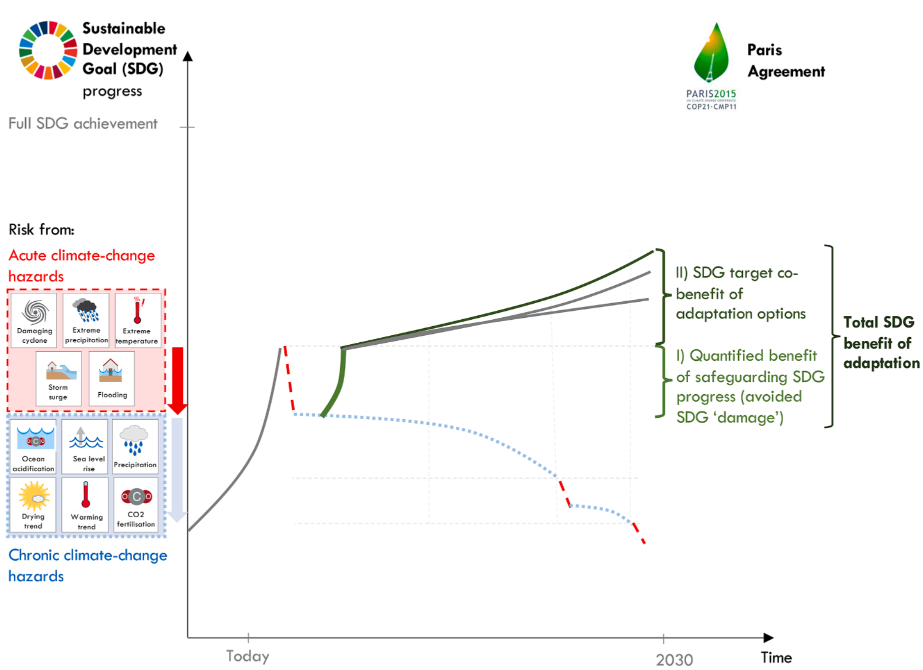

Fig. 1. Identifying the total Sustainable Development Goal (SDG) benefit of adaptation, which includes: I) the quantified benefit of safeguarding SDG progress against risks from acute and chronic climate-change hazards (red and blue arrows and lines, respectively), in other words, the avoided SDG 'damage' of adaptation, and II) the SDG target co-benefits of different adaptation options. Lines are not to any scale, acknowledging that even after adaptation, some residual risk remains.

Our proposed methodological process incorporates two main novel contributions. The first is a set of SDG-risk indicators, spatially translated to the asset-scale, which quantify where a nation's current biophysical adaptation needs are largest to safeguard a nation's SDG progress. The second is the creation of strategies of adaptation options designed to meet these adaptation needs, which are then evaluated for their ability to deliver SDG target co-benefits. The first main contribution of this paper - the quantified SDG-risk indicators - focuses on evaluating adaptation in the context of the SDG targets at one point in time, which can be expanded upon to enable dynamic adaptation assessments in the context of the SDGs. The second main contribution of this paper provides a starting point to qualitatively identify the full range of potential SDG target co-benefits of various adaptation strategies, which can be used by decision-makers as both a means to maximise potential SDG synergies and as a metric that complements other performance indicators, such as effectiveness or cost, in evaluating adaptation options. Whilst adaptation is often considered a local effort (Tompkins and Eakin, 2012; Hall and Persson, 2017), our proposed national-scale methodological process provides national decision-makers, who are tasked with allocating resources across regions, with a systematic process to maximise synergies and minimise trade-offs across climate and sustainable development goals, thereby ensuring that national adaptation is contributing, rather than detracting from, sustainable development.

We apply our proposed methodological process with real-world spatial data from Ghana's energy and transport sector, which provides one important step in helping to prioritise adaptation across different assets and regions in the context of the SDG targets, recognising that there are also human assets, non-spatial adaptation options (including community and institutional capacity building) and important power dynamics involved in sustainable adaptation, which are outside the scope of this paper.

The rest of the paper is organised as follows: Section 2 outlines the different steps of the proposed methodological process in the context of acute climate-change hazards. Section 3 presents the data and materials used in its application to a national adaptation assessment for Ghana's energy and transport sector. Section 4 discusses the results of this application, which is followed by a discussion of the managerial and theoretical contributions as well as avenues for future research. Section 5 provides concluding remarks.

2. Proposed methodology

Our proposed methodological process for integrating SDG targets into national adaptation assessments involves four steps (Fig. 2): (1) set a national SDG vision and identify a nation's current performance in relation to SDG targets representing this vision, (2) perform a climate risk analysis to quantify SDG target progress at-risk, thereby prioritising where adaptation can provide the largest contribution to safeguard SDG target progress, (3) identify and group adaptation options into distinctive strategies, and (4) evaluate the SDG target co-benefits of each adaptation strategy, thereby prioritising strategies to maximise SDG target co-benefits. The following paragraphs summarise these four steps, with the two novel methods developed in this paper (shown in green in Fig. 2) described in more detail.

2.1. Phase (I) Adaptation needs

2.1.1. Step (1) SDG vision and current performance

Conceptually, each of the 169 SDG targets can be linked to a nation's sector via the notion of SDG influences (Thacker et al., 2019; Fuldauer et al., 2022); we focus the first step of this analysis on direct SDG influences. A direct SDG influence is defined where an SDG target is explicitly described in terms of the sustainability of a sector's service provision. Thereby, a nation's SDG target progress can be described specifically in terms of indicators estimating how sustainable (how much, how environmentally sustainable, to whom) a sector's service is provided in relation to desired national performance values (Adshead et al., 2019).

According to an existing performance indicator framework (Adshead et al., 2019), progress on an SDG target described in terms of a single sector and a single sustainability indicator can be measured by a single performance indicator. For example, progress on SDG target 7.2 "increase the share of renewable energy …" may be estimated by a single performance indicator on the current baseline share of renewables in a nation's energy mix in relation to a desired share, thereby measuring the environmental dimension with respect to the energy sector. Conversely, SDG target 11.2 "By 2030, provide access to safe, affordable, accessible

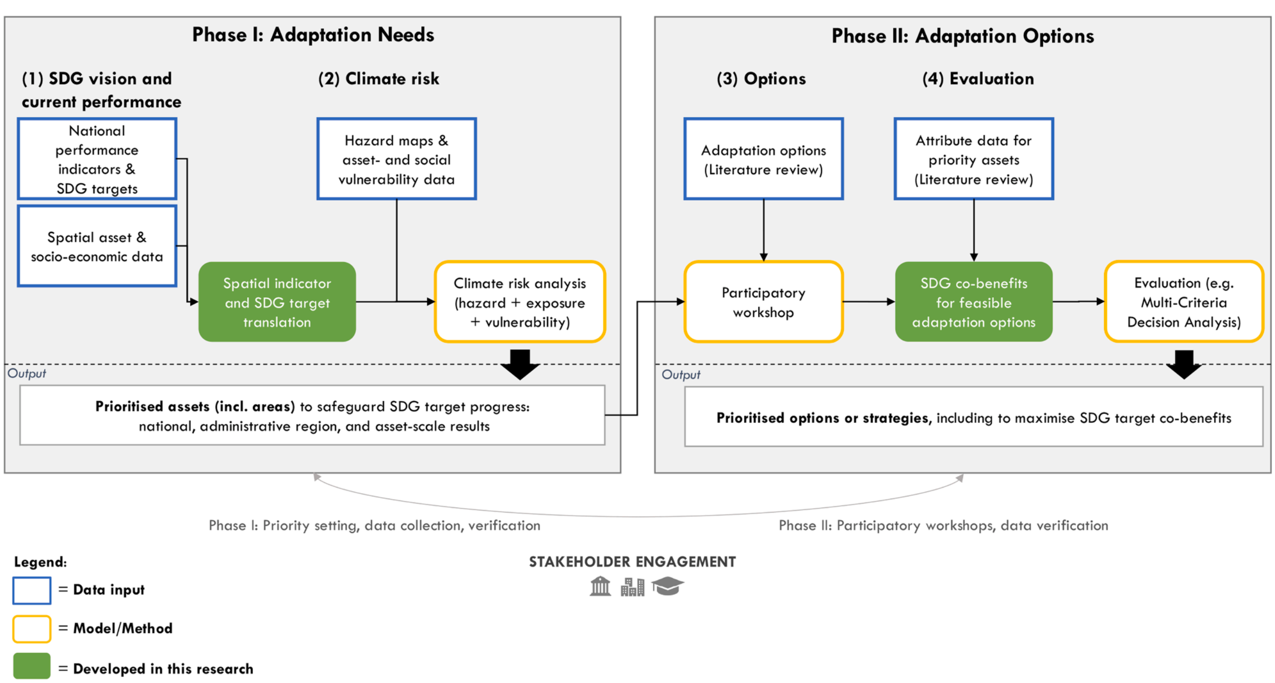

Fig. 2. Integrating SDG targets in national adaptation assessments.

and sustainable transport systems for all ...” incorporates all three sustainability dimensions of the transport sector; quantifying target progress therefore requires a minimum of three indicators within the transport sector, covering the service provision (how much), the environmental (how environmentally sustainable), and the accessibility (to whom) dimension (Adshead et al., 2019).

Here, we expand the above-described existing performance indicator framework by proposing a means to spatially translate baseline performance at the asset scale. Given this asset scale, our framework expansion focuses only on those performance indicators that can be spatially disaggregated to the asset scale, acknowledging that there are also important non-spatial indicators to measure SDG target achievement. Following Hall et al. (2016), we conceptualise each sector as a collection of physical built or natural assets, where each asset provides a certain quantity and quality of service. Assigning socio-economic data to each asset (e.g. the amount of renewable energy generated by each asset), we are able to ascertain its contribution to national current baseline performance, denoted by a_s. For assets that serve a specific population, we propose deriving their contribution to national baseline performance by assigning spatially distributed populations to assets (see Thacker et al., 2017a; Thacker et al., 2017c for details of such techniques). The sum of the contribution of each asset to national baseline performance for a given indicator therefore provides a spatial means to estimate the indicator score I_s for every sector/sustainability dimension s according to Eq. 1:

$$I_s = \frac{B_s}{O_s}, \quad s = 1, \dots, N \tag{1}$$

where

$$B_s = \sum_{n=1}^{A_s} a_{s,n}$$

The subscript s denotes one of the N combinations of sector/sustainability dimensions, B_s is the current national baseline performance for this sector/sustainability dimension s, O_s refers to the desired ‘optimal’ performance for a given national context, and $a_{s,n}$ is the contribution of each of the A_s assets for a given sector/sustainability dimension s to the national baseline performance.

The SDG target score, which represents SDG target progress to date, can be measured using a subset of one or more performance indicators across sector/sustainability dimensions. Thereby, each performance indicator is assigned a weight according to the importance of the indicator to SDG target achievement. For each of the M SDG targets, this yields the weight vector $\mathbf{w}_t$ as shown in Eq. 2:

$$\mathbf{w}_t = [w_{t,s=1}, w_{t,s=2}, \dots, w_{t,s=N}], \quad t = 1, \dots, M \tag{2}$$

where

$$\sum_{s=1}^{N} w_{t,s} = 1$$

$w_{t,s}$ is the weight attributed to the indicator I_s for the SDG target t, and M is the total number of SDG targets considered.

Approaches for indicator weighting include, amongst others, equal weighting (Adshead et al., 2019; Schmidt-Traub et al., 2017), prioritisation based on potential for catastrophic loss or policy gap (Allen et al., 2019) or a weighting based on the perceived importance of the indicator in the national context. Using a weighting considered appropriate in a given national context, the SDG target score Z_t can subsequently be calculated following Eq. 3:

$$Z_t = \sum_{s=1}^{N} w_{t,s} I_s, \quad t = 1, \dots, M \tag{3}$$

for each SDG target t, which gives an estimate of SDG target progress to date.

Our above-presented spatial estimation of a nation’s current performance towards an SDG target vision allows integration with spatial climate risk analysis, which in turn enables us to quantify adaptation needs in the context of the SDG targets.

