Climate adaptation for sustainable development



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A thesis presented for the degree of Doctor of Philosophy

School of Geography and the Environment

Michaelmas Term 2021

Acknowledgements

This DPhil was funded by the Engineering and Physical Sciences Research Council, and has been made possible by many people.

First and foremost, I would like to thank my supervisor Jim Hall for enabling me to embark on this DPhil journey. Jim, thank you for your invaluable guidance, reassurance, and support from the first day at Oxford. I owe much to my colleague and friend Scott Thacker. Scott, thank you for introducing me to the fascinating world of academia, for dedicating many hours discussing ideas, and for challenging me to get towards a deeper understanding. So many aspects of this journey would have been impossible without you. A special thanks to Daniel Adshead for many unforgettable dream team hikes, both the academic and the fun ones. I would also like to acknowledge my co-authors Francesco Fuso-Nerini, Robyn Haggis, Sarah Gall, and Robert Nicholls for their helpful feedback and inputs into this DPhil. Lisa Schipper and Pam Berry provided insightful feedback during earlier assessments in this journey. I am grateful for Tim O'Riordan for pushing me to take different roads - it has steered this DPhil into a more holistic direction.

I feel privileged to have been part of the Environmental Change Institute. Thanks to Raghav and Tom for providing technical help and advice; to Miriam and Tim for coordinating the field work; to superwoman Amelie for motivating me every single day in the final push for this thesis; to Nick and Jasper for many discussions that kept me engaged beyond my personal research; and to the rest of the ECI group: you have all filled the last three years with stimulating energy and made Paradise Island a sunny place to work.

Many thanks to the United Nations Office for Project Services for supporting this research and enabling many valuable collaborations - both in Saint Lucia and remotely in Ghana; to St Edmund Hall for making Oxford a great place to study and live; and to Allianz, for providing me with the opportunity to present my research to a wide audience.

My friends have been my core support throughout this journey, both the falls and highs. To my Teddy Hall babes, Tom and Caro; to the strong women of SEHBC, Eveliina, Jess, Rosie, and India; to my two favourite ECMers Simi, for demonstrating that no mountain is high enough, and Mo, for just being Mo! To Marcel, Hjördis, Josh, Silvia and all my wonderful friends for making me feel home in Oxford, Munich, or London.

Lastly, a huge thanks go to my family, who give me the strength to strive for something more; to my special family member Alina, who made every part of this journey easier and filled with good Swiss air; to Sven, for his endless reassurance throughout these past three years, his all-encompassing trust, and his unconditional love; and to my parents for encouraging me to do the right thing: my dad, from whom I seem to have inherited some perseverance; and to my mum, the best mother a child can wish for.

Abstract

With the impacts of climate change disproportionately affecting the most vulnerable nations and threatening hard-earned development progress, climate adaptation will be crucial to safeguard and contribute to sustainable development. But adapting to the impacts of climate change is challenging in the face of future uncertainties and the risk for wrong decisions to exacerbate development or climate challenges. Whilst an increasing body of research has addressed the need for improved planning of climate adaptation, there remains a gap in aligning such adaptation planning with sustainable development and the global agendas, in particular the Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change.

This thesis addresses this gap by investigating the complex links between sustainable development targets and climate change impacts to better inform climate adaptation planning for sustainable development. A conceptual framework is first developed to better understand the pathways of *how* sustainable development targets are linked to the impacts of climate change. The conceptual framework highlights the essential role of sectors of society, the economy, and the environment in mediating between achievement of SDG targets and impacts of climate change. This conceptual framework is operationalised through the development of two complementary national-scale methodologies: the first methodology holistically assesses where and how impacts of climate change affect sustainable development targets, whilst the second methodology evaluates how much and what type of adaptation can safeguard and contribute to sustainable development. By spatially translating sustainable development targets and indicators at the level of a nation's sectors and assets, these two methodologies integrate the largely siloed fields of sustainable development and climate change impacts research to inform a more coordinated approach to climate adaptation planning for sustainable development.

Application of the first methodology to the small island of Saint Lucia reveals the impacts of climate change across 22 sectors and half of the nation's built and natural assets, and shows how these impacts interact and propagate to influence 89% of SDG targets. The participatory methods and the cross-sectoral workshops as part of this application helped Saint Lucia add specificity and spatial granularity to 52 adaptation options under its National Adaptation Plan. The second methodology, applied in Ghana, grounds climate adaptation planning in a national sustainable development vision. Using an SDG-risk indicator set, Ghana's climate adaptation needs in the energy and transport sector are evaluated in terms of safeguarding existing SDG target progress. A feasible adaptation strategy to meet these needs is developed through a multi-stakeholder partnership, showing

how a combination of built and nature-based adaptation options can deliver up to 116 SDG target co-benefits.

Collectively, the contributions in this thesis provide valuable insights to conceptualise, assess, and 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, the transferable approaches and accompanying decision-support tools developed in this thesis can help ensure adaptation contributes to, rather than detracts from, sustainable development.

Publications

1. **Fuldauer, L.I.**, Thacker, S., Haggis, R., Fuso-Nerini, F., Nicholls, R., Hall, J.W. Targeting climate adaptation to safeguard and advance the Sustainable Development Goals. Revised version under review at *Nature Communications*. (**Chapter 4**).

2. **Fuldauer, L.I.**, Thacker, S., Hall, J.W. (2021) Informing national adaptation for sustainable development through spatial systems modelling. *Global Environmental Change*, 71 (11). (**Chapter 5**).

3. **Fuldauer, L.I** Adshead, D., Thacker, S., Gall, S., Hall, J.W. Evaluating the benefits of national adaptation to reduce climate risks and contribute to the Sustainable Development Goals. Under review at *Global Environmental Change*. (**Chapter 6**).

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List of Abbreviations

CBA . . . . . Cost-Benefit Analysis.

CICES . . . . . Common International Classification of Ecosystem Services

COP . . . . . Conference Of the Parties.

DMDU . . . . . Decision-Making under Deep Uncertainty.

GIS . . . . . Geographic Information Systems.

IUCN . . . . . International Union for Conservation of Nature

IPCC . . . . . Intergovernmental Panel on Climate Change.

ISIC . . . . . International Standard Industrial Classification of All Economic Activities.

m2 . . . . . square metre.

km . . . . . kilometre.

MESTI . . . . . Ministry of Environment, Science, Technology and Innovation, Ghana.

MCDA . . . . . Multi-Criteria Decision Approaches.

NAP . . . . . National Adaptation Plan.

NADMO . . . . National Disaster Management Organisation, Ghana.

NC . . . . . National Communications.

NDC . . . . . Nationally Determined Contributions.

NGO . . . . . Non-Governmental Organisation.

NISMOD . . . . National Infrastructure Systems MODel.

NIPP . . . . . National Integrated Planning and Programme Unit, Saint Lucia.

RDM . . . . . Robust Decision Making.

SDGs . . . . . Sustainable Development Goals.

SEEA . . . . . System of Environmental Economic Accounting.

SIDS . . . . . Small Island Developing States.

TWG . . . . . Technical Working Group, Ghana.

UN . . . . . United Nations.

UNFCCC . . . . United Nations Framework Convention on Climate Change.

UNOPS . . . . . United Nations Office for Project Services.

1 Introduction

1.1 Background and motivation

Achieving sustainable development outcomes and addressing climate change are two of the greatest challenges of the 21st century. As a response to these challenges, two global agendas were adopted by the world's nations in 2015: the Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change (United Nations 2015; UNFCCC 2015; TWI2050 2018; UN 2019). Adopted separately, the two global agendas share the vision of ensuring a sustainable and climate-resilient future for all (Zhenmin et al. 2019; Gomez-Echeverri 2018).

Yet, since their adoption in 2015, progress towards the shared vision of the global agendas remains insufficient (Messerli et al. 2019; Zhenmin et al. 2019). One reason for this insufficient progress is our limited understanding of the complex relationships between the sustainable development targets and the various impacts of climate change (Fuso Nerini et al. 2019; Nilsson et al. 2016). Lack of guidance on how to translate the shared vision of the global agendas at national scale further hampered synergistic action in practice (Allen, Metternicht, and Wiedmann 2019). At the same time, national decision-makers are under pressure to make decisions on climate action that overlap with various dimensions of sustainable development (O'Brien et al. 2000; Adger et al. 2018). This involves both decisions on *climate mitigation* to reduce climate forcing and

greenhouse gas emissions as well as *climate adaptation* to respond to the experienced and anticipated impacts of climate change.

In line with the 2020s having been termed the 'decade of action' (UNSDG 2020), the special report on 1.5°C global warming by the Intergovernmental Panel on Climate Change (IPCC) documented the links between achievement of the SDG targets and climate mitigation action (IPCC 2018). By translating these SDG-climate links to action at the level of sectors of society, the economy, and the environment, the report enables national decision-makers to better inform *climate mitigation* under the Paris Agreement in alignment with the SDG targets. Yet, no such sector-level research has been conducted to help better inform *climate adaptation* under the Paris Agreement in alignment with the SDG targets.

Climate adaptation at the level of sectors of society, the economy, and the environment is essential for achieving the SDG targets. As sectors are themselves affected by the impacts of climate change (Field et al. 2014), protecting them against these impacts can directly safeguard progress towards the SDGs. If planned and governed accordingly, the type of adaptation option chosen can deliver development co-benefits, such as restoring essential ecosystem services (Chausson et al. 2020; Seddon et al. 2021). Yet, not every adaptation action is sustainable (Eriksen et al. 2011). Prioritising carbon-intensive sectors for adaptation wastes financial resources that fail to deliver synergistic outcomes across development and climate objectives. Similarly, adopting the wrong adaptation options can reverse development gains or exacerbate climate change impacts, resulting in maladaptation (Barnett, Campbell, et al. 2010; Eriksen et al. 2011). An overemphasis on economic factors and poor cross-sectoral planning are the primary causes of maladaptation (Schipper 2020), making it difficult or impossible to achieve the shared vision of the SDGs and the Paris Agreement.

The urgency of climate adaptation planning in alignment with the shared vision of the global agendas is particularly prominent in developing countries, which are disproportionately impacted by climate change (IPCC 2014a; Mimura et al. 2014). Such disproportionate impacts can be attributed partly to geography, as many developing

countries are located in regions with more severe hazards such as storm surges or sea-level rise (Ranger et al. 2012). Besides geography, a greater share of the population in developing countries is exposed to climate-sensitive economic production or natural resources (Stern 2006). Developing countries also tend to be more vulnerable (World Bank 2010), often related to their weaker institutions and less resilient service provision (United Nations International Strategy for Disaster Reduction 2009; Huq et al. 2009; Hallegatte, Bangalore, Bonzanigo, et al. 2016) .

To deliver on the shared vision of the SDGs and the Paris Agreement, there is a great need to strengthen climate adaptation planning, especially in developing countries. Unlike climate mitigation, climate adaptation still has a long way to go in terms of its mainstreaming into national planning. At its core, a better conceptual understanding of the relationship between sustainable development targets and the various impacts of climate change is required to better inform climate adaptation planning to deliver on the global agendas. An improved conceptual understanding can help to establish methodologies that provide guidance for decision-makers to assess and evaluate national climate adaptation planning in the context of sustainable development targets, thereby yielding evidence to ensure adaptation contributes to, rather than distracts from, sustainable development.

1.2 Definitions of key terms

In light of the holistic focus of this thesis on tackling two major global challenges, it is useful to define key terms. Specifically, the following terms are narrowed down to the scope of this thesis: sustainable development, climate change impacts, climate adaptation, and socio-economic sectors and ecosystems as well as the services these provide.

Sustainable development. Sustainable development is defined according to the Brundtland definition as "development that meets the needs of the present without compromising the ability of future generations to meet their" (WCED 1987, p.43). This thesis adopts a normative definition of sustainable development, defining the concept through the 17 SDGs and its 169 targets, which bring together a broad spectrum of social, economic, and environmental dimensions of development (United Nations 2015).

Climate change impacts. The impacts of climate change refer to the effects or consequences arising from acute, short-term climatic impact-drivers (damaging cyclones or extreme precipitation) as well as chronic, gradual climatic impact-drivers (annual precipitation changes), which can have beneficial or adverse effects on social and economic assets, ecosystems, livelihoods, and services (IPCC 2018). In the context of adverse effects only, climatic impact-drivers are referred to as 'climate-change hazards' and climate change impacts are defined as the realised climate risks that result from the intersection of these climate-change hazards, exposure, and vulnerability (IPCC 2018).

Climate adaptation. Climate adaptation, used interchangeably with the term adaptation, refers to the process of adjusting to the experienced or anticipated impacts of climate change (IPCC 2018). Recognising the broad typologies and complexities involved in adaptation, discussed in detail in Chapter 2, this thesis focuses on adaptation planning. Adaptation planning refers to: i) an assessment of adaptation needs based on where impacts and risks from climate change are highest; and ii) an ex-ante evaluation of adaptation options, defined as the array of measures (including policies or investments) available to address adaptation needs. Adaptation needs and options can be assessed and evaluation through bio-physical, social, institutional, or financial lenses. The practical work in this thesis (Chapter 5 and 6) focuses mainly on bio-physical adaptation needs and options that help reduce risk from high and medium frequency climate-change hazards, acknowledging that addressing social or financial adaptation needs, accounting for the effects of low frequency climate-change hazards, and considering transition risks are also essential components of adaptation.

Socio-economic sectors and ecosystems, and the services these provide. Sectors of society, the economy, and the environment, hereafter referred to as socio-economic sectors and ecosystems, refer to the physical built and natural environment assets as well as the human assets and institutions required to ensure sectors deliver essential services that all life ultimately depends on. Socio-economic sectors include electricity, transport, public administration, healthcare, education, and arts, amongst others (UN 2008). Natural and semi-natural ecosystems include grasslands, savannas, forests, rivers, wetlands and peatlands, polar/alpine, and croplands, amongst others (Anderson et al. 1976; Bogaart et al.

2019). Both socio-economic sectors and ecosystems provide services that are essential to deliver on societal needs. This thesis adopts international classifications to define all sectors' services. The International Standard Industrial Classification of all economic activities (ISIC) is used to classify different socio-economic sectors and the range of services these provide, such as infrastructure, manufacturing, or government services (UN 2008). Similarly, the Common International Classification of Ecosystem Services (CICES) is adopted to classify the services provided by ecosystems into regulating, cultural, supporting, and provisioning services (EEA 2018).

1.3 Research gaps

Whilst research on the broad links between sustainable development targets and climate change impacts has proliferated over recent decades (Griggs et al. 2014; Weitz et al. 2014; Nilsson et al. 2016; Gomez-Echeverri 2018; Le Blanc 2015; ICSU 2015; Fuso Nerini et al. 2019) (see Chapter 2), several research gaps remain.

1. Linking sustainable development targets and impacts from climate change via sectors

Research to date allows for assessments of how climate change can impact upon sectors linked to development, for example through empirical evidence or methods of statistical inference (Field et al. 2014; Carleton et al. 2016). Similarly, research has enabled a better understanding on global progress towards sustainable development, and how such progress can be measured using global SDG indicators (Schmidt-Traub et al. 2017). To account for the growing criticism that existing SDG indicators are often not able to encapsulate all aspects of the related SDG target (Mair et al. 2018; Miola et al. 2019), additional means are required that can help assess progress towards sustainable development, especially in less developed countries where data is scarce. In response, various authors have conceptualised how sectors, and the services these provide (such as energy, water, or ecosystem services), can influence sustainable development targets, using the concept of sector-SDG influences (Thacker et al. 2019; Velis et al. 2017; Fuso Nerini et al. 2018; Singh et al. 2018; Wood et al. 2018; Vinuesa et al. 2020). Some

SDG targets can be directly described in terms of the services provided by a specific sector (such as the provision of energy). For other SDG targets, improving the services provided by a sector can advance achievement of a target, in other words, there is an indirect SDG influence (Thacker et al. 2019). However, to date, the identification and application of such sector-SDG influences has not yet been conducted systematically across all of a nation's socio-economic sectors and ecosystems and has not accounted for the interdependencies between these, despite increasing calls for the importance of explicitly considering such interdependencies (Stafford-Smith et al. 2016). Further, the application of sector-SDG influences has not been integrated with advances on assessing how the impacts of climate change affect sectors. Adopting a sector-scale approach provides a useful means to conceptualise the complex links between sustainable development targets and climate change impacts in the context of the global agendas, as many national development and adaptation plans under the SDGs and the Paris Agreement are formulated at the scale of sectors. Better informing national adaptation to deliver on the global agendas therefore requires conceptual exploration on the complex ways of *how* sectors mediate between sustainable development targets and impacts of climate change.

2. Assessing climate change impacts on sustainable development targets

Whilst a conceptual exploration on the links between sustainable development targets and the impacts of climate change at the scale of sectors is useful, it requires further development and analysis if it is to be utilised to inform national adaptation planning in alignment with the SDG targets in practice. Achieving such alignment requires decision-makers to assess the impacts of climate change on sustainable development targets at a specificity that is coherent with existing national documents and that enables making investment decisions. Spatial climate risk and adaptation assessments can provide such specificity. Such spatial climate risk and adaptation assessments help national decision-makers practically identify which sectors and physical assets are particularly exposed to a climate-change hazard, and quantify the corresponding disruption of services with the aim of identifying where and how much adaptation is needed (Thacker, Pant, et al. 2017; Pant et al. 2016). Increasingly, such spatial climate risk and adaptation assessments have

taken a systems approach, thereby considering different socio-economic sectors of the built environment (Dawson et al. 2018) and accounting for interdependencies between such sectors (Pant et al. 2019). Yet, despite unequivocal evidence on the importance of the natural environment in mediating the impacts of climate change (Jones et al. 2012; Chausson et al. 2020; Cohen-Shacham et al. 2016), these are rarely integrated in systems approaches. To help achieve sustainable development practically, the concept of sector-SDG influences has recently been translated to the national scale (Adshead et al. 2019), but it has not been spatially translated. Spatially assessing where the impacts of climate change affect a holistic set of sectors and assets across the built and natural environment, and how these impacts propagate and interact to influence SDG targets, can provide decision-makers with the spatial granularity and specificity to better target national adaptation to safeguard SDG targets. Furthermore, such information can provide the necessary evidence for decision-makers to revise or develop national adaptation plans under the Paris Agreement that are aligned with the SDG targets.

3. Using sustainable development targets to evaluate climate adaptation

An ex-ante evaluation of a nation's climate adaptation needs and options is critical to ensure adaptation cost-effectively reduces risks from climate-change hazards. However, evaluating adaptation purely from a risk-reduction standpoint can distract from a nation's achievement of sustainable development targets and the SDGs (Jafino et al. 2021). Whilst the SDG targets are not typically used in the evaluation of adaptation needs and options, they are now widely recognised as a framework to identify and evaluate sustainable development needs and options to guide development plans (Prakash et al. 2017; OECD 2019; Adshead et al. 2019; Adshead et al. 2021). However, to date, no study has grounded national adaptation assessments in an SDG vision or used the specificity of the SDG targets to evaluate adaptation needs and options. A more holistic SDG-based evaluation of adaptation is especially important to account for the benefits of nature-based adaptation options, which are increasingly considered essential for climate adaptation and for achieving sustainable development, yet are difficult to quantify in monetary terms (Seddon et al. 2021; Malhi et al. 2020). Integrating both climate adaptation

and sustainability assessments, thereby explicitly including both built and nature-based adaptation options, can play a large role in helping national decision-makers to evaluate adaptation to safeguard existing SDG progress and deliver SDG co-benefits.

4. Supporting practical decision-making through action research

Beyond gaps in the need for improved conceptual and methodological approaches, there are also gaps for practical application of such approaches and action research to support the integration of sustainable development and climate adaptation more directly. Typically, national decisions on sustainable development and climate adaptation are made in sectoral or ministerial siloes with separate and disconnected mandates (Howells et al. 2013). Often, these decisions are entrenched in power dynamics, political interests, or based on available project funding attached to specific conditions (Moore 2012). As more nations implement the SDGs and the Paris Agreement, it is critical to overcome these siloed approaches that have been met with limited success to date (Allen et al. 2018). Researchers, in partnership with civil society, governments and the private sector, can contribute to overcoming siloed practices and help suppress power dynamics by: i) applying national-scale methodologies using real-world data to provide depoliticised evidence to underpin adaptation decisions; and ii) engaging in dialogue with stakeholders, using participatory methods and cross-sectoral workshops, to create ownership of adaptation planning and implementation that safeguards and advances sustainable development (Allen, Metternicht, and Wiedmann 2021).

Safeguarding sustainable development progress against the impacts of climate change is important in all countries, but nowhere more so than in Small Island Developing States (SIDS). SIDS are considered to be among the most vulnerable nations to climate change and face many development challenges, including small administrations and dependency on few critical assets (UNEP 2014; Nurse et al. 2014). Service disruptions due to asset failure in a specific area can cause unforeseen disruptions to all other industries, stalling hard-earned progress towards achievement of the SDGs. At the same time, SIDS have strong commitments to sustainable development and adaptation to climate change (UN General Assembly 2014), but will depend on international partnerships and funding to

translate these high-level commitments into action (Allen, Metternicht, Wiedmann, and Pedercini 2021). Encouraging action requires applying national-scale methodologies to deliver evidence on where and how climate-change hazards affect SDG achievement to make the case for adaptation to safeguard SDG targets.