2.1.2. Step (2) Climate risk

Climate risk analysis is a useful tool to help decision-makers identify and evaluate adaptation needs based on an understanding where and how hazard, exposure, and vulnerability intersect (IPCC, 2014; IPCC, 2019). Different current and future scenarios of climate-change hazards are here defined using indicative hazard maps h of a given return period and magnitude, including variables such as flow volumes, flood depth, and/or duration (see Thacker et al. (2017a) and Pant et al. (2016) for detailed descriptions of climate risk analysis). These various scenarios of hazard maps are overlaid with sectoral asset data to provide a first-order estimate of which assets are potentially exposed to a certain hazard scenario, denoted as $ae_{s,h}$.

Asset vulnerability is integrated in the hazard exposure calculation using a sensitivity parameter $r_{a,s,h}$, which represents the sensitivity of the asset and the services it provides to the hazard scenario h with a given return period/magnitude, dependent on fragility variables such as the depth of inundation an asset can withstand before it ceases to function (Cairns et al., 2013). This sensitivity parameter can take a value between 1 and 0, where 1 refers to the asset and the services it provides ceasing to function under hazard h; and 0 refers to the asset and the services it provides fully functioning under hazard h. Therefore, it is possible that an asset is located in a hazard-exposed area without compromising SDG target progress due to the existing resilience of the asset and the services it provides.

By summing across the contribution of all exposed assets for a certain sector/sustainability dimensions, we derive national baseline performance exposed, denoted by $BE_{s,h}$. The resulting national performance indicator exposure score for a given sector/sustainability dimension is denoted by Eq. 4:

$$IE_{s,h} = \frac{BE_{s,h}}{O_s} \tag{4}$$

where

$$BE_{s,h} = \sum_{n=1}^{N_{ae,s,h}} ae_{s,h,n}$$

and

$$ae_{s,h,n} = a_s \, ^{*} r_{a,s,h}$$

The resulting performance indicator exposure score provides an initial, static assessment of the performance indicator score exposed to a certain hazard scenario, based on a nation’s current assets. An assessment of various different future hazard scenarios and future asset developments can help identify how future hazard intensity and future asset development interact to affect future exposure of the indicator score.

Depending on country priorities, the individual performance indicator exposure scores can be compared among one another or aggregated under their respective SDG targets to estimate SDG target exposure score $ZE_{t,h}$ for each SDG target t and each hazard scenario h, using the weighting described under step 2.1.1 (Eq. 5):

$$ZE_{t,h} = \sum_{s=1}^{N} w_{t,s} IE_{s,h} \quad t = 1, \dots, M \tag{5}$$

To provide a more holistic picture of climate risk, social vulnerability should be considered alongside hazard exposure and asset sensitivity (Koks et al., 2015). Social vulnerability can, amongst other factors, be conceptualised using proxy indicators such as adaptive capacity, which is a combination of a community's socio-economic background, its ability to cope with hazards, accessibility to essential services, and a community's broader institutional and governance factors (see Cutter et al., 2003; Cutter et al., 2013; Denton et al., 2015; Lemos et al., 2013). Given the focus on communities in such definitions, proxy indicators for social vulnerability are typically summarised at the level of a nation's administrative regions or districts. Therefore, each asset is multiplied with a social vulnerability value based on the social vulnerability proxy of the administrative region/district that asset serves, which allows identifying administrative regions/districts and associated assets that provide the largest contribution to the indicator at-risk score $IR_{s,h}$ and SDG target at-risk score $ZR_{t,h}$ (see Supplementary Appendix A.1 for equations).

In summary, by integrating SDG- and climate risk analysis spatially via SDG-risk indicators, we are able to assess adaptation needs in terms of SDG targets. This adaptation needs assessment allows us to identify where and which administrative regions, districts, or assets play the largest role in safeguarding *national* SDG progress against climate risk. The prioritised assets from this Phase I assessments can be verified and discussed during stakeholder engagement processes, and placed in the context of other adaptation assessments.

2.2. Phase (II) Adaptation options

2.2.1. Step (3) Options

No single adaptation option exist to meet a nation's adaptation needs. A national adaptation plan is therefore typically composed of a set of adaptation options to protect prioritised assets against climate risk. Acknowledging the breadth of potential adaptation options available to decision-makers (Noble et al., 2015; Biagini et al., 2014), here we consider the two main physical types of adaptation options to protect specific assets against climate risk: i) built adaptation options, which include hard-engineered options such as seawalls, and ii) nature-based adaptation options, comprised of options that either protect, sustainably manage, or restore nature (Cohen-Shacham et al., 2016).

We propose conducting an initial literature and document review to determine potential built and nature-based adaptation options that might be implemented to protect Phase I prioritised assets in a given country. Multi-stakeholder partnerships that involve representatives across the public and private sector, academia and vulnerable populations can, amongst other benefits, help scope out further potential adaptation options and verify the feasibility of different adaptation options in relation to a set of prioritised assets (Singh et al., 2020; Williams et al., 2021). This initial step results in a list of adaptation options that could be feasibly implemented in a given country.

2.2.2. Step (4) Evaluation

Not every adaptation options is sustainable (Schipper, 2020; Eriksen et al., 2021; Eriksen et al., 2011). Adaptation options can have unintended consequences and/or result in maladaptive outcomes (Barnett and O'Neill, 2010). With the aim of maximising the SDG target co-benefits of built and nature-based adaptation options, we propose a method to explore the number of potential direct and indirect influences of adaptation options on SDG targets, based on previously published service-SDG influences introduced in Section 2.2.1. Whilst we do not aim to assess the magnitude of SDG target co-benefits, a systematic understanding of the number of all potential SDG influences of adaptation options before these are implemented can be used by decision-makers as a guide to realise these *potential* influences in practice whilst reducing the maladaptive development outcomes of adaptation (Eriksen et al., 2021; Barnett and O'Neill, 2010).

Previous work has identified how sectors of the built environment provide manufacturing, infrastructure, and social services that influence the SDG targets, whilst the natural environment provides a range of provisioning (e.g. food, water), supporting (e.g. habitat provision), cultural (e.g. heritage), and - importantly - regulating (e.g. climate adaptation) services that can be linked to each of the SDG targets (Fuldauer et al., 2022). We apply these service-SDG influences in novel ways to estimate the number of potential direct and indirect SDG target co-benefits of each adaptation option, based on the adaptation, construction, or ecosystem services it entails (see Supplementary Appendix A.2 for a detailed step-by-step overview of the proposed co-benefits method and Supplementary Information Excel Table 1 for the evidence of relevant direct and indirect SDG influences).

The resulting SDG target co-benefits can be ascertained for each option individually or for sets of options in combined 'strategies'. In prior studies of national infrastructure planning across sectors, strategies have been formulated to explore and evaluate different policy alternatives, and have therefore been organised by broader categories with different directions of policy (Hall et al., 2016; Otto et al., 2016) or different national visions (Adshead et al., 2019; Fuldauer et al., 2019). Here, we apply the formulation of strategies to national adaptation assessments, differentiating by built or nature-based strategies or alternative combinations of portfolios of adaptation options.

The use of simulation models and Multi Criteria Decision Analysis (MCDA) as established in previous studies provides a useful means to assess various combinations of options to their performance across a set of metrics such as cost, carbon, implementation time, etc. (Hickford et al., 2015; Singh et al., 2020). Our proposed SDG target co-benefit metric – the total number of SDG targets that can potentially be influenced directly or indirectly by an adaptation strategy – can complement such evaluations.

3. Application

3.1. Research design and test case

We apply our proposed methodological process with its four steps to a recent adaptation assessment in Ghana (Adshead et al., 2022). Ghana was chosen as a case study for a number of reasons. Firstly, Ghana has been considered a nation highly vulnerable to climate change, affected by re-occurring floods that threaten livelihoods (Mcsweeney et al., 2010). With its population expected to almost double by 2050, the country also faces sustainable development challenges, including how service provision can be ensured for future populations in an equitable and environmentally sustainable manner (Abubakari et al., 2018; NDPC, 2019). Secondly, given Ghana's relatively large open-access data repertoire - especially compared to other Sub-Saharan countries - it was possible to collect the relevant data and engage in the national decision-making process. Thirdly, as a developing country strongly committed to both the SDGs and climate adaptation across sectors (Asante and Amuakwa-Mensah, 2015), Ghana, and more specifically Ghana's Ministry of Environment, Science, Technology and Innovation (MESTI), was particularly interested in implementing adaptation measures that contribute to sustainable development. Before implementation decisions are made, a thorough evaluation of adaptation measures for progress on the global development agendas in line with existing planning documents is required. For example, Ghana is in the process of revising its Nationally Determined Contributions under the Paris Agreement, and has proposed a number of adaptation options across sectors, which however to date are non-spatial and often not prioritised, especially not in relation to sustainable development (Antwi-Agyei et al., 2018; Dovie, 2015; EPA, 2020).

The application of the proposed methodological contributions to Ghana focused on the energy and transport infrastructure sectors, with a view that these sectors have received comparatively little attention for adaptation, as most Ghana-based studies to date relate to agricultural adaptation (Acheampong et al., 2014; Antwi-Agyei et al., 2012; Apuri et al., 2018). Yet, the energy and transport sectors are critical for adaptation, as they are both highly exposed to climate-change hazards and provide essential energy and transport services that underpin development for the most vulnerable populations (Antwi-Agyei, 2020).

The energy and transport sectors have also been identified amongst the seven prioritised sectors in Ghana's NDCs and underpin the livelihood of the majority of Ghanaians.

A participatory approach to data collection and analysis was adopted, which is essential for improving adaptation practice in developing countries (Conway and Mustelin, 2014) and which has been successfully applied to national infrastructure planning (Fuldauer et al., 2019; Adshead et al., 2021). Key stakeholders and experts were consulted throughout a one-year research period, which were chosen through snowballing methods based on initial contact via MESTI, as described in Adshead et al. (2022). Stakeholder engagement was conducted with a total of 130 individuals across over 20 ministries and institutions, including: MESTI; Ministry of Transport; Ministry of Finance; Ministry of Spatial Planning, Ministry of Energy, Ministry of Roads and Highways; the National Disaster Management Organisation (NADMO); Ghana Statistical Services; Ghana Meteorological Agency; National Development Planning Commission; the University of Ghana; the Kwame Nkrumah University of Science and Technology; the Land Use and Spatial Planning Authority; the Council for Scientific and Industrial Research (CSIR); the Centre for Remote Sensing and Geographic Information Services (CERSGIS), etc. Of these 20 ministries and institutions, 11 agreed to be part of a formal 'Technical Working Group' (TWG). Three main virtual events were conducted with the TWG in February 2021, June 2021 and August 2021 with the purpose of collecting data as well as verifying data and results. The specific data collected and methods used in the Ghana application of the proposed methodological process for Phase I and II are described in the following paragraphs.

3.2. Phase (I) Adaptation needs

Chosen based on a literature search and stakeholder input, the following key national development documents were reviewed in order to identify national performance indicators and desired performance values under step (1): the Ghana Infrastructure Plan (2018), the National Energy Policy (2010), National Water Policy (2007), and National Transport Policy (2008) as well as the Ghana SDG plan (2016). A total of 18 national performance indicators with respective desired performance values for Ghana were identified, which were reduced to three performance indicators for which high-resolution geospatial data was available at the national scale. These three performance indicators focus on the service provision and environmental dimension of sustainability, and were assigned to a total of 10 SDG targets (see Supplementary Table A.2). In line with Ghana's national development planning documents, the target year was set to 2047 as opposed to the global SDG target year of 2030. This choice did not influence the results (see Discussion).

The scope of asset and related socio-economic data utilised in this assessment included all currently existing assets for the specified sectors in Ghana, as well as assets which are due to be completed by the end of 2021 (see Supplementary Table A.3). Data confidence with each of these data values was encoded into an accompanying adaptation assessment database, which also details the methods used to assign baseline performance values spatially (see Supplementary Information Excel Table 2).

In the estimation of the performance indicator and SDG target score, only those SDG targets that can be influenced by the energy and transport sector were considered (see Supplementary Table A.3). Thereby, we assumed that progress of other performance indicators across sector/sustainability dimensions for which data was not available does not skew the prioritisation of assets. Having calculated national performance indicator and SDG target scores according to the equations as described in sub-Section 2.1.1, a composite SDG score C, alongside a composite SDG score exposed CE_h and a composite SDG score at-risk CR_h was estimated using an equal weighting across indicators, across the targets within each goal, and across all considered goals. Calculations were repeated at the level of Ghana's 16 administrative regions and 216 districts.