Using SDG targets to evaluate adaptation options is particularly important in countries characterised by long-term development challenges and facing severe climate-change hazards. Africa faces the biggest development challenges of any continent (Sachs et al. 2004; Commission for Africa 2005), and has been considered a region highly vulnerable to climate change (IPCC 2014a; World Bank 2010). Yet, to date, many African countries are failing to align climate and national development planning (Jones et al. 2015). With its growing population and endangered ecosystems, there is a specific imperative for integrating climate adaptation with advancements on sustainable development in African countries (GCA 2021). Encouraging such integration requires applying national-scale methodologies to evaluate climate adaptation to safeguard existing development gains and to advance sustainable development co-benefits.

1.4 Aim and research questions

To address the abovementioned gaps in the literature, the aim of this DPhil is to develop and apply transferable approaches that investigate the complex links between sustainable development targets and climate change impacts to better inform climate adaptation planning in the context of the SDGs and the Paris Agreement. In doing so, this thesis examines the role of national planning across socio-economic sectors and ecosystems as a way of informing climate adaptation, shifting the focus from fragmented and economic approaches towards formalised and holistic adaptation assessments aligned with the global agendas. Engaging with decision-makers through participatory methods and action research is thereby considered a key component to inform practical adaptation decisions. Contributing to this broad aim, this thesis differentiates between three research questions and related objectives described below and visualised in Figure 1.1:

Research Question 1: How can the links between global sustainable development targets and climate change impacts be **conceptualised** at a scale useful to inform adaptation?

Related objectives:

- To develop a conceptual framework that allows systematically linking the SDG targets and various impacts from climate change via the services provided by socio-economic sectors and ecosystems.
- To demonstrate one potential global application of the conceptual framework.
- To outline considerations for operationalising the conceptual framework at national scale.

Research Question 2: How can the impacts of climate-change hazards on sustainable development targets be spatially **assessed** to inform national adaptation?

Related objectives:

- To develop a national-scale methodology that allows spatially assessing impacts of climate-change hazards across all of a nation's sectors and physical assets, and the way these impacts interdependently influence SDG targets.
- To apply the methodology to a SIDS test case study to make the case for, and inform where and how to prioritise, adaptation under the Paris Agreement in line with sustainable development targets.
- To engage with national decision-makers throughout the methodology application to help support practical decision-making for assessing adaptation under the Paris Agreement in alignment with SDG targets.

Research Question 3: How can adaptation needs and options be **evaluated** based on sustainable development targets?

Related objectives:

- To develop a national-scale methodology that allows identifying the SDG benefit of adaptation, including evaluating adaptation needs in terms of SDG target progress *and* evaluating adaptation options to advance SDG target co-benefits.

- To apply the methodology to an African test case study to inform how much SDG progress can be safeguarded by adaptation, and what type of options can reduce climate risk and maximise SDG target co-benefits.
- To engage with national decision-makers throughout the methodology application to help support practical decision-making for evaluating adaptation under the Paris Agreement in alignment with SDG targets.

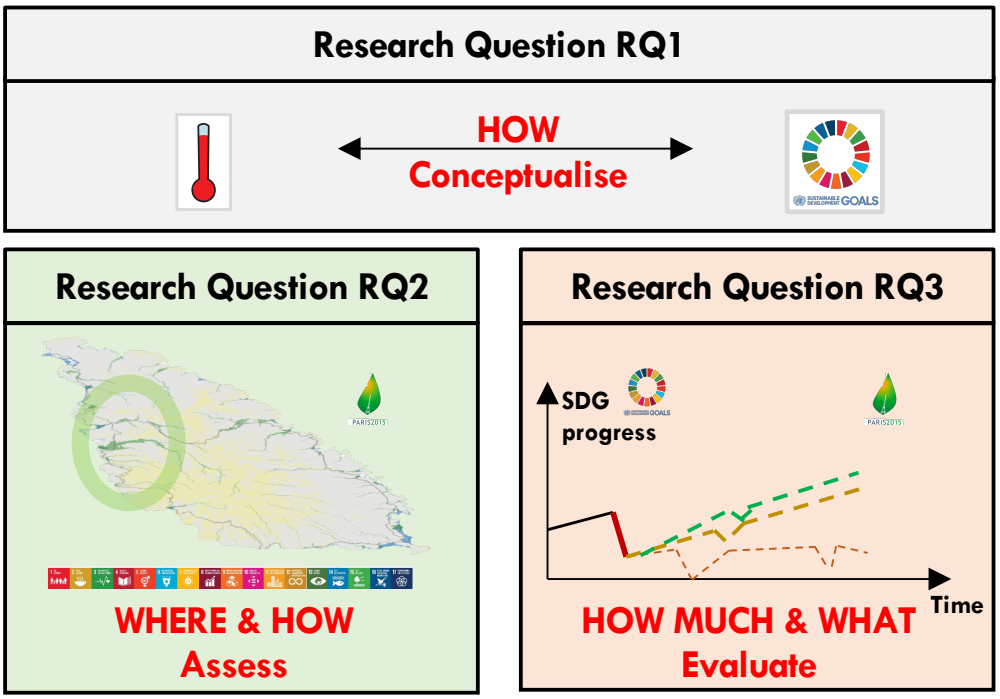


Figure 1.1: Visualising the components of the three research questions of this thesis.

1.5 Addressing the research questions

The three research questions are addressed through three substantive chapters of this thesis, which are written in the form of first-author journal publications. Research Question 1 is addressed in the first paper (Chapter 4) through the development of a framework on conceptualising the links between sustainable development targets and different climate change impacts at the scale of sectors (see Figure 1.2). The second paper (Chapter 5) makes use of this conceptual framework by developing a national-scale methodology that utilises climate-change hazards as a starting point of a climate adaptation assessment

(climate-first approach). This methodology allows spatially assessing the impacts of climate-change hazards on all a nation's sectors and physical assets and its interdependent impacts on the SDG targets, addressing the methodological objective of Research Question 2. The third paper (Chapter 6) grounds national adaptation assessments in an SDG vision, by developing a national-scale methodology that uses the SDG targets as a starting point of a climate adaptation assessment (development-first approach). This methodology allows evaluating how much and what type of adaptation can safeguard and advance SDG targets, addressing the methodological objective of Research Question 3.

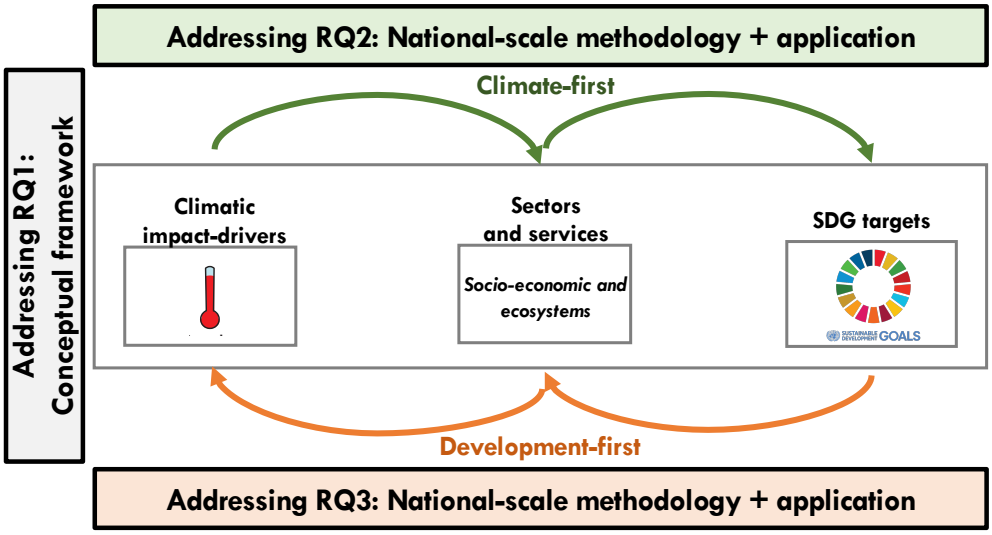


Figure 1.2: Addressing the three research questions through three substantive chapters of this thesis.

To account for the applied and practical action research objectives embedded in Research Question 2 and 3, the two national-scale methodologies are tested in Saint Lucia and in Ghana, respectively (see Chapter 3 for details and justification). As a small island located in a hazard-prone area, Saint Lucia is highly exposed to hazards such as storm surges or flash floods. Assessing the impacts of these hazards on all dimensions of sustainable development is particularly important for Saint Lucia to make the case for adaptation, apply to global climate finance, and prioritise adaptation across assets and sectors. As an African country, Ghana faces not only severe climate-change hazards, but also numerous development challenges. Evaluating national adaptation, grounded in a sustainable development vision, is especially important for Ghana's decision-makers

to ensure climate adaptation not only reduces risks, but also safeguards and advances sustainable development outcomes. Both national governments of Saint Lucia and of Ghana show a strong commitment towards achievement of the SDGs and the Paris Agreement, and are interested in aligning national adaptation planning with the global agendas. Application of the proposed methodologies as well as engagement with national decision-makers in these two countries can therefore play an important role in providing guidance for national decision-makers to inform adaptation to deliver on the shared vision of the SDGs and the Paris Agreement.

1.6 Outline of thesis

This thesis is comprised of six chapters. This **first** chapter has provided the background and motivation for investigating the complex links between sustainable development and climate change impacts to better inform national adaptation planning in the context of the global agendas. It has outlined the major conceptual, methodological, and applied research gaps and identified three research questions and related objectives. The chapter concluded with an overview of how the three research questions are addressed in the three substantive chapters of this thesis.

The **second** chapter provides a comprehensive literature review of the key *conceptual* and *methodological* research that underpins the work in this thesis. The conceptual literature review focuses on the main origins and themes to better understand the concepts of sustainable development and climate change impacts, whilst the methodological literature review highlights best practices to assess and evaluate national adaptation planning through developing and applying national-scale methodologies. The final sections of both the conceptual and the methodological literature review outline remaining literature gaps, which form the basis of the three research questions that are addressed throughout each of the three substantive chapters of this thesis (see Table 1.1).

The **third** chapter describes the overarching research design used in this thesis. It introduces the test case studies for the practical applications of this thesis (Chapter 5 and 6) and briefly summarises all methods and data.

Table 1.1: Addressing the research questions through three journal papers.