Applying step (2) of the proposed methodological process to Ghana covered two climate-change hazards, namely flooding and landslides, which have been identified to become more intense or frequent with future climate change (Winsemius et al., 2016; EPA, 2020). Accounting for the growing recognition that hazards are often connected (Raymond et al., 2020; Zscheischler et al., 2018), a multi-hazard was added that combines the spatial footprint across the two considered hazards. To represent the spatial extent of these hazards, we used existing flood and landslides maps provided by NADMO (2015), which have been used for informing national adaptation assessments in Ghana (EPA, 2020). The flood maps gave areas identified as having low, medium, and high hazard likelihood under a current timeline (2010) based on historic data and a future timeline (2050) based on a regional climate projections under the A1B scenario. For landslides, the maps cover low, medium, and high hazard susceptibility for a current timeline only (2010). For consistency purposes and given the analysis presented herein focuses on current assets, we present results for the current timeline (2010) and the high hazard scenario.

The hazard maps were superimposed on assets and their associated contributions to baseline performance across the different sectors as shown in Fig. 3. Due to limited data on asset vulnerability, we assumed that without adaptation, hazard exposure exceeds existing asset design standards. Therefore, the sensitivity parameter $r_{h,a}$ was assumed to take a binary value 0,1.

The social vulnerability of Ghana's population was assessed using the inverse of the proxy indicator 'adaptive capacity', which was available at the scale of the 216 districts in Ghana within Ghana's Forth National Communication to the UNFCCC (see EPA, 2020 188). The adaptive capacity indicator is a score that refers to the adaptive capacity of people within each of Ghana's districts, quantified using the following

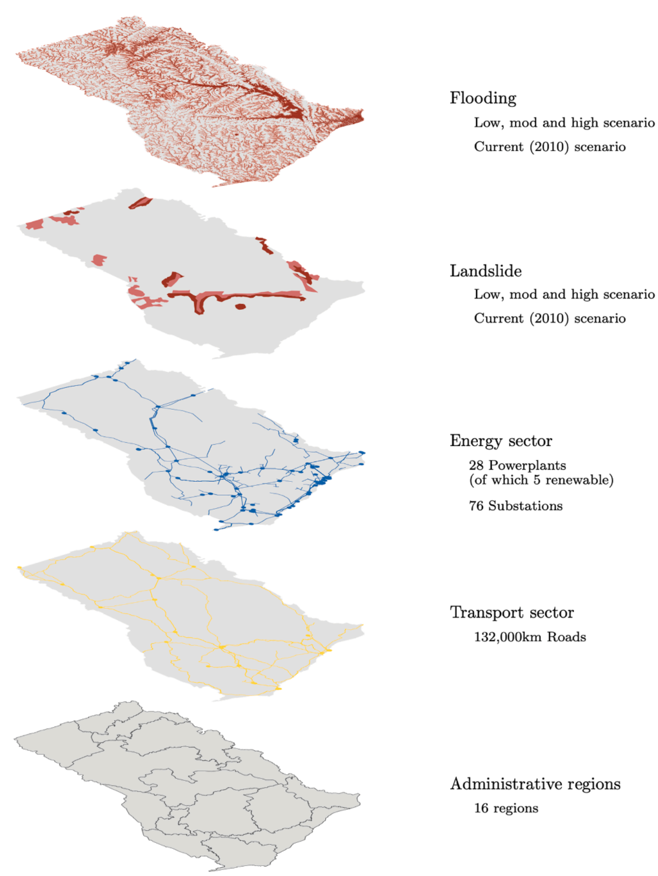

Fig. 3. Superimposing the spatial footprint of climate-change hazards on spatial data across different sectors in order to derive results at the national, regional, and asset-scale.

seven parameters: i) economic activity, ii) education, iii) sanitation, iv) rural water availability, v) health, vi) security and effectiveness, and vii) poverty. Thereby it uses the following spatial data layers as described by the EPA (2020, p. 188): agricultural employment, district capacity, night light distribution, percentage in poverty, poverty depth, severity, Gini index. Ghana's EPA-created social vulnerability index was integrated in our calculation of the performance indicator and composite SDG indicator score at risk, by assigning it to the respective energy or transport assets using the voronoi method or based on location (see Supplementary Table A.3 and Supplementary Information Excel Table 2 for details).

3.3. Phase (II) Adaptation options

In order to derive proposed and suggested adaptation options under step (3) of the proposed methodological process, an extensive desk-based review of key documents on climate change in Ghana was conducted, including Ghana's intended Nationally Determined Contributions (Dovie, 2015), the National Climate Change Policy (2013), NAP Framework (2018), the National Climate Change Adaptation Strategy (2012), National Climate Change Master Plan (MESTI, 2015), Ghana's Adaptation Strategy (Antwi-Agyei, 2020), and Ghana's Third and Forth National Communications to the UNFCCC (EPA, 2015; EPA, 2020). Relevant academic studies and project reports were also reviewed to identify potentially applicable adaptation options. Amongst others, these included an adaptation database (European Environment Agency, 2021; University of Oxford, 2020), and several review papers on adaptation options (Chausson et al., 2020; Malhi et al., 2020; Hanson et al., 2020; Williams et al., 2021). A participatory workshop with 32 TWG stakeholders across 9 different ministries, institutions and academia was organised to identify the feasibility of the proposed adaptation options as well as to suggest alternative adaptation options. This workshop resulted in the identification of a total of 10 economically, technically, and politically feasible adaptation options to protect Ghana's prioritised Phase I assets against floods and landslides (Supplementary Table A.4). These options were grouped into three strategies: 1) a built strategy, focusing solely on built adaptation options for the Phase I prioritised assets, 2) a nature-based strategy, focusing solely on applicable nature-based adaptation options for the Phase I prioritised assets, and 3) a combined SDG-based strategy, which combines built and nature-based adaptation options for the Phase I prioritised assets to meet the identified adaptation needs across sectors and across hazards (Table 1).

Using the set of 12 feasible adaptation options for the considered sectors, the SDG co-benefit analysis method under step (4) of the proposed methodological process was applied. Land-use data obtained from engagement with Ghana's Land Use and Spatial Planning Authority was utilised to link the identified nature-based adaptation options to specific natural environment types, which allowed identification of SDG target co-benefits from nature-based adaptation options (see Supplementary Information Excel Table 3).

Table 1
Overview of adaptation strategies which include combinations of adaptation options for prioritised assets (see Supplementary Information Excel Table 3 for application of co-benefits method to proposed adaptation options and links to specific prioritised assets).

Strategy	Hazard	Options	Sector
Built	Flood	Elevation of assets	All
	Flood	Re-enforcing road structure	Road transport
	Flood	Construct temporary barrier	All
	Landslides	Built slope stabilisation (anchors/bolts)	Energy: distribution
Nature-based	Flood	Catchment-level water management	All
	Flood	Protection of riparian vegetation	Road transport, Energy: generation
	Flood	Urban green areas and trees	Road transport, Energy: distribution
	Landslides	Natural slope stabilisation	Energy: distribution
Combined SDG	Flood	Sponge city, catchment-level measures, urban drainage	All
	Flood	Construct temporary barriers	All
	Flood	Urban green areas and trees	Road transport, energy: distribution
	Flood	Protection of riparian vegetation	All
	Landslides	Natural and built slope stabilisation	Energy: distribution

4. Results: application of the methodology

The next sections summarise the results of applying our proposed methodological contributions to the energy and transport sector in Ghana. In our presentation of Phase I results, we use three spatial scales: national, administrative region, and asset (including districts for the transport sector). In our presentation of Phase II results on the evaluation of SDG target co-benefits, our aim is to showcase the range of potential SDG co-benefits across adaptation strategies. This provides an important starting point for decision-makers to be able to maximise these potential SDG co-benefits in practice rather than a final score.

4.1. Phase (I) Adaptation needs

4.1.1. National-scale results

At the national-scale, our evaluation across the three considered performance indicators shows that Ghana's indicator score I_s and the exposed indicator score under the multi-hazard $IE_{s,h}$ is highest for 'Electricity access' (Fig. 4). Currently, 85% of Ghana's population has access to electricity, with a desired optimal performance value set by the government of reaching 100% by 2047. Applying Eq. 1, we find that of these 85%, 30% are exposed to the multi-hazard, resulting in an indicator exposure score of 26%, which refers to the percentage exposure in relation to the desired performance.

In contrast, only 19% of the desired percentage of renewables in Ghana's energy generation mix is currently achieved. However, almost 90% of this baseline performance to date is exposed to the multi-hazard of floods and landslides. Despite the large exposure of existing renewable energy generation assets, the resulting 'Renewables' indicator exposure score is - with an indicator exposure score of 17% (Fig. 4) - relatively small compared to the 'Electricity access' exposure score. This finding can be attributed to the overall lower progress towards renewables in Ghana's energy generation mix to date as compared to progress towards electricity access.

For the road sector, we find that the indicator score for 'Road length' currently lies at 52%. Approximately 19% of this current score is exposed to the multi-hazard, resulting in an indicator exposure score of 10% (Fig. 4), the lowest as compared to the other two indicator scores.

Next, we examine how progress and exposure of these national indicator scores may translate into SDG target progress to date (SDG target score Z_t) and SDG target progress exposure (SDG target exposure score $ZE_{t,h}$) (Fig. 5). Given that progress on SDG target 7.1. is measured solely by the indicator on 'Electricity access', we find that 26% of progress for target 7.1 is exposed to the multi-hazard, the largest across all individual SDG targets. The exposure scores for SDG targets 7.2, 7.b, 9.4, 9.a, and 11.6, which are solely assessed in terms of the indicator 'Renewables', lie at 17%, whilst the exposure score for SDG target 11.2 and 11.a is calculated at 10% based on the directly assigned 'Road length' indicator. For those SDG targets measured by more than one performance indicator (SDG target 9.1 and 11.1), the SDG target exposure scores reach 16% and 16.5%, respectively, similar to most other SDG targets. Across all affected SDG targets, we find that the composite SDG score C, which denotes average progress towards the infrastructure-affected targets, is 40%. This composite SDG score across the sector-specific targets is exposed by 17%, implying that failure to adapt the energy and transport sector to a multi-hazard has the potential to set back Ghana's progress

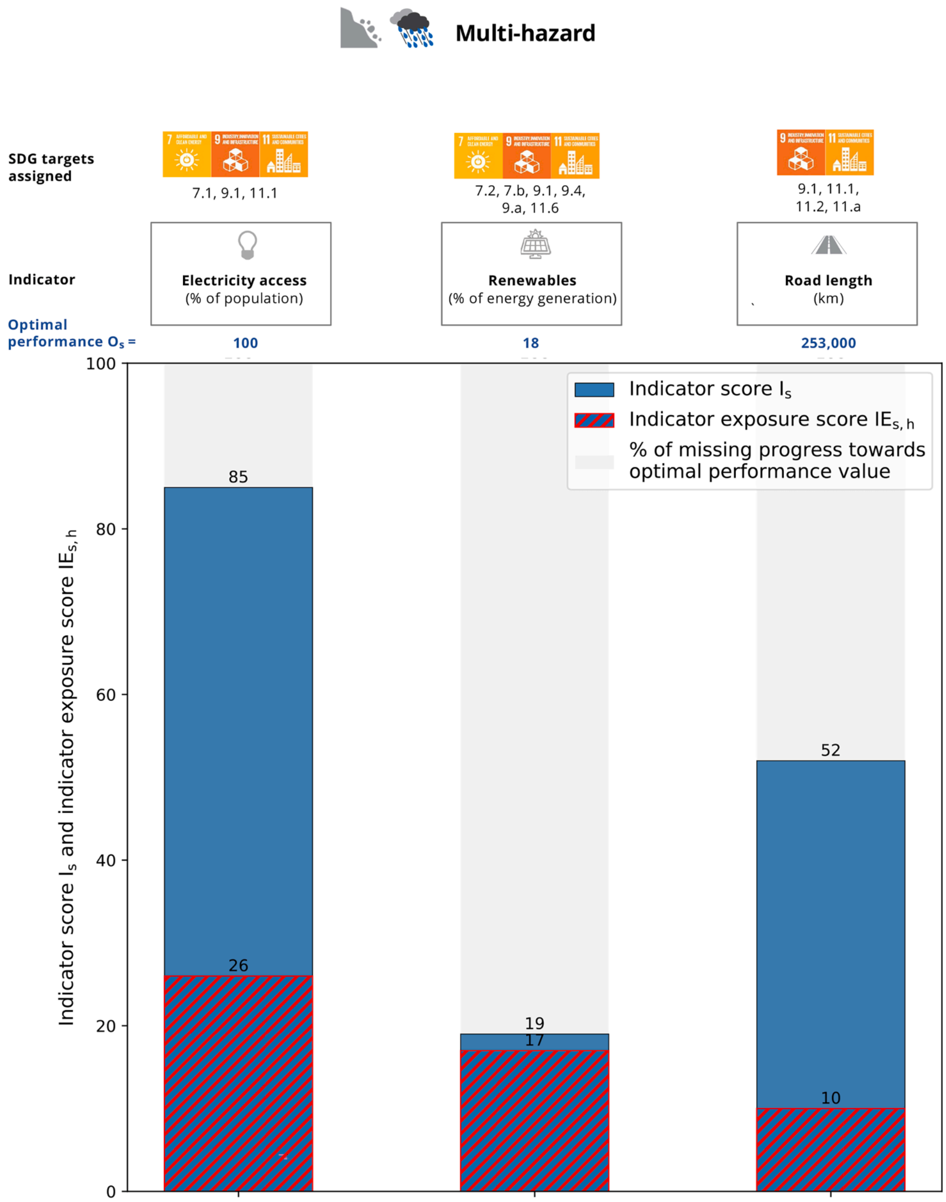

Fig. 4. National performance indicator scores and national performance indicator scores exposed to multi-hazard. Icons image courtesy of United Nations.

on sustainable development with regard to energy and transport.

4.1.2. *Regional and asset-level results*

Calculating performance indicator and composite SDG at-risk scores requires integrating the exposure results with Ghana's social vulnerability data, which differs by administrative region. Therefore, we compare the contribution of each administrative region to: a) the three performance indicator scores and the composite SDG score, b) their respective exposure scores, and c) their respective at-risk scores (Fig. 6).

First, in comparing the contribution of each of Ghana's 16 administrative regions towards the various indicator scores I_s, we find that the Ashanti region in Ghana's mid-west plays the largest contribution to a single performance indicator 'Electricity access'. Taken together in a composite SDG score, we find that no one particular region plays a particularly large contribution to the composite SDG score, with Ashanti and North Eastern Region playing a larger contribution compared to the other regions (Fig. 6a). This picture drastically changes when identifying *exposure* of the respective indicator scores. We identify the Greater Accra region to play the largest role in the contribution to the 'Electricity access' exposure score, the North East region to play the largest role in the contribution to the 'Renewable' exposure score, and the south of Ghana to play the most important role in the contribution to the 'Road length' exposure score – though this latter contribution is less obvious compared to the other indicators. For the composite SDG exposure score, we identify the North Eastern Region as well as Brong Ahafo and the Greater Accra Region to show the largest contributions (Fig. 6b). When also considering the social vulnerability component of climate risk (Fig. 6c), the adaptation needs in the North Eastern Region as compared to the Brong Ahafo and Greater Accra region are more pronounced, in other words, these regions show the largest adaptation need to safeguard existing SDG progress at-risk from the multi-hazard.

Whilst the administrative region analysis provides important insight into *where* adaptation needs across sectors are largest, it is also critical for decision-makers to identify which specific assets contribute most to adaptation needs in terms of safeguarding sustainable development progress. Therefore, we rank assets based on both the largest contribution to indicator exposure score and the social vulnerability of the population served by the asset. Fig. 7a-c shows the specific assets which play the largest role in safeguarding indicator progress at-risk, while Fig. 7d shows those with largest contribution to composite SDG progress

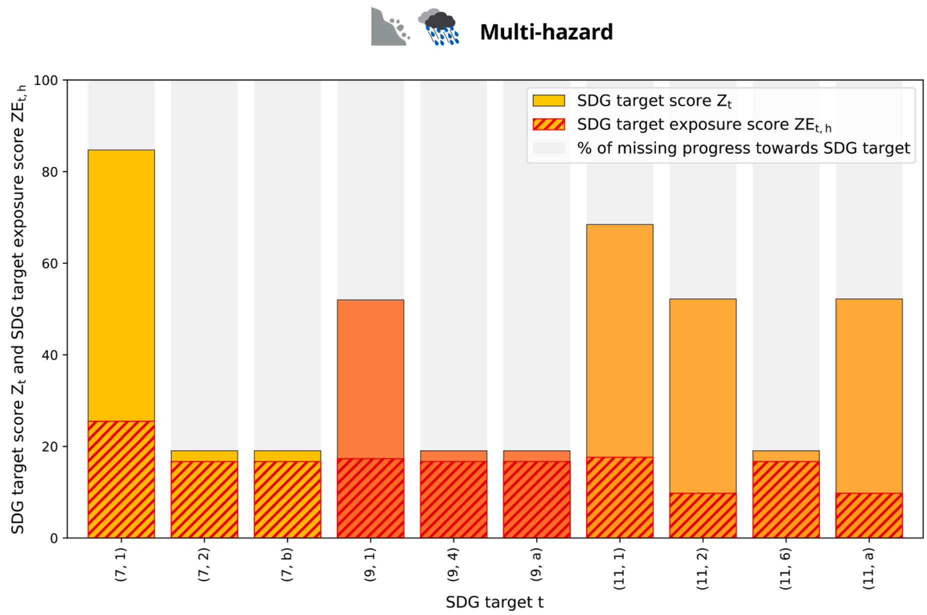

Fig. 5. SDG target score, and SDG target score exposed to multi-hazard.

at-risk: the Pwalugu hydro, Bui PV and Pwalugu solar plant, as well as a set of specific electricity substations. Based on stakeholder feedback in a participatory workshop, the resulting prioritised assets were slightly adjusted to represent assets across all three sectors, including the road sector (see Supplementary Information Excel Table 3 for prioritised assets).

4.2. Phase (II) Adaptation options

The relative performance of the built– versus nature-based strategy differs in relation to the total count of SDG co-benefits (see Fig. 8). Whilst the built strategy can provide SDG co-benefits across a total of 62 of 169 SDG targets, these benefits increase to 102 SDG target co-benefits under a nature-based strategy. The additional 65% of SDG target influences by the nature-based strategy can be attributed to the multi-functionality of using nature as an adaptation service. Using nature-based options such as conserving Ghana's riparian wetland and grassland vegetation, scaling up green urban areas, or creating natural slope stabilisation through afforestation can – apart from their adaptation services – also yield an increase in the other services nature provides. These services include cultural services through the conservation of cultural and educational practices around riparian wetlands and grasslands, regulating services such as carbon sequestration or pollination, supporting services such as maintenance of genetic diversity or provisioning services such as freshwater, medicinal resources, food or raw materials. It is not surprising therefore that compared to the built strategy, the nature-based strategy provides co-benefits across more than double as many targets under SDG2 ('zero hunger'), SDG4 ('education'), SDG5 ('gender'), SDG7 ('energy'), SDG14 ('life below water'), and SDG15 ('life on land') (see Fig. 8a versus Fig. 8b).

The combined SDG strategy outperforms both individual strategies: we find that implementation of the combined strategy across built and nature-based options can have co-benefits across 116 of 169 SDG targets. This larger overall SDG co-benefit result is achieved by maximising the unique (i.e. mutually-exclusive) co-benefits of the built as well as the nature-based option. Notably, the unique co-benefits of the built strategy can be attributed to the improved waste- and wastewater-management benefits of implementing urban drainage, a critical component of the drainage option for the capital Accra. Further, if protective barriers and slope stabilising anchors and bolts are manufactured and constructed within Ghana – rather than imported – this adaptation option unlocks further co-benefits from the use of domestic manufacturing and construction services. Thereby, we find that combining feasible adaptation options from the built and natural environment can maximise SDG target co-benefits.

5. Discussion

Whilst past research has advanced the field of sustainable adaptation (Fuso Nerini et al., 2019; Fuldauer et al., 2022; Fuldauer et al., 2021; Gómez Martín et al., 2020), to date, no paper has demonstrated a methodological process to quantitatively embed an SDG vision at the outset of adaptation needs assessments (Phase I) or to evaluate the full range of SDG target co-benefits of implementing alternative adaptation strategies (Phase II). Such information is however critical for decision-makers to evaluate and maximise the full SDG benefits of adaptation in their national context. The methodological contributions developed in this paper aim to address this gap.

5.1. Implications for adaptation in Ghana

While the application of our proposed methodological process to Ghana inevitably lacked perfect information, this application nevertheless provides important first insights for national decision-makers to integrate SDG targets in national adaptation assessments, focused on the biophysical dimensions of adaptation needs and options.

Whilst research on the development of adaptation strategies under Ghana's commitment to the Paris Agreement has recently been conducted (Antwi-Agyei, 2020; Dovie, 2015), this has not yet employed a systematic means to prioritise specific assets for adaptation of infrastructure sectors and has not been targeted to safeguard Ghana's hard-earned development progress. Application of our proposed methodology that integrates SDG-aligned national performance values in adaptation assessments enables national decision-makers to identify and prioritise administrative regions or assets for adaptation which are future-proof, i.e. they make a large contribution to Ghana's SDG progress. Especially with respect to access to essential services such as energy and transport, we identify the poorest districts in Greater Accra as being in high need for adaptation, which points to the importance of policy to support infrastructure adaptation in these areas. Whilst service provision in these areas has improved over the past decades, this development progress is at risk of flooding impacts. Our finding aligns with previous

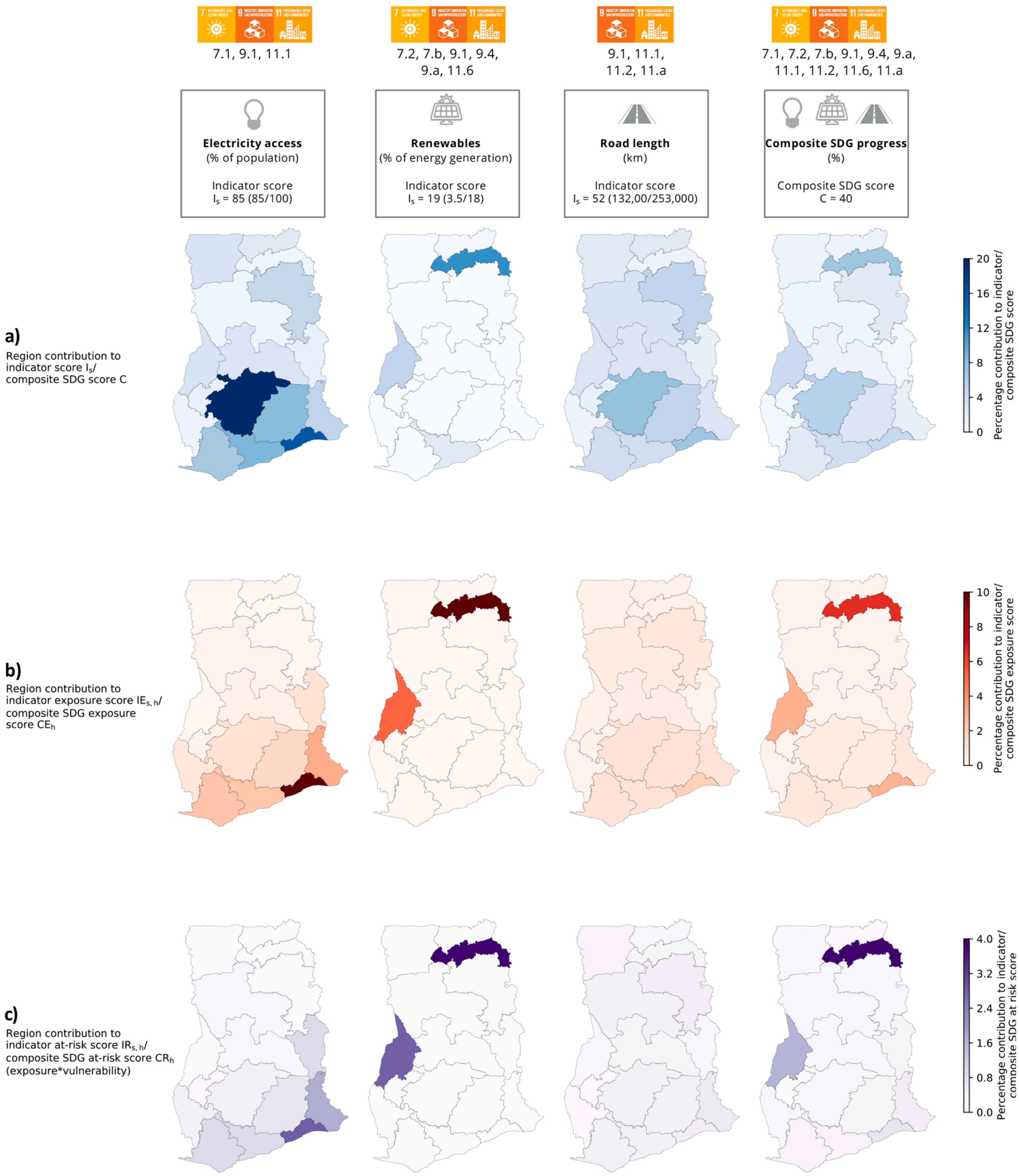

Fig. 6. Spatial translation of adaptation needs in the context of three national performance indicators and a composite SDG score, with the contribution of administrative regions to a) indicator and composite SDG score, (b) indicator and composite SDG exposure score, (c) indicator and composite SDG at-risk score. Icons image courtesy of United Nations.

studies on the importance of policies that help build adaptive capacity in urban slums in Accra (Owusu and Nursey-Bray, 2019). It also underscores the importance of conducting additional on-the-ground adaptation planning to assist low adaptive capacity communities in preparing for the impacts of climate-change hazards, which should not only include a detailed evaluation of built asset protection and nature-based adaptation options, but also broader enabling environment and social options that help build adaptive capacity (Lawson et al., 2019).