Research Question (RQ) and related gap	**Related objectives**	**Related literature review**	**Written according to journal guideline (Status)**	**Addressed in Chapter**
RQ1 Conceptualise links between SDG targets and climate change impacts	Conceptual	Chapter 2.1	Nature Communications (Revision submitted)	Chapter 4
RQ2 Assess impacts of climate change on SDG targets	Methodological Practical	Chapter 2.2	Global Environmental Change (Accepted)	Chapter 5
RQ3 Evaluate adaptation based on SDG targets	Methodological Practical	Chapter 2.2	Global Environmental Change (Submitted)	Chapter 6

The **fourth** chapter addresses Research Question 1 by developing a framework to better conceptualise the various pathways of how socio-economic sectors and ecosystems mediate between the SDG targets and climate change impacts. A global application demonstrates one potential application of this framework. The chapter concludes by discussing considerations for how this understanding can help inform national adaptation under the Paris Agreement in alignment with the SDG targets.

The **fifth** chapter addresses Research Question 2 by developing a national-scale methodology to holistically assess where and how climate-change hazards can affect the 169 SDG targets at the scale of all a nation's physical assets. The chapter applies the methodology to the SIDS Saint Lucia to guide practical decision-making.

The **sixth** chapter addresses Research Question 3 by developing a national-scale methodology to evaluate adaptation not only to reduce climate risk but also to safeguard and advance the SDG targets, thereby grounding national adaptation assessments in an SDG vision. Using Ghana's energy and transport sector as a test case, the chapter applies the methodology to help inform practical decision-making.

The **seventh** chapter summarises the key contributions of this thesis and discusses its conceptual, methodological, and applied implications. Key limitations are highlighted and described in the context of future extensions of the work presented in this thesis.

Throughout this thesis, care was taken to reduce repetition between the three self-contained substantive chapters and the rest of the thesis. Cross-referencing between

the substantive chapters was considered necessary as the various chapters are closely related. In line with the journal guidelines of the papers that correspond to the three substantive chapters, chapter-specific supplementary tables are presented at the end of each substantive chapter. Supplementary information excel files for each of the three substantive chapters are attached to this thesis, and can be downloaded via the following link: https://doi.org/10.5281/zenodo.5643953.

2
Literature Review

This thesis makes a conceptual and methodological contribution to informing national-scale climate adaptation within the sustainable development narrative, via the lens of interdependent socio-economic sectors and ecosystems. Numerous approaches to conceptualising, assessing, and evaluating the links between sustainable development, climate change impacts and adaptation have been advanced throughout the academic literature, increasingly in the context of the global agendas. This chapter provides a comprehensive, but by no means exhaustive, review of this academic literature on the main conceptual as well as methodological advances and literature gaps underpinning the research questions and results presented in this thesis.

The first section of this chapter focuses on the main **conceptual** advances with respect to understanding the two challenges of sustainable development and climate change impacts and adaptation. These two challenges are discussed in three parts: a) providing a brief history of key concepts and debates in the field, b) summarising recent advances in the field, and c) discussing the academic literature on the key global agendas related to sustainable development and climate change impacts. Subsequently, advances on conceptually linking sustainable development and climate change impacts are summarised. Finally, key literature gaps pertaining to better conceptualise the links between the two main challenges in the context of the global agendas are outlined. These literature gaps directly underpin Research Question 1, which this thesis aims to

address by means of developing a conceptual framework to inform climate adaptation that contributes to the global agendas.

Drawing on a wide range of disciplinary scholarship, the second section of this literature review turns to reviewing existing **methodological** approaches with respect to assessing and evaluating the challenges of sustainable development and climate change impacts to inform decision-making in the context of the global agendas. These approaches include: good practices in decision-making, participatory methods and governance approaches, formalised methodologies for sustainable development assessments, and formalised methodologies for climate change impact and adaptation assessments. Finally, best practices and remaining literature gaps are outlined. These literature gaps directly underpin Research Question 2 and 3, which this thesis aims to address by means of developing and applying two national-scale methodologies.

2.1 Conceptual advances and the global agendas

2.1.1 Sustainable development and the SDGs

The concept of sustainable development is growing in prominence across all sectors and areas of society. In examining the conceptual origin and recent advances in the field of sustainable development, this section brings to light scholarly interpretations of the concept as well as its political translation: the Sustainable Development Goals. This scholarship has been widely influenced by a range of disciplines, including economics, international development, politics, and geography. As described in the below paragraphs, these disciplines have increasingly been brought together under the umbrella discipline of sustainability science.

Conceptual origin

The concept of sustainable development originally emerged from the awareness of the global links between socio-economic issues related to poverty and inequality and increasing environmental problems (IUCN 1980). Its aim is therefore most often stated in terms of delivering improved human well-being whilst sustaining environmental services, thereby adhering to intra- and inter-generational equity (Sen 1999; Von Bernard et al.

2010; Kates et al. 2001; Mensah 2019). This aim is also incorporated in the most commonly adopted Brundtland definition of sustainable development of "meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs" (WCED 1987, p.43). The term needs thereby refers to essential socio-economic needs such as access to water and energy, especially for the world's poorest, within the environment's ability to meet present and future needs (Rao 2000).

Debates on various interpretations of the Brundtland definition followed (Sachs 1999; Middleton et al. 1993; Haughton 1999; O'Riordan 1989), often distinguishing between what analysts sought to *sustain* and what they sought to *develop* (Kates et al. 2005). An important study by the Board on Sustainable Development identified mainly life support systems, community, and nature under the heading on 'what to sustain' (National Research Council 1999), emphasising ecosystem services, amongst others, for the utilitarian life support of humankind. Similarly, numerous distinct ideas emerged on 'what to develop', with the attention shifting from economic development towards human development and considerations of values that include life expectancy, equity, opportunity, education, and social capital (Kates et al. 2005). Whilst broad agreement emerged on combining what needs to be sustained with what is to be developed, the definition and relative weight given to each remained ambiguous. To this date, debates on the definitions and weights of sustainable development remain largely unresolved. Scholars continue to criticise the anthropocentric nature of sustainable development definitions that aim to sustain the environment due to merely its instrumental value for human well-being. Instead, they argue, more biocentristic interpretations that emphasise the intrinsic value of nature in the context of sustainable development are needed (Keitsch 2018; Meurs et al. 2018; Spahn 2018). Similarly, scholars continue to represent sustainable development in different ways, including those that depict the three pillars of sustainable development - the economic, social, and environmental - as three intersecting circles with equal weights (UN 2002) and those that consider achievement of socio-economic needs within environmental limits (Purvis et al. 2018).

Trade-offs between linking the 'what to sustain' with the 'what to develop' are inherent in all conceptualisations of sustainable development, especially when accounting for intra- and inter-generational equity. Debates on these trade-offs have largely been shaped by economics scholars. Weak sustainability scholars argue that the ecosystem services provided by nature are largely substitutable with man-made built capital such as infrastructure (Daly et al. 1989; Haughton et al. 1994). Therefore, it is possible for ecosystems to degrade as long as sufficient compensation is provided. Strong sustainability scholars criticise this viewpoint, pointing out that man-made capital cannot replace the multitude of ecosystem services vital to human existence such as regulating the water cycle or photosynthesis (Rees 1998; Roseland 1998).

In light of the various debates on what comprises sustainable development, scholars have critiqued the concept for being too broad and therefore open to potential disguise of environmentally or socially destructive activities, whilst others have emphasised that each definitional attempt is an important aspect of a dynamically changing dialogue (Kates et al. 2005). The concept is therefore an evolving idea that can be adapted to fit specific contexts across time and space.

Conceptual advances in understanding sustainable development

Since its origin, advances have emerged to better conceptualise sustainable development at global and national scales. At the global scale, sustainable development is increasingly defined through a normative dimension of goals and targets, thereby defining the concept through what it seeks to achieve. Others have defined sustainable development in terms of how it is measured, including measuring socio-economic progress through composite development indices (Booysen 2002) or measuring environmental limits through indicators on planetary boundaries (Rockström et al. 2009; Steffen et al. 2015). Efforts to integrate socio-economic and planetary boundaries emerged through the 'doughnut framework' (Raworth 2017), which calls for regenerative and distributive interventions towards sustainable development. Yet other scholars have defined sustainable development in practical terms, highlighting how the framework of 'sustainomics' can help identify practical interventions that improve the quality of life at a lower resource intensity.

Improvements in the quality of life at lower resource intensity can be achieved by aiming to maintain six important social, economic, or natural capitals (people, communities, infrastructure, finance, biodiversity, and ecosystems) whilst generating and managing the services from these capitals that are critical for sustainable development (Munasinghe 2009; Islam et al. 2003). Scaling up service provision from socio-economic capital for sustainable development for example includes investing in sustainable infrastructure investments (Thacker, Hall, et al. 2017). Increasingly however, there have been acknowledgements that unlike socio-economic capital, only some aspects of the natural capital can be managed by human interventions (Maseyk et al. 2017).

In efforts to better conceptualise the contribution of natural capital to sustainable development, the Common International Classification of Ecosystem Services (CICES) formally identified the range of ecosystem services provided by the world's natural capital, which contribute to sustainable development (EEA 2018). Building on earlier works of the Millenium Ecosystem Assessment (2005), the CICES classification consists of different categories of ecosystem services. Whilst regulating (e.g. regulating soil quality) and supporting services (e.g. habitat provision) are mainly hidden from our view, cultural (e.g. natural heritage sites) and provisioning services (e.g. food provision) have more detectable outcomes, so have typically received most attention in sustainability debates (Dasgupta 2020). However, the multi-functionality of natural capital in providing multiple ecosystem services simultaneously is one of their key features that differentiates them from socio-economic capital, or the built environment, which typically provide a single service (Bateman et al. 2020). For example, mangroves can provide protection from extreme storms, habitat for fisheries, recreational value, and freshwater services simultaneously. Whilst each function might be replaced by socio-economic capital to provide a higher level of individual service delivery towards a specific sustainability target (e.g. storm protection or provision of freshwater), this is usually confined to a specific service at one time. Most recent literature therefore suggests that the substitutability between natural and socio-economic capital is low, aligned with arguments from strong sustainability scholars (Fitter 2013).

Whilst the concept of the services provided by socio-economic or natural capital, also referred to as socio-economic sectors and ecosystems, emerged as a useful means to explore interdependencies and trade-offs for achieving sustainable development, ambiguities in the conceptualisation of sustainable development remain to this date. In the academic discourse, these are often referred to as wicked problems (Rittel et al. 1973), whereby cause-effect relationships and potential solutions are characterised by complex interdependencies for which no single solution exists. Achieving sustainable development instead demands multi-sector and multi-actor efforts at local, national, and global levels.

The SDGs as a global response towards sustainable development

In an attempt to formulate a global definition of sustainable development that helps stir multi-sector and multi-action efforts, United Nations member states adopted the Agenda 2030 for Sustainable Development. This Agenda is a political compromise of efforts to achieve sustainable development, and defines a normative blueprint for prosperity for the planet and the people. At its heart are 17 Sustainable Development Goals (SDGs), which are made tangible by their 169 targets that cover economic, social, and environmental dimensions of sustainability and all sectors of society (UN 2015). The SDGs represent a progression in scope and ambition from the previous Millennium Development Goals (MDGs), which have been criticised for their narrow focus on socio-economic needs of the poorest (Fukuda-Parr 2014; Langford et al. 2013). Unlike the MDGs, the SDGs highlight the equal weight and importance of the environment, and include both developing and developed countries.