Research in Ghana has recently identified adaptation options to broadly prepare the nation's sectors to climate-change hazards (Dovie, 2015; Hellmuth et al., 2017; Antwi-Agyei, 2020). Yet, to date, these are formulated in broad terms such as 'Scale up natural resource management' to 'climate-vulnerable infrastructure', limiting their potential to be utilised in specific adaptation funding proposals or as a first step in adaptation implementation. By assigning feasible adaptation options to prioritised assets, the results from our research help add specificity to the broadly formulated options represented in Ghana's national documents. Our findings provide decision-makers with spatially-explicit information on adaptation prioritisation, for example to focus on the 'Protection of riparian vegetation' on the climate-vulnerable renewables: Solar Pwalagu and Hydro Pwalagu. Thereby, our results can help specify assets and options under the broadly proposed adaptation priorities, including under Ghana's Adaptation Strategy and Action Plan for the Infrastructure Sector (Antwi-Agyei, 2020).

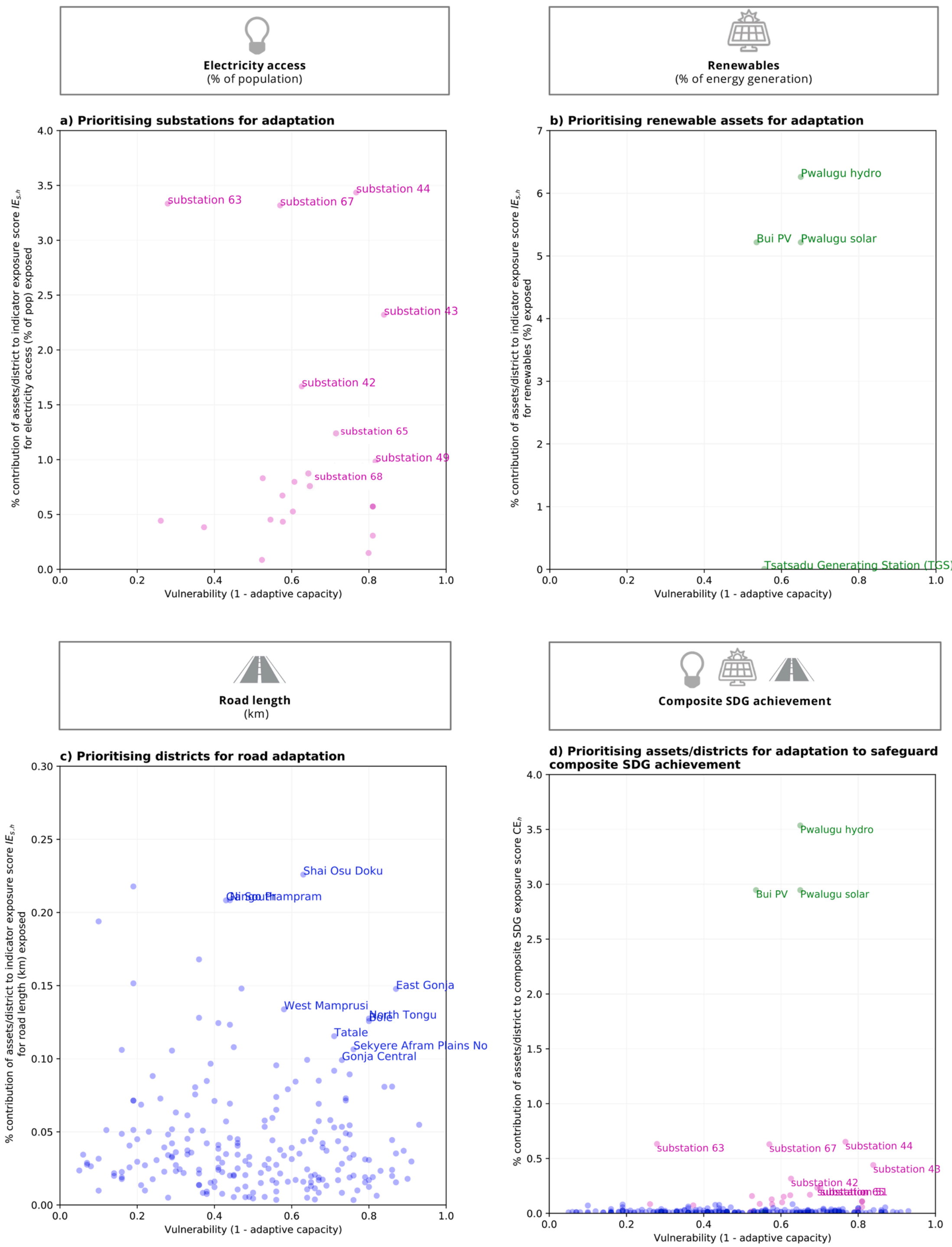

Fig. 7. Prioritising assets to safeguard largest progress on the indicator and composite SDG target scores against climate risk, where (a)-(c) show asset contributions to indicator at-risk scores $IR_{t,s}$ and (d) shows asset contributions to composite SDG at-risk score CR_t (d). Axis scaled for visualisation purposes.

Furthermore, our results provide depolicised evidence to help develop Ghana's National Adaptation Plan (NAP) that is aligned with SDGs, thereby helping to overcome limitations of NAP to date that have been critiqued for their lack of specificity and alignment with sustainable development (Hardee and Mutunga, 2009; Termeer et al., 2012).

Previous studies on sustainable adaptation (Eriksen et al., 2021; Schipper, 2020; Antwi-Agyei et al., 2018) have not yet enabled decision-makers to evaluate the full range of SDG target co-benefits of different adaptation options. Such information however is important to be able to maximise synergies of national adaptation plans with the SDG targets, a broadly unmet requirement for national adaptation planning under the Paris Agreement to date (Fuldauer et al., 2022). Our result on the range of potential SDG target co-benefits of different adaptation strategies in Ghana provides an important first step to illustrate the range of non-quantifiable benefits of adopting nature-based adaptation options, including their potential to protect biodiversity, sequester carbon, and contribute to important cultural practices, amongst others, thereby responding to a literature gap as identified by Seddon et al., 2021 and Seddon et al., 2020. Our results demonstrate that nature-based adaptation options have the potential to contribute to all SDGs. This result

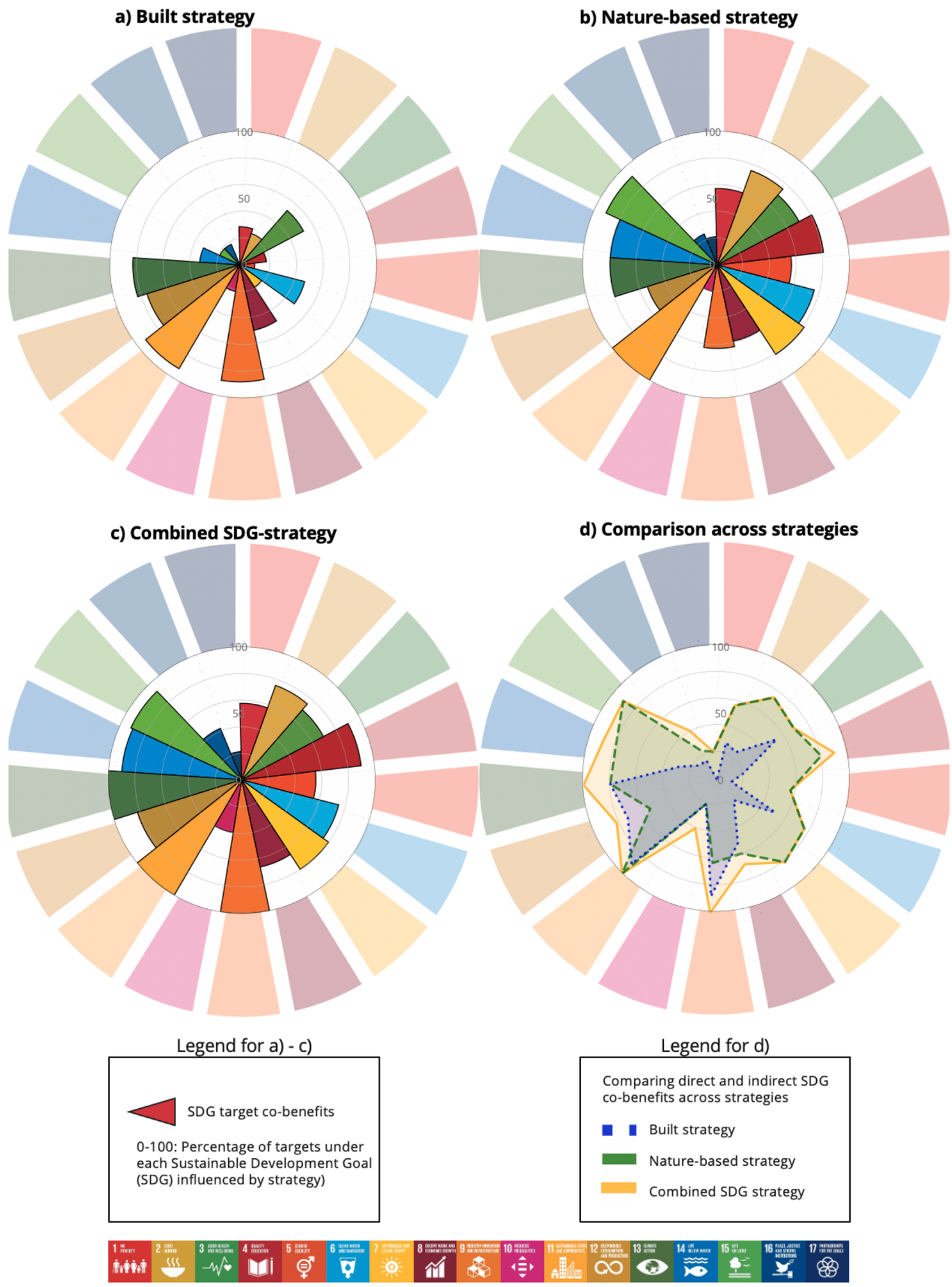

Fig. 8. Evaluating SDG target co-benefits of adaptation strategies across the energy and transport sectors. Icons image courtesy of United Nations.

goes beyond the often-cited direct SDG benefits of nature-based adaptation options in contributing to three main goals: SDG13 ('climate action'), SDG14 ('life below water'), and SDG15 ('life on land') (UNEP, 2022) and complements existing studies on the contribution of ecosystem services and biodiversity to the SDG targets (Wood et al., 2018; Blicharska et al., 2019). By identifying the broad range of all *potential* SDG target influences of adaptation options at the outset of the adaptation planning process, it is possible to more systematically maximise these potential influences whilst minimising the potential maladaptive consequences of adaptation prominent in Ghana (Antwi-Agyei et al., 2018). Thereby, our results go beyond previously existing sustainability categories to evaluate adaptation in Ghana, which typically focused on the following limited number of categories: 'job creation', 'costs', 'implementation time', 'fund availability', 'implementation ensured', which do not capture the range of sustainable development dimensions as described in the 169 SDG targets (Dovie, 2015).

To date, only 25% of tracked global climate finance goes to adaptation (Editorial, 2021). Our finding of the range of SDG target co-benefits that can be realised from the implementation of adaptation strategies provides an additional rationale for investing in adaptation in Ghana and other developing countries. The application of our proposed methodological process demonstrates that adaptation does not only help reduce climate risk, but – if planned and implemented accordingly – can deliver up to 116 SDG target co-benefits. However, our results also suggest that these co-benefits are only achieved if adaptation makes use of local construction and manufacturing services and if nature-based solutions are designed to deliver biodiversity and local adaptation benefits, thereby complementing previous studies (Seddon et al., 2021).

More broadly, establishing an SDG vision at the outset of adaptation planning can help to pave the way towards identifying synergies between adaptation and Ghana's future development investments. Based on the Phase I findings of where and how much administrative regions currently contribute to SDG progress (Fig. 6), it is also possible to identify where proposed future sustainable infrastructure developments may be prioritised within and across sectors to ensure the largest SDG gains. National documents such as the Ghana Infrastructure Plan or Ghana's Adaptation Strategy under the Paris Agreement propose sets of future infrastructure developments to meet desired targets (NDPC, 2019; Antwi-Agyei, 2020). However, it is not yet clear where such infrastructure developments can have the largest contribution to sector-specific indicator progress or cross-sectoral composite SDG progress. Whilst not quantitatively performed in this paper, the methodological process developed here can be used to evaluate adaptation options for their potential to increase baseline performance with regard to desired targets. One example is a recently proposed adaptation option "Expansion of energy infrastructure to reduce pressure on the existing electricity grid in the face of climate change" (Antwi-Agyei, 2020), which not only adds adaptive redundancy to the electricity network, but also increases the quantity of service provision. If such an adaptation option is focused on areas inhabited by populations with no or little access to electricity, it is possible to achieve synergies between risk-reduction and absolute SDG progress, which is critical for ensuring climate-resilient development in Ghana (Antwi-Agyei et al., 2017). Therefore, application of our proposed methodological process can help decision-makers in Ghana target policy and investment efforts to areas where gains from synergistic implementation of risk-reduction and sustainable development measures are highest.

5.2. Theoretical implications

The choice of method to evaluate the benefits of adaptation to climate risk is crucial. To date, most evaluations of adaptation options focus on economic cost-benefit analyses, especially those around infrastructure adaptation in the energy and transport sectors (Thacker et al., 2017b; Pant et al., 2016; Kheradmand et al., 2018). However, the sole use of economic cost-benefit assessments as a method for adaptation evaluation has important shortcomings (Verschuur et al., 2020), including in meeting the increasing calls to link adaptation and sustainable development (Jafino et al., 2021). The benefit value, corresponding to the avoided damage of asset protection, is inherently biased towards more costly infrastructure. As a result, the benefits derived from adaptation are likely also biased towards more costly and larger infrastructure assets, irrespective of the asset's contribution to sustainable development. Our proposed methodological contributions, which use the SDG targets and related indicators as an additional metric to assess adaptation benefits, can help account for the shortcomings of economics-based methods. In light of the global acceptance of the SDG framework, our proposed methodology is transferable to other nations and can be applied across a range of sectors to align national adaptation with the SDG targets, an unmet requirement for adaptation planning under the Paris Agreement to date (Fuldauer et al., 2022).

More broadly, by integrating quantitative performance indicators linked to the SDG targets at the outset of adaptation needs assessments, our proposed methodology responds to calls in the literature to assess adaptation with respect to baseline development trends (Jafino et al., 2021). Our work thereby expands upon an existing SDG indicator framework (Adshead et al., 2019) by spatially translating indicators to the asset scale, which for the first time allows integration with spatial climate risk analysis. This asset-scale enables a new specificity and granularity for informing climate adaptation planning in the context of each SDG target. Notably, the resulting spatial maps from application of our proposed methodological process visualise natural environment assets in the context of climate adaptation, thereby addressing an unmet need for integrating spatial information in adaptation commitments under the Paris Agreement as identified by Khan and Schmidt-Traub (2020).

With respect to the evaluation of different adaptation options to protect a set of assets or areas against climate risk, numerous authors have highlighted the lack of clear objectives to measure and evaluate specific adaptation options (Tompkins et al., 2018; Owen, 2020; Nalau and Verrall, 2021; Seddon et al., 2021). There is no single metric which can capture the aggregate effects of any adaptation option in the complex process related to adaptation. In other words, there is no adaptation equivalent to the CO_2 metric which is widely used to measure the benefits of different mitigation options (Owen, 2020). Our proposed metric of potential SDG target co-benefits provides a useful first step in evaluating adaptation options across a range of sustainable development dimensions. Given the difficulty in quantifying the magnitude of SDG target co-benefits across all development dimensions, our proposed additional metric of an estimated number of SDG target co-benefits should not necessarily be regarded a substitute to other metrics. Rather, it can be an additional metric which is evaluated alongside other metrics such as economic cost-benefit ratio (Thacker et al., 2017b), feasibility criteria (Singh et al., 2020; Williams et al., 2021), implementation time, and others.

5.3. Limitations and further research

We discuss key limitations of our study and outline avenues for future research. First, the application of the proposed methodology in Ghana focused on a limited set of sector/sustainability dimensions and three performance indicators – those for which national-scale geospatial data and desired optimal performance values could be extracted from available datasets and national official documents. The focus on three performance indicators and extrapolation for 10 SDG targets in this Ghana application involves double counting of indicators based on SDG target influences, which affects the final results. Future work should consider additional indicators as well as a broader range of sector/sustainability dimensions. This notably includes considerations of the quality of service, environmental sustainability-, affordability-, and accessibility indicators, amongst others. Such a broader indicator range, ideally across sectors, would provide decision-makers with a more nuanced quantification of the SDG benefits of adaptation.

Furthermore, the available performance values focused on the Ghana-aligned sustainable development agenda, which uses 2047 - rather than the SDG-specific 2030 - timeline as a target year. Therefore, results should be interpreted as Ghana-specific SDG-aligned results, taking into account the timeline differences. A global application of the proposed methodological process may use performance values for the 2030 timeline to better align with the global SDGs.

Second, the composite SDG scores in this paper should be interpreted as guiding metrics. Any composite score suffers from potential biases in the way weights are assigned and aggregated with respect to the importance of different indicators as well as the substitutability of different criteria (Greco et al., 2018). In the absence of Ghana stakeholder-elicited preferences, we used equal weights and a linear aggregation approach, which is based on the arithmetic mean, following the approach adopted by the global SDG Index (Lafortune et al., 2018). One critical limitation of linear aggregation is its compensatory nature such that poorly-performing indicators can be outweighed by strong-performing ones (Greco et al., 2018). In the context of the SDG indicators and targets, the use of such a linear aggregation approach assumes that each component of the resulting composite SDG score is perfectly substitutable and that regress on one indicator can be offset by progress on another (Lafortune et al., 2018). Future assessments could explore different aggregation and weighting approaches to identify how scores might change, including the use of: a) a Leotief production function where the composite SDG target and goal score is determined by the lowest individual indicator scores, b) the use of a geometric mean often used to aggregate heterogeneous variables with limited substitutability, c) participatory expert-elicited weightings to determine weights and aggregations, including on the substitutability and importance of individual indicators in composite SDG performance (we refer readers to Miola and Schiltz, 2019 for a discussion and implication of different weightings and to Booysen, 2002 as well as the OECD and

European Union Joint Research Centre, 2020 for an additional discussions on composite indices). Following Lafortune et al., 2018 and Adshead et al., 2019, we justify the use of: a) equal weights at the goal level by the fact that all SDGs are considered as having equal importance and at the target and indicator level in that all alternatives can be considered less satisfactory, and b) a linear aggregation for its simplicity of interpretation (see Lafortune et al., 2018 for details).

Third, the climate risk application in this paper was based on assumptions that are parameterised using Ghana-based sources, including NADMO-specific hazard maps. Whilst the hazard maps have been verified with inundation experiences in country and have been widely used in national official documents (EPA, 2020), they do not provide inundation depths, duration information, or quantified probabilities. Therefore, it is merely possible to identify exposure and risk in terms of the broad classification of low, medium, or high hazard likelihood (see NADMO, 2015). Additionally, the climate risk application relies on the assumption that asset exposure disrupts service provision, i.e. that asset sensitivity to hazards is high, an assumption that should be parameterised with quantitative values. Thereby, the presented climate risk analysis is limited to a stress-test rather than a probabilistic climate risk assessment. Future work could update the analysis with probabilistic hazard maps (see Ward et al., 2020), sector-specific depth-damage functions and/or fragility curves that can better estimate asset vulnerability (Winsemius et al., 2016; Meyer et al., 2013; Huizinga et al., 2017), as well as further uncertainty and sensitivity assessments around the datasets (see Koks et al., 2019). Moreover, given that the scope of considered hazards largely determines asset prioritisation results, future assessments might include a broader range of hazards, including chronic climate-change hazards alongside acute ones. This could, for example, be achieved by quantifying the impact of gradual reduced river runoff on drinking water provision, which is directly linked to SDG6 ('clean water').

Lastly, our proposed methodological contribution for integrating SDG targets into adaptation assessments focuses on current assets and climate-change hazard scenarios. Yet, adaptation to climate change is highly dynamic. Accounting for future infrastructure development, urbanisation, population growth (see Adshead et al., 2019; Allen et al., 2019; Allen et al., 2021) as well as future hazard scenarios will be critical to complement the proposed methodological contributions towards identifying synergistic adaptation-development strategies towards reducing future climate risk and maximising contributions towards achieving the SDG agenda by 2030.

6. Conclusion

This paper makes a number of methodological and practical contributions to the field of climate adaptation. Methodologically, this paper for the first time proposes a process for grounding national adaptation assessments in an SDG vision, which helps decision-makers develop spatially-explicit adaptation strategies under the Paris Agreement that safeguard existing SDG target progress whilst delivering SDG target co-benefits. Practically, an application of the proposed methodological process to Ghana demonstrates that adoption of a combined built and nature-based adaptation strategy across SDG prioritised assets has the potential to safeguard development progress and contribute to 116 SDG targets across all 17 SDGs. The high spatial resolution of the resulting findings can be used by decision-makers to take important steps towards the action needed to align climate adaptation planning and sustainable development in Ghana.

Collectively, the contributions in this paper provide valuable insights to evaluate climate adaptation in the context of the SDGs and the Paris Agreement. These contributions transcend traditional economic adaptation assessments by placing the global agendas at the heart of the adaptation planning process. As more nations develop and revise their adaptation commitments under the Paris Agreement, iterative application of the proposed methodological process can help spur coordination across adaptation and development planning into the future, thereby bringing together knowledge across national and local government, non-governmental organisations as well as the private sector.

Given the increasing frequency and intensity of hazards with climate change, inaction with respect to adaptation will set back progress on sustainable development. Through a case study in Ghana, this paper quantitatively and qualitatively demonstrates how integrating SDG targets at the outset of national adaptation assessments can help better evaluate sustainable adaptation strategies, thereby ensuring that adaptation contributes to *both* a climate-resilient and a sustainable future.

CRediT authorship contribution statement

Lena I. Fuldauer: Conceptualization, Methodology, Software, Data curation, Formal analysis, Validation, Visualization, Project administration, Writing – original draft, Writing – review & editing. **Daniel Adshead:** Methodology, Project administration, Writing – review & editing. **Scott Thacker:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Sarah Gall:** Data curation, Formal analysis, Writing – review & editing. **Jim W. Hall:** Conceptualization, Funding-acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The transferable python code to conduct the analysis can be requested from the corresponding author upon reasonable request. This research was conducted at the Environmental Change Institute at the University of Oxford and was supported by the UK Engineering and Physical Sciences Research Council by grants EP/R513295/1, EP/N509711/1, and EP/N017064/1 as well as the United Nations Office for Project Services (UNOPS). We thank the UNOPS team, the Ministry for the Environment, Science, Technology and Innovation (MESTI), the Global Centre for Adaptation, and the Technical Working Group in Ghana for facilitating this research as well as all stakeholders consulted for providing valuable insights and useful data. We further wish to thank colleagues at the University of Oxford, in particular Nicholas Chow, Dr. Raghav Pant, and Tom Russel, as well as the reviewers and editors for providing valuable contributions to this project. We acknowledge the image courtesy of the United Nations Sustainable Development Goals: https://www.un.org/sustainabledevelopment. The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

Supplementary data.