From the outset of SDG conceptualisations, the importance of understanding synergies and trade-offs within the SDGs was established (Nilsson et al. 2013), resulting in extensive analyses of SDG interlinkages. Initial attempts to systematically structure SDGs interlinkages included clustering them by their systemic functions (Breuer et al. 2019). For example, using the 'doughnut framework' as a basis, Niestroy (2016) describes a circle model consisting of people-centered SDGs at the heart, grounded by production and resource distribution SDGs, which in turn are dependent on nature-centered SDGs. Peace and global partnership goals are the overarching enabling goals. Beyond goal analysis,

the interlinkages between the SDGs have increasingly been analysed and quantified at the level of SDG targets (Nilsson et al. 2016; Bennich et al. 2020; Le Blanc 2015; Weitz et al. 2018). Thereby, maximising synergies whilst carefully negotiating trade-offs amongst interlinked goals and targets has been considered essential to ensure progress towards the SDGs (Pradhan et al. 2017).

Literature has also aimed to quantitatively understand the interlinkages between the SDGs by applying the sustainomics framework and network science. For example, Lusseau et al. (2019) estimate the network of SDG interactions with the use of global time series data of SDG indicators for countries across various income levels, which underscores the prevalence of mainly synergies across goals for low-income countries and some trade-offs across goals especially for high-income countries. However, despite the usefulness of such indicator-based assessments to consider SDG interdependencies, their quantitative approach can be criticised for relying on limited global data and current SDG indicator availability (Diaz-Sarachaga et al. 2018).

To provide a broader conceptualisation of interlinkages between the SDGs, including in an effort to identify practical action towards achievement of the SDGs, various studies have focused on identifying interlinkages, also termed 'SDG influences', between sectors and their services and the SDG targets. Building on the concept of the services provided by sectors, qualitative analyses at the SDG target level have been completed for some socio-economic sectors and ecosystems to identify potential influences on SDG target outcomes. These analyses typically use expert elicitation, surveys, or evidence-mapping to identify the contributions of sectors to each SDG target. Past work includes understanding the influence of energy, water, soils, some ecosystems, biodiversity, or infrastructure sectors to the SDG targets (McCollum et al. 2018; Velis et al. 2017; Wood et al. 2018; Blicharska et al. 2019; Singh et al. 2018; Thacker et al. 2019).

Beyond single sectors, the importance of systems thinking has been highlighted to enable a range of development benefits (Mulugetta et al. 2019). Such systems approaches can help examine interactions amongst multiple sectors, thereby helping to uncover synergies and detect trade-offs in the context of the SDGs (Liu et al. 2018). Despite the scholarly progress on the topic, the literature stresses that key gaps remain in terms of

assessing interdependencies in the context of putting the SDG targets into action (Allen et al. 2018). In particular, Stafford-Smith et al. (2016) argue that greater attention on interdependencies is required in three key areas: a) across *sectors* (energy, transport, agriculture, etc.), b) across *actors* (government agencies, private and civil society), and c) across low, medium and high-income *countries*. Based on two literature reviews of SDG conceptualisations, Bennich et al. (2020) highlight the need for future studies to take truly holistic approaches to SDG influences that consider all 169 SDG targets; whilst Breuer et al. (2019) argue for a stronger conceptual focus in relation to SDG implementation that can be operationalised by nations in spite of potential data availability issues.

2.1.2 Adaptation to climate change impacts and the Paris Agreement

Similar to the concept of sustainable development, adaptation also has a diverse legacy, originating from a variety of disciplines that include ecology, evolutionary biology, anthropology, disaster risk, geography, and development (Ford et al. 2010; Malone et al. 2011; Jurgilevich et al. 2017; Sietsma et al. 2021). This thesis focuses on the concept of climate adaptation, in other words, adapting to the impacts of climate change.

Conceptual history

Early years of climate change research were characterised by mathematical and hazard modelling studies to identify where and how much climate adaptation is needed, mainly based on where impacts of climate change are being experienced or anticipated (Bjurström et al. 2011; Klein et al. 2017). The initial hazard-focused framing in climate change research adopted numerous concepts from the disaster risk community, including the framing that risk is the product of the likelihood of hazards and their negative consequences (Burton 1993). The main goal of disaster risk management, namely the reduction of current and near-term risks from hazards, has increasingly been applied in the context of climate adaptation. Thereby, scholars recognised that compared to disaster risk management, climate adaptation is a longer-term process of adjusting to both the negative, but also potential opportunities arising from the impacts of climate

change (Schipper et al. 2016). Assessments of climate change based on a hazard-focused framing mainly focused on analysing risk from climate change on productive sectors and people in order to identify where physical adaptation options can help cost-effectively reduce such risk. Thereby, adaptation was conceptualised directly as a response to risk from climate change. To this date, risk-reduction remains one of the central objectives of climate adaptation (Tompkins et al. 2018).

Given critiques of hazard-focused research for failing to incorporate broader socio-economic processes of climate adaptation (Burton et al. 2002), vulnerability-focused adaptation research increasingly recognised climate change as a problem of development, with Least Developed Countries (LDCs) considered as particularly vulnerable (Adger et al. 2003). Vulnerability has most often been defined through inherent social interpretations, such as the multiple socio-economic and political predispositions to be adversely affected (Füssel 2007), or through the term adaptive capacity, defined as the potential for communities or systems to adjust effectively to the impacts of climate change (O'Brien et al. 2004; Ribot 2014; Adger et al. 1999). The socio-economic aspects of vulnerability became important areas for innovative research and helped to understand social adaptation needs. The importance of reducing vulnerability, both on social and economic capital, emerged as another central objective of adaptation, which includes strengthening adaptive capacity (Huq 2001; Smith et al. 2003). Research identified the determinants of adaptive capacity, including the availability of financial resources, structures of institutions, stocks of social and economic capital, and decision-maker's ability to manage information (Yohe et al. 2002). Poverty and development studies added to this by highlighting the importance of capabilities and entitlement to reducing socio-economic vulnerability and increasing adaptive capacity (Adger 2006). Other scholars emphasised that vulnerability is not only a socio-economic concept, it is also closely linked to reliance on natural resources and ecosystem services (Roy et al. 2002). In this context, interactions between social and ecological resilience were studied, whereby building socio-ecological resilience is considered a further key objective of climate adaptation to this date (Tompkins et al. 2018), defined as the capacity to resist and recover from perturbations and maintain the flow of ecosystem services (Pimm 1984; Holling 1995).

With the aim of bringing together disciplinary scholars, integrated approaches between hazard-focused and vulnerability-focused research gained traction to study adaptation (Liverman 1990a; Liverman 1990b; Kates 1987). Frameworks such as the pressure-and-release (PAR) model emerged, which bring together hazard and vulnerability (Wisner et al. 2004), whereby vulnerability involves both locally vulnerable conditions as well as socio-economic root causes. Notable is the hazard-of-place approach (Cutter 1993; Cutter et al. 2000; Cutter et al. 2003) with roots in geography, which defines vulnerability as spatial interactions of the hazards of place with social profiles of communities (Cutter 1993).

Building on such integrated hazard-of-place approaches, the IPCC's most recent definition of climate change impacts and risks entails one of the most cited conceptualisations for understanding climate change and the role of adaptation, which is adopted in this thesis (Figure 2.1) (Oppenheimer et al. 2014; IPCC 2012; IPCC 2019; IPCC 2018). Whilst acknowledging the potential positive effects from climatic impact-drivers, this widely used IPCC conceptualisation focuses mainly on negative impacts. These impacts are defined as the realised risks resulting from the interactions between: i) hazards, triggered by acute or chronic climatic impact-drivers, ii) exposure, which includes the assets, ecosystems, or people located in hazard-prone areas, and iii) vulnerability, the sensitivity to harm.

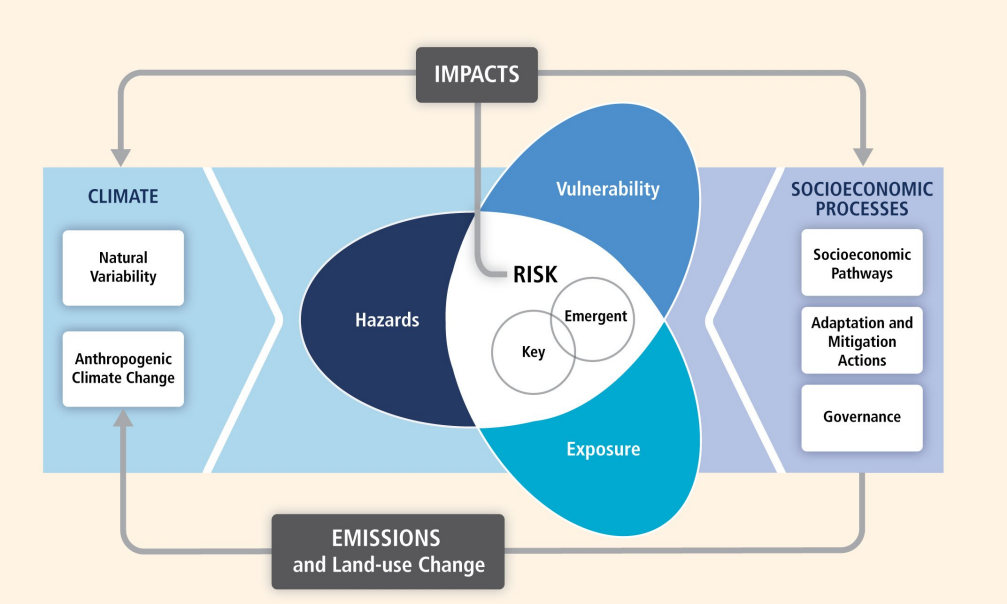


Figure 2.1: Conceptualisation of climate change impacts and adaptation. Source: Oppenheimer et al. (2014)

Importantly, to account for a broader understanding of the vulnerability context of climate change, the IPCC adjusted its wording on vulnerability towards a conceptualisation of vulnerability independent of the physical hazard, which includes adaptive capacity. It has been argued that this shift allows for a deeper understanding of the contextual factors and lends itself to alternative sets of policy options (O'Brien et al. 2007). In line with these more integrated approaches, the IPCC also broadened its definition of adaptation needs across a variety of dimensions and sectors. These include bio-physical, social, financial, and institutional dimensions of needs as well as sectors spanning water, ecosystems, food, human settlements and infrastructure, health and wellbeing, and poverty (IPCC 2012; IPCC 2021; Yokohata et al. 2019).