Supplementary Appendix and Supplementary Tables as well as the Supplementary Material Excel associated with this article can be found in the online version at https://doi.org/10.1016/j.gloenvcha.2022.102575.

References

Abubakari, M., Asamoah, P.K.B., Agyemang, F.O., 2018. Ghana and Sustainable Development: The 40-Year National Development Plan in Retrospective. J. Human Resource Sustain. Stud. 06, 24–36. https://doi.org/10.4236/jhrss.2018.61024.

Acheampong, E.N., Ozor, N., Owusu, E.S., 2014. Vulnerability assessment of Northern Ghana to climate variability. Clim. Change 126. https://doi.org/10.1007/s10584-014-1195-z.

Adshead, D., García, O.R., Thacker, S., Hall, J.W., 2021. Infrastructure strategies for achieving the global development agendas in small islands. Earth's Future 9. https://doi.org/10.1029/2020EF001699.

Adshead, D., Thacker, S., Fuldauer, L., Hall, J.W., 2019. Delivering on the Sustainable Development Goals through long-term infrastructure planning. Global Environ. Change 59, 101975. https://doi.org/10.1016/j.gloenvcha.2019.101975.

Adshead, et al., 2022. Ghana Resilient Infrastructure Roadmap. Technical Report. University of Oxford, Global Centre on Adaptation and the Ministry of Environment, Science, Technology and Innovation. Accra, Ghana. URL: https://gca.org/wp-content/uploads/2022/03/Ghana_Roadmap-for-Resilient-Infrastructure-in-a-Changing-Climate.pdf.

Allen, C., Metternicht, G., Wiedmann, T., 2019. Prioritising SDG targets: assessing baselines, gaps and interlinkages. Sustain. Sci. 14, 421–438. https://doi.org/10.1007/s11625-018-0596-8.

Allen, C., Metternicht, G., Wiedmann, T., Pedercini, M., 2019. Greater gains for Australia by tackling all SDGs but the final steps will be the most challenging. Nat. Sustain. 2, 1041–1050. https://doi.org/10.1038/s41893-019-0409-9.

Allen, C., Metternicht, G., Wiedmann, T., Pedercini, M., 2021. Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states. Global Sustain. 4, 1–13. https://doi.org/10.1017/SUS.2021.13.

Antwi-Agyei, P., 2020. Ghana's Adaptation Strategy and Action Plan for the Infrastructure Sector (Water, Energy, and Transport Sectors) (Technical Report). Environmental Protection Agency, Accra, Ghana. URL: https://www.napglobalnetwork.org/wp-content/uploads/2020/06.

Antwi-Agyei, P., Dougill, A.J., Stringer, L.C., 2017. Assessing Coherence between Sector Policies and Climate Compatible Development: Opportunities for Triple Wins. Sustainability 9, 2130. https://doi.org/10.3390/su9112130.

Antwi-Agyei, P., Dougill, A.J., Stringer, L.C., Codjoe, S.N.A., 2018. Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. Clim. Risk Manage. 19, 83–93. https://doi.org/10.1016/j.crm.2017.11.003.

Antwi-Agyei, P., Fraser, E.D., Dougill, A.J., Stringer, L.C., Simelton, E., 2012. Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data. Appl. Geogr. 32, 324–334. https://doi.org/10.1016/J.APGEOG.2011.06.010.

Apuri, I., Peprah, K., Achana, G.T.W., 2018. Climate change adaptation through agroforestry: The case of Kassena Nankana West District, Ghana. Environ. Develop. 28, 32–41. https://doi.org/10.1016/J.ENVDEV.2018.09.002.

Asante, F.A., Amuakwa-Mensah, F., 2015. Climate Change and Variability in Ghana: Stocktaking. Climate 3, 78–99. https://doi.org/10.3390/CLI3010078.

Barnett, J., O'Neill, S., 2010. Maladaptation. Global Environ. Change 20, 211–213.

Beck, M.W., Losada, I.J., Menéndez, P., Reguero, B.G., Díaz-Simal, P., Fernández, F., 2018. The global flood protection savings provided by coral reefs. Nat. Commun. 9, 1–9. https://doi.org/10.1038/s41467-018-04568-z.

Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., McNeeley, S.M., 2014. A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. Global Environ. Change 25, 97–108. https://doi.org/10.1016/j.gloenvcha.2014.01.003.

Blicharska, M., Smithers, R.J., Mikusiński, G., Rönnbäck, P., Harrison, P.A., Nilsson, M., Sutherland, W.J., 2019. Biodiversity's contributions to sustainable development. Nat. Sustain. 2, 1083–1093. https://doi.org/10.1038/s41893-019-0417-9.

Booysen, F., 2002. An Overview and Evaluation of Composite Indices of Development. Soc. Indic. Res. 59, 115–151. https://doi.org/10.1023/A:1016275505152.

Cairns, G., Ahmed, I., Mullett, J., Wright, G., 2013. Scenario method and stakeholder engagement: Critical reflections on a climate change scenarios case study. Technol. Forecast. Soc. Chang. 80, 1–10. https://doi.org/10.1016/j.techfore.2012.08.005.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob. Change Biol. 26, 6134–6155. https://doi.org/10.1111/gcb.15310.

Cohen-Shacham, E., Janzen, C., Maginnis, S., Walters, G., 2016. Nature-based solutions to address global societal challenges (Technical Report). International Union for Conservation of Nature, Gland. https://doi.org/10.2305/IUCN.CH.2016.13.EN.

Conway, D., Mustelin, J., 2014. Strategies for improving adaptation practice in developing countries. Nat. Clim. Change 4, 339–342. https://doi.org/10.1038/nclimate2199.

Cutter, S., Boruff, B.J., Shirley, W.L., 2003. Social vulnerability to environmental hazards. Soc. Sci. Q. 84, 242–261. https://doi.org/10.1111/1540-6237.8402002.

Cutter, S., Emrich, C.T., Morath, D.P., Dunning, C.M., 2013. Integrating social vulnerability into federal flood risk management planning. J. Flood Risk Manage. 6, 332–344. https://doi.org/10.1111/JFR3.12018.

Denton, F., Wilbanks, T.J., Abeysinghe, A.C., Burton, I., Gao, Q., Lemos, M.C., Masui, T., O'Brien, K.L., Warner, K., Bhadwal, S., Leal, W., Van Ypersele, J.P., Wright, S.B., 2015. Climate-resilient pathways: Adaptation, mitigation, and sustainable development, in: Field, C., Barros, V., Dokken, D., Mach, K., Mastrandrea, M., Bilir, T., Chatterjee, M., Ebi, K., Estrada, Y., Genova, R., Girma, B., Kissel, E., Levy, A., MacCracken, S., Mastrandrea, P., White, L. (Eds.), Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects. Cambridge University Press, United Kingdom and New York, NY, USA, pp. 1101–1131. DOI: 10.1017/CBO9781107415379.025.

Dovie, B., 2015. Ghana's intended Nationally Determined Contributions (iNDCs) 2020–2030: Options Paper on Adaptation (Technical Report). MESTI, Accra, Ghana.

Editorial, 2021. Financing adaptation. Nat. Clim. Chang. 11, 887 (2021). https://doi.org/10.1038/s41558-021-01213-4.

EPA, 2015. Ghana's Third National Communication Report to the UNFCCC (Technical Report). Environmental Protection Agency, Accra, Ghana. URL: https://unfccc.int/resource/docs/natc/ghanc3.pdf.

EPA, 2020. Ghana's Fourth National Communication to the United Nations Framework Convention on Climate Change (Technical Report). Environmental Protection Agency, Accra, Ghana.

Eriksen, S., Aldunce, P., Bahinipati, C.S., Martins, R.D., Molefe, J.I., Nhemachena, C., O'Brien, K., Olorunfemi, F., Park, J., Sygna, L., Ulsrud, K., 2011. When not every response to climate change is a good one: Identifying principles for sustainable adaptation. Clim. Develop. 3, 7–20. https://doi.org/10.3763/cdev.2010.0060.

Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., West, J.J., 2021. Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Dev. 141, 105383 https://doi.org/10.1016/j.worlddev.2020.105383.

European Environment Agency, 2021. Climate-Adapt. https://climate-adapt.eea.europa.eu/.

Fuldauer, L., Ives, M.C., Adshead, D., Thacker, S., Hall, J.W., 2019. Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. J. Clean. Prod. 223, 147–162. https://doi.org/10.1016/j.jclepro.2019.02.269.

Fuldauer, L.I., Thacker, S., Haggis, R.A., Fuso Nerini, F., Nicholls, R.J., Hall, J.W., 2022. Targeting climate adaptation to safeguard and advance the Sustainable Development Goals. Nature Commun. 13, 3579. https://doi.org/10.1038/s41467-022-31202-w.

Fuldauer, L., Thacker, S., Hall, J., 2021. Informing national adaptation for sustainable development through spatial systems modelling. Global Environ. Change 71, 102396. https://doi.org/10.1016/j.gloenvcha.2021.102396.

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H., Milligan, B., 2019. Connecting climate action with other Sustainable Development Goals. Nat. Sustain. 2, 674–680. https://doi.org/10.1038/s41893-019-0334-y.

Gomez-Echeverri, L., 2018. Climate and development: Enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). Philos. Trans. R. Soc. A 376. https://doi.org/10.1098/rsta.2016.0444.

Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P., Máñez Costa, M., 2020. Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. Sci. Total Environ. 738, 139693 https://doi.org/10.1016/J.SCITOTENV.2020.139693.

Greco, S., Ishizaka, A., Tasiou, M., Torrisi, G., 2018. On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. Soc. Indic. Res. 141, 61–94. https://doi.org/10.1007/S11205-017-1832-9.

Hall, J., Tran, M., Hickford, A., Nicholls, R., 2016. The future of national infrastructure: A systems-of-systems approach. Cambridge University Press, Cambridge.

Hall, N., Persson, A., 2017. Global climate adaptation governance: Why is it not legally binding? Eur. J. Int. Relations 24, 540–566. https://doi.org/10.1177/1354066117725157.

Hanson, H.I., Wickenberg, B., Alkan Olsson, J., 2020. Working on the boundaries-How do science use and interpret the nature-based solution concept? Land Use Policy 90, 104302. https://doi.org/10.1016/J.LANDUSEPOL.2019.104302.

Hardee, K., Mutunga, C., 2009. Strengthening the link between climate change adaptation and national development plans: Lessons from the case of population in National Adaptation Programmes of Action (NAPAs). Mitig. Adapt. Strat. Glob. Change 15, 113–126. https://doi.org/10.1007/s11027-009-9208-3.

Hellmuth, M., Bruguera, M., Ankoh, M., 2017. Ghana integrated resource and resilience planning program: Risks And Resiliency In Ghana's Electric Power Sector. Technical Report. United States Agency for International Development. URL: https://www.researchgate.net/publication/337154965.

Hickford, A., Nicholls, R., Otto, A., Hall, J., Blainey, S.P., Tran, M., Baruah, P., 2015. Creating an ensemble of future strategies for national infrastructure provision. Futures 66, 13–24. https://doi.org/10.1016/j.futures.2014.11.009.

Huizinga, J., Moel, H.d., Szewczyk, W., 2017. Global flood depth-damage functions: Methodology and the database with guidelines (Technical Report). European Union, Luxembourg. https://doi.org/10.2760/16510.

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Technical Report October 2013. Intergovernmental Panel on Climate Change. Geneva. 10.1017/CBO9781107415379.

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (Technical Report). IPCC.

Jafino, B.A., Hallegatte, S., Rozenberg, J., 2021. Focusing on differences across scenarios could lead to bad adaptation policy advice. Nat. Clim. Change 11, 394–396. https://doi.org/10.1038/s41558-021-01030-9.

Khan, M., Schmidt-Traub, G., 2020. Use of spatial information in national climate strategies An analysis of Nationally Determined Contributions (NDCs) and Long-Term Low-Emission Development Strategies (LT-LEDS) (Technical Report). SDSN, Paris, France.