Conceptual advances in understanding adaptation needs

Advances in better understanding the three main components of climate risk (hazard, exposure, vulnerability) continuously shape adaptation needs. First, this includes a better *hazard* understanding in terms of experienced as well as observed climate change, derived from detection and event attribution studies (Otto 2017); and in terms of anticipated future hazard severity and intensity with climate change, derived from empirical (Dell et al. 2012; Burke et al. 2015) and process-based models that translate projected changes in climate into specific processes such as frequency of river flooding (Frieler et al. 2017). Second, it involves a better *exposure* understanding, including from combining process-based hazard models with advances in bio-physical and socio-economic modelling. This improved exposure understanding helps researchers better estimate hazard exposure of populations and critical infrastructure sectors, such as roads or ports at high spatial granularity (Winsemius et al. 2016; Koks, Rozenberg, et al. 2019; Izaguirre et al. 2021). Third, it includes a better *vulnerability* understanding, derived from an increasing availability of fragility and depth-damage functions that characterise asset vulnerability, as well as a better understanding of adaptive capacity and social and ecological determinants of vulnerability (Ford et al. 2010).

Taken together, these conceptual advances have resulted in calls to consider complex risks in adaptation assessments, resulting from multiple acute and chronic hazards,

cross-sectoral exposure, vulnerability, and adaptation responses (Simpson et al. 2021). Whilst previously, most studies focused on evaluating impacts of single hazards on specific sectors (Kappes et al. 2012; Santini et al. 2010; Feyen et al. 2012; Hinkel et al. 2011), it became clear that such a focus does not capture the holistic, integrated understanding of multiple risks triggered by different hazards and with impacts across sectors (Glade et al. 2005; Marzocchi et al. 2012). Increasingly, the field of climate impact modelling has moved towards such integrated impact assessments, which aim to identify interdependencies between hazards as well as between sectoral impacts (Harrison et al. 2015; Harrison et al. 2016; Frieler et al. 2017). For example, Harrison et al. (2016) show that single sector studies often misrepresent the spatial patterns, directions, and magnitudes of most impacts, as they omit complex interdependencies, such as between food provision and water extraction. In contrast, complex risk frameworks help decision-makers better identify potential impacts from different and potential simultaneous acute and chronic hazards, resulting in a more holistic understanding of bio-physical, social, institutional, and financial adaptation needs (Yohe et al. 2002; Adger 2006; Eakin et al. 2006).

Conceptual advances in understanding adaptation options

As a response to the improved understanding of adaptation needs, there has been no dearth of conceptual advances on adaptation options to meet these needs. There are numerous ways in which the range of adaptation options might by classified into categories (Burton 1993; Berrang-Ford et al. 2011; Lesnikowski et al. 2011; Lesnikowski et al. 2013), so no one categorisation is considered universal (Noble et al. 2015). The literature on existing categorisations generally focuses on five areas for differentiating between adaptation options (Biagini et al. 2014; Carter et al. 1994; Fidelman et al. 2013):

1. timing relative to a stimulus, thereby differentiating by anticipatory, concurrent, and reactive actions,
2. intent, which focuses on autonomous versus planned action,
3. scope, which includes local, regional, and/or national decision-making,

4. types of options, which include for example adaptation research, social vulnerability, engineering, nature-based, behavioural, or institutional actions, and
5. degree of change, differentiating by incremental responses that address impacts based on current practices as well as transformational responses, which involve innovations that challenge business-as-usual approaches.

In the context of informing national adaptation planning - the focus of this thesis - the timing, intent, and scope of adaptation is predefined as being an anticipatory and planned set of options assessed and evaluated ex-ante at the national level. Yet, the types of options and degree of change are largely inter-related and determined by conceptualisations of adaptation more broadly.

To categorise the types of options in the context of national adaptation planning, Lesnikowski et al. (2013) differentiate between *recognition* options that demonstrate awareness, *groundwork* options that inform and prepare stakeholders for action through for example adaptation research, and *targeted adaptation options* that refer to tangible actions. Whilst all three types are essential for national adaptation, the latter type is most aligned with the conceptualisation adopted by the IPCC and in this thesis. This IPCC conceptualisation of targeted adaptation options specifically refers to options that: reduce hazards (addressing the source for example through restoring mangroves that lessen hazard severity), reduce exposure (addressing the pathway for example through land-use planning), and reduce vulnerability (addressing the receptor for example through emergency responses, insurance, or social protection schemes) (Masson-Delmotte et al. 2018). Such a conceptualisation of targeted adaptation options can be expanded by further tailoring the choice of adaptation option by the type of hazard and the type of exposure and vulnerability context. Different hazards require different responses, for example sea-level rise may benefit from improved coastal land-use planning, whilst heatwaves in urban areas may benefit more from natural greening solution. Similarly, a different type of exposure or vulnerability context might render certain adaptation options more or less relevant (Klijn et al. 2021; Zommers et al. 2018).

In practice, adaptation options are rarely taken in silo. Portfolios of adaptation options are often designed that aim to reduce all three components of risk together (Jongman

2018), helping to reduce limitations when relying on individual options. For example, wetland protection might help in buffering low-impact/ high-frequency hazard events, but is less likely to be able to protect livelihoods in the case of high impact/ low frequency hazard events. Notably, Mechler et al. (2014) suggest a risk-layering concept to determine the type of adaptation option based on the probability of occurrence and the degree of impact, which differentiates by different types of climate-change hazard events. For low-impact/high-frequency hazard events, hazard and exposure-based adaptation options can efficiently reduce risk. For medium-impact and frequency hazard events, options that reduce hazard and exposure might be combined with vulnerability-based options. For high-impact/low-frequency hazard events, public and donor post-disaster assistance is necessary, as insurers are unlikely to cover risks (Mechler et al. 2014).

The development of portfolios of option is a challenging process, and largely depends on complex political processes and institutional set-ups (Khan 2013). Whilst there are a set of adaptation opportunities that make it easier to plan and implement adaptation actions (such as public awareness), adaptation constraints can restrict the effectiveness of options and include for example the lack of financial resources, lack of connectivity and environmental quality for ecosystems, as well as other social, cultural, and bio-physical factors (Klein et al. 2014). It is well documented that the interaction of these factors with climate change can result in adaptation limits. Adaptation limits are defined as the point at which it is not possible to avoid intolerable risk to the sustainability of a system or an actor's objectives through adaptation (Klein et al. 2014). Soft adaptation limits include circumstances in which adaptation options do not currently exist, whilst hard adaptation limits include circumstances where adaptation appears infeasible, resulting in unavoidable impacts. Despite the existence of adaptation constraints and limits, the scholarly literature on climate change impacts unequivocally points to the understanding that there are a broad range of adaptation options that can practically be adopted by national governments to reduce climate risk, especially for medium/high-frequency hazards that are likely to further increase in frequency or severity into the future (Wilby et al. 2010).

The Paris Agreement as a global response to the impacts of climate change

In an effort to translate the scientifically necessary action to respond to climate change into the politically possible, 196 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have ratified the Paris Agreement in 2015. This Agreement commits both developing and developed countries to keep the global temperature increase below 2 degrees in the twenty-first century whilst pursuing efforts to limit this increase to 1.5 degrees *and* to adapt to the impacts of climate change (UNFCCC 2016a). Unlike mitigation, national adaptation under the Paris Agreement is not considered with the same responsibility or commitments for states. Hall et al. (2017) argue that one of the reasons for the low obligatory nature of the adaptation commitments under the Paris Agreement is its contested conceptual legacy. This contested legacy includes debates on whether adaptation is a local private good or a global public good that is under-provided and needs international cooperation (Khan 2013; Magnan et al. 2016).

Whilst avoiding a binding obligation on adaptation, the Paris Agreement does, for the first time, commit all state parties to a global adaptation goal of "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development…". (Article 7, point 1). Article 7 signals an ambitious and universal attitude towards adaptation, strengthening the focus on reporting and assessing adaptation and encouraging the expansion of adaptation planning to all parties (Helgeson et al. 2015; Magnan et al. 2016; Adaptation Committee 2016). The Paris Agreement therefore reinforces and expands existing efforts established in prior UNFCCC negotiations that typically focused on less developed countries (Morgan et al. 2019), including: i) National Adaptation Programmes of Actions initiated at the Conference Of the Parties (COP) 7 in 2001, which focussed on addressing urgent and immediate adaptation needs; ii) the Adaptation Fund operationalised at COP13; and iii) a process for developing NAPs established in the Cancun Adaptation Framework at COP16, which included technical guidance on preparing NAPs for less developed countries. The Paris Agreement calls on all parties to submit NAPs and adaptation commitments to the UNFCCC (UNFCCC 2016b).

Since the adoption of the Paris Agreement in 2015, much scholarly research focused on providing the scientific basis to implement national adaptation. With the aim of moving forwards on adaptation, rather than being constrained by debates on its conceptual definitions, Tompkins et al. (2018) propose ways forward to help nations document adaptation under commitments of the Paris Agreement, thereby focussing on the broadly agreed and worthwhile objectives of climate adaptation: i) to address disaster risk; ii) to reduce socio-economic vulnerability; iii) to support social-ecological resilience (Adger et al. 2007; Noble et al. 2015; Smit et al. 2001). Yet, as stated by Lesnikowski et al. (2017), much work remains to be done to meaningfully realise the long-term global goal for adaptation as set out in the Paris Agreement. Most notably, this includes strengthening national adaptation planning to: i) aid actionable decision-making, ii) involve multi-agency committees (Woodruff et al. 2019), and iii) explicitly link national adaptation planning to sustainable development (Preston et al. 2011).

2.1.3 A critical review: development-adaptation links

The links between the concepts of sustainable development and climate adaptation are complex and cross-cutting (Denton et al. 2015). Scholarly literature has emphasised these links in the context of the SDGs and the Paris Agreement, yet much scope remains to better conceptualise the pathways of *how* sustainable development targets are linked to different impacts of climate change, and how adaptation can contribute to achieving the global agendas.

Climate change impacts, adaptation, and sustainable development

Impacts of climate change may stall sustainable development efforts (Fuso Nerini et al. 2018). These impacts are already affecting numerous sectors such as energy, agriculture, forestry, and water (World Bank 2010; Adger et al. 2011; IPCC 2012), which provide essential services that underpin sustainable development. As the previous sub-section observed, definitions of adaptive capacity often include a function of the distribution and accessibility to the services provided by sectors such as energy or water; the strength of a nation's institutions and governance; and factors such as age, gender, or social status

(Smith et al. 2003; Beg et al. 2002; Huq et al. 2009). Therefore, the conditions that define adaptive capacity are firmly rooted in development processes, including service provision or structural deficits (Brooks et al. 2005; Lemos et al. 2013).

It follows that strengthening a population's adaptive capacity can be conceptualised as one of the key mediating responses to both achieving sustainable development and helping to adapt to climate change impacts (Denton et al. 2015; Schipper 2006). Enhancing adaptive capacities of vulnerable population groups has been considered one of the four ways in which also sustainable development can lead to effective adaptation (IPCC 2018), with the other three ways including: i) adopting an integrated, inclusive, transparent decision-making approach that addresses current vulnerabilities within the development context (Fankhauser et al. 2014; Lemos et al. 2016), ii) multi-scale planning across sectors and issues (Antwi-Agyei et al. 2018), and iii) addressing social inequalities and mobilising finance to strengthen the enabling environment for resilience-building (O'Brien 2016; O'Brien 2017; Halonen et al. 2017).

Similarly, adaptation options that prioritise sustainable development are often conceptualised as also being better at implementing successful adaptation (Forsyth 2007; Brown 2011). These reinforcing loops between sustainable development and adaptation have been brought together under the umbrella term of 'climate-resilient development pathways', which can be framed as iterative, continuously evolving processes for managing climate change to realise the goal of sustainable development (Denton et al. 2015; Singh et al. 2021). In this context, Nature-based Solutions (NbS), defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, which address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016), have been conceptualised as a useful means by which to contribute to climate-resilient development pathways.

Avoiding maladaptation

With a growing evidence base on potential synergies between climate adaptation and sustainable development, there is also a growing number of critiques that recognise that not every response to climate change is consistent with sustainable development, and

indeed, some responses may result in maladaptation (Eriksen et al. 2011; Eriksen et al. 2021; Seddon et al. 2020). Maladaptation is defined as the negative effects resulting from adaptation that increases vulnerability or erodes the preconditions for sustainable development (Juhola et al. 2016). Schipper et al. (2020) argue that poor planning is the primary cause of maladaptation, but unless the drivers of vulnerability are directly addressed, maladaptation is likely to prevail. Similarly, not all development policies build overall adaptive capacity, and some may exacerbate climate change impacts, such as developments in hazard-prone areas (Bizikova et al. 2007; Garg et al. 2009; Lemos et al. 2013). To reduce maladaptation, scholars have argued for the need to: i) explicitly highlight the potential sustainability implications of adaptation at the core of adaptation planning, ii) engage adaptation practitioners and the local population participating in adaptation actions, and iii) build local capacity, including making the voices of vulnerable groups heard in decision-making (Eriksen et al. 2021; Seddon et al. 2021).

Yet, whilst extensively called for, linking adaptation and development is rarely documented in practice, and complicated by poor stakeholder coordination, politics, power, and fragmented knowledge on sustainable development and climate adaptation (Schipper et al. 2016; Patterson et al. 2017). In practice, a major factor constraining the integration of sustainable development and climate adaptation is the separation between nations' own development agendas and access to globally-available adaptation funds (Hardee et al. 2009; Seballos et al. 2011). Therefore, literature has called on the academic community to develop means by which to support national decision-makers to better target adaptation for sustainable development (Denton et al. 2015), which is particularly important to inform synergistic action in the context of the shared vision of the global agendas.

The scale of sectors and services can provide a useful means for the academic community to bring together advances in the conceptualisation of sustainable development and climate change impacts. The sector-scale can also help support national decision-making, as nation's own development agendas are often described in terms of sectors. Yet, to date, the majority of scholarly literature to date has focused on bringing together mitigation under the Paris Agreement and the SDGs (Soergel et al. 2021), including at

the level of socio-economic sectors and ecosystems (IPCC 2018). Whilst adaptation has featured in some SDG target analyses alongside climate change impacts (Fuso Nerini et al. 2019), this to date has not accounted for the potential of action across interdependent socio-economic sectors and ecosystems to both adapt to different acute and chronic climatic impact-drivers *and* safeguard and advance SDG target achievement.

2.1.4 The need for an overarching conceptual framework

The studies reviewed in this conceptual literature review section highlight that sustainable development and climate change impacts are complex and deeply intertwined challenges, shaped by numerous disciplines and world views (Singh et al. 2021). As a compromise between the scientifically necessary and the politically possible (Kanie et al. 2019), the adoption of the SDGs and the Paris Agreement in 2015 represent the best global response and operalisation towards addressing sustainable development and climate change impacts in practice. Advances in the literature allow conceptualising the links between sustainable development targets and climate mitigation at a scale useful to inform *climate mitigation* decisions (IPCC 2018). Yet, to date research has not conceptualised the complex links between sustainable development targets and climate change impacts at a scale useful for informing *climate adaptation* decisions in practice (Fuso Nerini et al. 2019; TWI2050 2018; Gomez-Echeverri 2018). In order to provide a structure for understanding these complex links, a conceptual framework is needed to help decision-makers better target national climate adaptation under the Paris Agreement in alignment with sustainable development targets.

In reviewing the conceptual literature on sustainable development, climate change impacts and adaptation, a number of considerations and existing limitations emerge that can be used to underpin the development of such a conceptual framework.

1. Adopt widely-accepted and normative definitions for sustainable development and climate adaptation that guide decision-making in practice:

    - For sustainable development, this includes meeting socio-economic needs whilst protecting ecosystems and the services they provide.

- For climate adaptation, this includes addressing socio-economic vulnerability, building socio-ecological resilience, and reducing risk.
- Follow a globally-agreed upon understanding of what sustainable development and climate adaptation seeks to achieve, by conceptualising these terms through the global SDGs and the Paris Agreement.

2. Integrate socio-economic sectors and ecosystems (and the services these provide), which are essential for sustainable development and climate adaptation:

   - Meeting socio-economic needs within planetary boundaries, including by managing the services provided by sectors, are central foundations of sustainable development.
   - Sectors and the services these provide are also conceptualised as being at risk of climate change impacts. By making sectors more resilient, adaptation can safeguard the services that sectors provide, up to the limits of adaptation.
   - Improving adaptive capacity, including scaling up accessibility to services, can both increase sustainable development and help adapt to the impacts of climate change.
   - Adaptation options that prioritise sustainable development can help other sectors adapt to climate change and contribute to sustainable development.
   - Identifying SDG influences between sectors and SDG targets helps to provide a strong conceptual basis for identifying practical sustainability action in spite of SDG indicator limitations.

3. Account for advances in understanding sustainable development and climate adaptation, including in the context of the SDGs and the Paris Agreement:

   - Consider the multi-sector and multi-actor efforts required for achieving sustainable development.
   - Account for complex risks, including advances in the understanding of interdependencies between acute and chronic climate-change hazards, exposure across sectors, and vulnerability.

- No single adaptation option can reduce all risk; use risk layering and combinations of options to increase the effectiveness of adaptation strategies, which is particularly effective for high and medium frequency climate-change hazard events.
- Tailor adaptation options to the hazard they seek to reduce as well as to a nation's exposure and vulnerability context.
- Integrate sustainable development in national adaptation planning to help reduce maladaptation.

4. Systems approaches to climate adaptation that take a holistic framing are needed:

    - Despite their importance, interdependencies between sectors, between sustainable development targets and different impacts of climate change are seldom acknowledged in existing conceptualisations of development-climate links.
    - Explicitly acknowledging these interdependencies through systems approaches that integrate both socio-economic (built environment) sectors and ecosystems (natural environment), all 169 SDG targets, and different impacts of climate change are essential to operationalise adaptation commitments aligned with sustainable development.

The conceptual framework developed in this thesis builds on the existing frameworks and methods used in recent studies that identified: i) the role of some socio-economic sectors and ecosystems in influencing SDG targets, and ii) the influences of some climate change impacts directly on SDG targets (Fuso Nerini et al. 2019; Thacker et al. 2019). The conceptual framework extends the breadth of sectors and services considered, and explicitly accounts for indirect influences and the interdependencies between these, one of the key literature gaps identified in previous studies. Further, it expands upon previous studies on climate change impacts on SDG targets by differentiating between different types of climatic impact-drivers, including both acute and chronic climatic impact-drivers, aligned with the complex risk concept.

Taking an integrated, hazard-of-place focus to conceptualise climate change impacts on sectors, the proposed conceptual framework allows integration with emerging data

sources on negative climatic impact-drivers (i.e. climate-change hazards), potentially exposed assets, and vulnerability datasets at high spatial granularity. Thereby, the conceptual framework is particularly applicable to reducing the three components of risk for high and medium frequency climate-change hazard events, consistent with the risk-layering concept. In the context of the global agendas, application of the conceptual framework can be used to identify and determine synergies between climate adaptation and sustainable development outcomes, which remains a broadly unmet requirement for national adaptation planning under the Paris Agreement.

The proposed conceptual framework aims to consider the complexities and feedback loops highlighted both in the sustainable development and the climate adaptation literature through a more holistic conceptualisation of the various links between the achievement of the SDG targets and a range of impacts from climate change. It thereby explicitly highlights *potential* influences across a holistic set of sectors, acknowledging that experienced influences between sectors and SDG targets, and sectors and climatic impact-drivers are highly context-specific. To better account for these context-specific aspects, detailed national-scale methodologies must be developed and applied to operationalise the conceptual framework in practice.

2.2 Methodological advances

Beyond its conceptual focus, this thesis addresses the topic of developing and applying national-scale methodologies to assess and evaluate adaptation for sustainable development through the lenses of national decision-makers. National decision-makers include policymakers, managers, planners within government and its departments, practitioners, and a range of individuals from national-scale organisations and institutions. This section provides a review of applied methodologies for making good decisions through participatory methods and formalised approaches, including in the context of sustainable development as well as climate adaptation assessments. By highlighting differences, similarities, and best practices of assessments in each of the two fields, the need for integrated methodologies to better inform adaptation decision-making is emphasised.

2.2.1 Good decision-making

Whilst decision-making is inherently context-dependent, findings from the fields of decision theory, ethical reasoning, and risk governance offer general principles for strengthening the quality of decisions, which can be grouped into two main themes (Jones et al. 2014). Firstly, 'good' decisions emerge from participatory processes with strong governance frameworks; and secondly, the formalisation of the decision-making process helps better assess and evaluate decisions ex-ante, thereby increasing the likelihood for better outcomes (Townley 1992).

Grounded in participatory processes with strong governance frameworks, good decision-making transparently exposes decision criteria, makes the analysis publicly available, and builds capacity (Marcelo et al. 2015). Morgan et al. (1990) highlight the importance of using stakeholder co-production decision-making methodologies that involve stakeholders throughout the entirety of the decision-making process. Thereby, such decision-making methodologies provide 'decision-support', defined by the National Research Council (2009a) as "a set of processes intended to create the conditions for the production of decision-relevant information and for its appropriate use". Successful decision-support provides users with data or knowledge they consider useful (Mitchell 2006) and can be guided by the following characteristics: putting the user's needs at the heart of the decision-support process; emphasising the process over the outcome; building connections across disciplines and organisations to provide for the multidisciplinary nature of information; and incorporating learning and the strengthening of governance (National Research Council 2009b), which is especially important in the context of the global agendas.