Kheradmand, S., Seidou, O., Konte, D., Barmou Batoure, M.B., 2018. Evaluation of adaptation options to flood risk in a probabilistic framework. J. Hydrol.: Regional Stud. 19, 1–16. https://doi.org/10.1016/j.ejrh.2018.07.001.

Koks, E.E., Jongman, B., Husby, T.G., Botzen, W.J., 2015. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. Environ. Sci. Policy 47, 42–52. https://doi.org/10.1016/j.envsci.2014.10.013.

Koks, E.E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S.A., Hall, J. W., Hallegatte, S., 2019. A global multi-hazard risk analysis of road and railway infrastructure assets. Nat. Commun. 10, 1–11. https://doi.org/10.1038/s41467-019-10442-3.

Lafortune, G., Fuller, G., Moreno, J., Schmidt-Traub, G., Kroll, C., 2018. SDG Index and Dashboards: Detailed Methodological Paper Technical Report September. In: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). New York (NY, US).

Lawson, E.T., Alare, R.S., Salifu, A.R.Z., Thompson-Hall, M., 2019. Dealing with climate change in semi-arid Ghana: understanding intersectional perceptions and adaptation strategies of women farmers. GeoJournal 85, 439–452. https://doi.org/10.1007/S10708-019-09974-4.

Lemos, M.C., Agrawal, A., Eakin, H., Nelson, D.R., Engle, N.L., Johns, O., 2013. Building Adaptive Capacity to Climate Change in Less Developed Countries. In: Climate Science for Serving Society. Springer, Dordrecht, Dordrecht, pp. 437–457. https://doi.org/10.1007/978-94-007-6692-1_16.

Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K.C., Gleick, P., Kremen, C., Li, S., 2015. Systems integration for global sustainability. Science 347, 1258832. https://doi.org/10.1126/science.1258832.

Magnan, A.K., Ribera, T., 2016. Global adaptation after Paris. Science 352, 1280–1282. https://doi.org/10.1126/science.aaf5002.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B., Knowlton, N., 2020. Climate change and ecosystems: Threats, opportunities and solutions. Philosophical Transactions of the Royal Society B: Biological Sciences 375. https://doi.org/10.1098/rstb.2019.0104.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, Technical Report.

Mcsweeney, C., New, M., Lizcano, G., 2010. UNDP Climate Change Country Profiles: Ghana. Technical Report. http://www.geog.ox.ac.uk/research/climate/projects/undp-cp/.

Menéndez, P., Losada, I.J., Torres-Ortega, S., Narayan, S., Beck, M.W., 2020. The Global Flood Protection Benefits of Mangroves. Scientific Rep. 10, 1–11. https://doi.org/10.1038/s41598-020-61136-6.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van Den Bergh, J.C., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A.H., Viavattene, C., 2013. Review article: Assessing the costs of natural hazards-state of the art and knowledge gaps. Nat. Hazards Earth Syst. Sci. 13, 1351–1373. https://doi.org/10.5194/nhess-13-1351-2013.

Miola, A., Schiltz, F., 2019. Measuring sustainable development goals performance: How to monitor policy action in the 2030 Agenda implementation? Ecol. Econ. 164, 106373 https://doi.org/10.1016/J.ECOLECON.2019.106373.

Morgan, E.A., Nalau, J., Mackey, B., 2019. Assessing the alignment of national-level adaptation plans to the Paris Agreement. Environ. Sci. Policy 93, 208–220. https://doi.org/10.1016/j.envsci.2018.10.012.

NADMO, 2015. National level Flood and Drought Risk Assessment and Mapping - Technical Report (Technical Report). NADMO, Government of Ghana, Accra, Ghana.

Nalau, J., Verrall, B., 2021. Mapping the evolution and current trends in climate change adaptation science. Clim. Risk Manage. 32, 100290 https://doi.org/10.1016/j.crm.2021.100290.

NDPC, 2019. Ghana Infrastructure Plan (2018 – 2047) Volume One. Technical Report. National Development Planning Commission. Accra, Ghana.

Noble, I.R., Huq, S., Anokhin, Y.A., Carmin, J.A., Goudou, D., Lansigan, F.P., Osman-Elasha, B., Villamizar, A., Patt, A., Takeuchi, K., Chu, E., 2015. Adaptation needs and options, in: Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects. Intergovernmental Panel on Climate Change, pp. 833–868. DOI: 10.1017/CBO9781107415379.019.

OECD, 2019. Measuring Distance to the SDG Targets 2019: An Assessment of Where OECD Countries Stand (Technical Report). OECD, Paris, France.

OECD and European Union Joint Research Centre, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD publications, Paris, France.

Otto, A., Hall, J., Hickford, A., Nicholls, R., Alderson, D., Barr, S., 2016. A quantified system of systems modeling framework for robust national infrastructure planning. IEEE Syst. J. 10, 11. https://doi.org/10.1109/JSYST.2014.2361157.

Owen, G., 2020. What makes climate change adaptation effective? A systematic review of the literature. Global Environ. Change 62, 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071.

Owusu, M., Nursey-Bray, M., 2019. Socio-economic and institutional drivers of vulnerability to climate change in urban slums: the case of Accra, Ghana. Clim. Develop. 11, 687–698. https://doi.org/10.1080/17565529.2018.1532870.

Pant, R., Thacker, S., Hall, J., Alderson, D., Barr, S., 2016. Critical infrastructure impact assessment due to flood exposure. J. Flood Risk Manage. 11, 1–12. https://doi.org/10.1111/jfr3.12288.

Prakash, M., Teksoz, K., Espey, J., Sachs, J.D., 2017. Achieving a Sustainable America. The U.S. Cities Sustainable Development Goals Index 2017. Technical Report. Sustainable Development Solutions Network. New York, USA. https://doi.org/10.13140/RG.2.2.25012.09601.

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S.G., Camargo, S.J., Hess, J., Kornhuber, K., Oppenheimer, M., Ruane, A.C., Wahl, T., White, K., 2020. Understanding and managing connected extreme events. Nat. Clim. Change 10, 611–621. https://doi.org/10.1038/s41558-020-0790-4.

Reichstein, M., Riede, F., Frank, D., 2021. More floods, fires and cyclones – plan for domino effects on sustainability goals. Nature 592, 347–349. https://doi.org/10.1038/d41586-021-00927-x. URL: https://www.nature.com/articles/d41586-021-00927-x.

Schipper, E.L.F., 2020. Maladaptation: When Adaptation to Climate Change Goes Very Wrong. One Earth 3, 409–414. https://doi.org/10.1016/J.ONEEAR.2020.09.014.

Schipper, E.L.F., Thomalla, F., Vulturius, G., Johnson, K., 2016. Linking disaster risk reduction, climate change and development. Int. J. Disaster Resilience Built Environ. 7, 216–228. https://doi.org/10.1108/IJDRBE-03-2015-0014.

Schmidt-Traub, G., Kroll, C., Teksoz, K., Durand-Delacre, D., Sachs, J.D., 2017. National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. Nat. Geosci. 10, 547–555. https://doi.org/10.1038/NGEO2985.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B 375. https://doi.org/10.1098/rstb.2019.0120.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. Glob. Change Biol. 27, 1518–1546. https://doi.org/10.1111/gcb.15513.

Singh, C., Ford, J.D., Ley, D., Bazaz, A., Revi, A., 2020. Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. Clim. Change 162, 255–277. https://doi.org/10.1007/s10584-020-02762-x.

Termeer, C., Biesbroek, R., Van Den Brink, M., 2012. Institutions for adaptation to climate change: Comparing National Adaptation strategies in Europe, in: European Political Science, Palgrave. pp. 41–53. www.palgrave-journals.com/eps/. doi: 10.1057/eps.2011.7.

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., Hall, J.W., 2019. Infrastructure for sustainable development. Nat. Sustain. 2, 324–331. https://doi.org/10.1038/s41893-019-0256-8.

Thacker, S., Barr, S., Pant, R., Hall, J.W., Alderson, D., 2017a. Geographic Hotspots of Critical National Infrastructure. Risk Anal. 37, 2490–2505. https://doi.org/10.1111/risa.12840.

Thacker, S., Kelly, S., Pant, R., Hall, J.W., 2017b. Evaluating the Benefits of Adaptation of Critical Infrastructures to Hydrometeorological Risks. Risk Anal. 38, 134–150. https://doi.org/10.1111/risa.12839.

Thacker, S., Pant, R., Hall, J.W.J., 2017c. System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures. Reliab. Eng. Syst. Saf. 167, 30–41. https://doi.org/10.1016/j.ress.2017.04.023.

Tompkins, E.L., Eakin, H., 2012. Managing private and public adaptation to climate change. Global Environ. Change 22, 3–11. https://doi.org/10.1016/j.gloenvcha.2011.09.010.

Tompkins, E.L., Vincent, K., Nicholls, R.J., Suckall, N., 2018. Documenting the state of adaptation for the global stocktake of the Paris Agreement. Wiley Interdiscip. Rev.: Clim. Change 9. https://doi.org/10.1002/wcc.545.

UNEP, Nature-based Solutions for Disaster and Climate Resilience. https://sdgacademy.org/course/nature-based-solutions-for-disaster-and-climate-resilience/.

University of Oxford, 2020. Nature-based solutions evidence platform. https://www.naturebasedsolutionsevidence.info/.

Verschuur, J., Koks, E.E., Haque, A., Hall, J.W., 2020. Prioritising resilience policies to reduce welfare losses from natural disasters: A case study for coastal Bangladesh. Global Environ. Change 65, 102179. https://doi.org/10.1016/j.gloenvcha.2020.102179.

Ward, P.J., Jongman, B., Aerts, J.C., Bates, P.D., Botzen, W.J., DIaz Loaiza, A., Hallegatte, S., Kind, J.M., Kwadijk, J., Scussolini, P., Winsemius, H.C., 2017. A global framework for future costs and benefits of river-flood protection in urban areas. Nat. Clim. Change 7, 642–646. doi:10.1038/nclimate3350.

Ward, P.J., Winsemius, H.C., Kuzma, S., Bierkens, M.F.P., Bouwman, A., Moel, H.D., Loaiza, A.D., Eilander, D., Englhardt, J., Gilles, E., Gebremedhin, E., Iceland, C., Kooi, H., Ligtvoet, W., Muis, S., Scussolini, P., Sutanudjaja, E.H., Beek, R.V., Bemmel, B., Huijstee, J.V., Rijn, F.V., Wesenbeeck, B.V., Vatvani, D., Verlaan, M., Tiggeloven, T., Luo, T., 2020. Aqueduct Floods Methodology. Technical Report January. World Resources Institute. www.wri.org/publication/aqueduct-floods-methodology.

Williams, P.A., Simpson, N.P., Totin, E., North, M.A., Trisos, C.H., 2021. Feasibility assessment of climate change adaptation options across Africa: An evidence-based review. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/ac092d.

Winsemius, H.C., Aerts, J.C., Van Beek, L.P., Bierkens, M.F., Bouwman, A., Jongman, B., Kwadijk, J.C., Ligtvoet, W., Lucas, P.L., Van Vuuren, D.P., Ward, P.J., 2016. Global drivers of future river flood risk. Nat. Clim. Change 6, 381–385. https://doi.org/10.1038/nclimate2893.

Wood, S.L., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., Gordon, L.J., Kappel, C.V., Mandle, L., Mulligan, M., O'Farrell, P., Smith, W.K., Willemen, L., Zhang, W., DeClerck, F.A., 2018. Distilling the role of ecosystem services in the Sustainable Development Goals. Ecosyst. Services 29, 70–82. https://doi.org/10.1016/j.ecoser.2017.10.010.

Xu, Z., Chau, S.N., Chen, X., Zhang, J., Li, Y., Dietz, T., Wang, J., Winkler, J.A., Fan, F., Huang, B., Li, S., Wu, S., Herzberger, A., Tang, Y., Hong, D., Li, Y., Liu, J., 2020. Assessing progress towards sustainable development over space and time. Nature 577, 74–78. https://doi.org/10.1038/s41586-019-1846-3.

Zhenmin, L., Espinosa, P., 2019. Tackling climate change to accelerate sustainable development. Nat. Clim. Change 9, 494–496. https://doi.org/10.1038/s41558-019-0519-4.

Zscheischler, J., Westra, S., Van Den Hurk, B.J., Seneviratne, S.I., Ward, P.J., Pitman, A., Aghakouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Change 8, 469–477. https://doi.org/10.1038/s41558-018-0156-3.