Moreover, formalisation of the decision-making process has been called for, which integrates various principles for good-decision making: using evidence-based processes in which parties are explicit about their goals; following agreed-upon rules and norms; utilising best available science and data; considering a range of alternative options; and evaluating the potential consequences of options and their trade-offs carefully from a range of viewpoints (Jones et al. 2014). The use of such formalised decision processes can help suppress power dynamics and bolster authority to guide practical decision-making

(Eriksen et al. 2021). In the context of adaptation decision-making, such formalised processes may however be viewed as technocratic assessments that consider adaptation planning a problem-free process, thereby underestimating the complexity of adaptation as a social process (Mimura et al. 2014). Therefore, it is critical to place participatory methods and effective governance arrangements at the heart of formalised sustainability and climate adaptation assessments, including through action research.

2.2.2 Participatory methods and governance

There is extensive literature on the importance for action research to support decision-makers in working to effectively address the major challenges humanity is facing, including the SDGs (Allen, Metternicht, and Wiedmann 2021) and climate-resilience (Díaz et al. 2019; Steffen et al. 2015). Sustainability science emerged as a discipline whereby building capacity and generating actionable knowledge through research is considered particularly essential (Kates 2011; Ostrom 2007; Jerneck et al. 2011). Approaches to enable such action research include, amongst others, participatory methods and knowledge co-production (Lang et al. 2012). At its core, such research requires scholars to work with multiple societal actors to contribute to sustainability or climate action, including through context-based, pluralistic, goal-oriented and interactive principles (Norström et al. 2020). Whilst the need for action research to support decision-making through such participatory and co-production methods is well-recognised, its realisation in practice is difficult (Dilling et al. 2011) and remains a contested topic, both in the research and policy domain (Ojha et al. 2020). Decision-making in practice is often based on politics and does not always consider scientific evidence; at the same time, scientists do not always account for the practical dimensions of decision-making when carrying out and communicating research (Weichselgartner et al. 2010).

Participatory methods in sustainability and climate assessments for decision-support

One means by which researchers can deliver action research is through the use of participatory methods in the development and application of methodologies that help provide decision-support (Leitch et al. 2019). Integrating participatory methods throughout the

process of the development and application of methodologies and tools for decision-support has been considered critical for three main reasons: firstly, so that the content of such methodologies and tools contains the highest quality of data collected and verified with stakeholders; secondly, so that the process of developing methodologies and tools builds trust and encourages buy-in to policy proposals (Robinson et al. 2011); and thirdly, so that stakeholders become active learners, thereby sharing views, learning collaboratively, and co-producing knowledge (Caniglia et al. 2020). The latter step is particularly important in the process of backcasting, i.e. working backwards from visions to strategies and pathways of options towards achieving sustainability or climate adaptation goals. Peterson et al. (2003) argue that the integration of a range of stakeholders in exploratory thinking and backcasting provides a foundation for bringing together a range of stakeholders on the discussions about the future, including how change can be directed. Such participatory-based methods are thereby considered more likely to yield coordinated actions from a range of actors (Robinson et al. 2011).

With an increased interest for decision-support methodologies and tools to guide practical action, academic research on their (mis)use has also proliferated (Leitch et al. 2019). Whilst considered useful to help support decision-making, critics of decision-support methodologies and tools point out concerns about low take-up by target users (Valls-Donderis et al. 2014), the subjectivity of stakeholders involved at the time of the research, and the possibility of the engagement process to reinforce ingrained power relations and inequalities, including on the basis of gender, marginalisation, or literacy (Ballard 2005; Eriksen et al. 2021).

To help overcome these limitations, research has suggested to increase the levels of participation, devolution of information and power in decision-support methodologies and tools from: first, engaging stakeholder in information gathering, to collaborating with them to include developments of alternatives and preferred solutions, and lastly, to empower them and place final decision-support methodologies and tools in the hands of decision-makers (IAPS 2007; Leitch et al. 2019). Further, the literature suggests the need for the development and application of decision-support methodologies to be designed to promote collaborative learning, to be adaptive to the cultural and local contexts (Tschakert

et al. 2016), and to consider researchers own roles in economic and social power relations (Cai et al. 2021). Whilst large methodological challenges for the science-policy agenda remain, small steps of developing and applying decision-support methodologies and tools together with at-risk countries are important starting points to help stir practical action towards sustainable development and climate resilience.

In practice, participatory methods have increasingly been used across governments and sectors to better plan sustainability and climate action (Newig et al. 2014). Plans developed together with a range of stakeholders have shown to increase the likelihood of their implementation at reduced cost and time efforts (Sultana et al. 2008). In the context of the SDGs, adopting participatory methods allowed aligning long-term plans with a range of sustainable development targets (Fuldauer et al. 2019; Adshead et al. 2021). Yet, Alawadi et al. (2016) highlight how placing planning decisions into the hands of a few elites poses a constraint to successful participatory planning approaches in practice. Instead, good governance, based on participation of the most vulnerable, is essential in envisioning and realising pathways towards future sustainability.

Governance for sustainability, adaptation, and global agendas

Governance has often been termed one of the key levers to enable the transformations required to enable successful sustainable development and climate decision-making (Independent Group of Scientists 2019; Srivastava et al. 2021). Not only is governance an essential determinant of the sustainable growth of nations (Acemoglu et al. 2013) and explicitly recognised as one of the global SDGs (SDG16 'peace'), it is also considered a key condition for successful adaptation across sectors (Klein et al. 2014; Eisenack et al. 2014). With explicit reference to governance for sustainable development, Glass et al. (2019) find that participation is one of the four critical determinants of governance that serve to explain SDG achievement, with the others including policy coherence, reflexivity, and democratic institutions. Participation and engagement with stakeholders is considered essential to represent the broad interest and potential trade-offs embedded within the SDGs (Meuleman et al. 2015; Emerson et al. 2012) and to contribute to knowledge generation and consensus building in sustainability governance (Verweij et al.

2013). Especially in the context of the infrastructure SDGs (SDG 6 'clean water', SDG7 'energy', SDG9 'innovation and infrastructure', SDG11 'sustainable cities', amongst others), Waage et al. (2015) argue that a lack of synergies across these infrastructure goals can be attributed to governance issues. Governance mechanisms characterised by deliberation, participation, and transparent decision-making are required for achieving the SDGs, especially those for which decisions are typically taken by powerful elites and technical experts, which might otherwise exacerbate inequalities (Waage et al. 2015).

Rather than focusing on qualitative acknowledgements of the importance of governance, Andrijevic et al. (2020) make a quantitative argument for considering governance both in the transition towards sustainable development and climate adaptation. Based on different future scenarios, Andrijevic et al. (2020) find that there are remaining limits to adaptive capacity even under the most optimistic future scenarios, thereby highlighting the importance of accounting for governance in national assessments of both sustainable development and climate adaptation.

2.2.3 Formalised assessments for sustainable development

A number of recently-developed sustainability assessments have formalised the national decision-making process to help ensure good decision-making towards the SDGs (Allen, Metternicht, and Wiedmann 2021). These include targets and indicators, scenario planning to deal with uncertain futures, as well as national-scale assessments that help underpin sustainable development decision-making in practice.

Targets and indicators can guide sustainability assessments

Deciding on which options to pursue for sustainable development requires assessing sustainability needs, which provides the basis for choosing amongst sustainability options (technologies, policies). Traditional methods of assessing sustainability needs emphasised economic dimensions over the environmental and social 'pillars of sustainable development' (IADB 2018), yet increasingly, a sustainability needs assessment includes all three dimensions of sustainable development. Multi-criteria decision analyses and

modelling tools are now often employed to help decision-makers evaluate trade-offs and choose amongst different options (Böhringer et al. 2006).

As introduced briefly in the conceptual section of this literature review, the formulation of the SDGs has resulted in interest to measure progress towards these global goals (Lu et al. 2015; SDSN 2015). A first set of 230 indicators across social, economic, and environmental dimensions of sustainable development has been recommended by the UN Statistical Commission to measure SDG achievement (Nilsson et al. 2016; IEAG 2016), some of which have been used by Schmidt-Traub et al. (2017) to develop an SDG index across 149 countries. Whilst the composite SDG index is a useful tool to compare baseline SDG performance across countries, it does not lend itself to be utilised to plan or evaluate future action towards sustainability at the national scale. Kroll et al. (2019) project SDG trends based on this SDG index to identify how future trade-offs could be turned into synergies, yet they rely on past trends to project the future. Reliance on past trends is not a method well suited to drive future ambitious sustainability action in the face of uncertain futures.

Dealing with uncertain futures in sustainability assessments

Scenario planning has emerged as a particularly useful method to drive sustainability action in the context of long-term planning under uncertain futures (Kok et al. 2007; Raskin et al. 2010; Bradfield et al. 2005), including at the national scale (Allen et al. 2018). In applications of scenario modelling to national sustainable development planning, Vergragt et al. (2011) differentiate between three types of scenarios: a) probable scenarios on what is likely to happen (using trend extrapolations, business-as-usual (BAU), no-action scenarios); b) possible scenarios on what could happen (using forecasting, foresight), and c) desireable scenarios on what should happen (using backcasting, desireable futures, visions). Whilst forecasting can be used to develop possible scenarios that reflect future uncertainties such as population growth, backcasting can be used to develop desirable scenarios, also termed strategies or pathways, that 'bend the curve' towards long-term sustainability and the SDGs (Allen et al. 2017). Different pathways can subsequently

be evaluated for their performance on a range of indicators and compared to business-as-usual, thereby enabling an evaluation of the potential outcomes of different pathways before decisions are made.

State-of-the-art approaches have integrated probable, possible, and desireable scenarios across sectors. Most notably, international efforts have resulted in the development of global 'shared socio-economic pathways' (O'Neill et al. 2014), which describe futures of socio-economic development across sectors. Similarly, the 'Roads to Rio' pathways focus on alternative policy pathways for achieving sustainable development (TWI2050 2018; O'Neill et al. 2014; Riahi et al. 2017; van Vuuren et al. 2015). Based on an integrated assessment model, Moyer et al. (2019) build on such global scenarios to explore the extent to which nine human development-related SDGs are achievable. Although well established as a tool to support development planning, integrated assessment models require alterations to directly inform sustainable development planning based on the context of each nation.

National-scale sustainability assessments

Allen et al. (2017) suggest a five-step process for informing sustainable development planning based on nation's contextual factors. This process includes: identifying priorities and targets; selecting appropriate models; projecting baseline scenarios; and analysing intervention options and pathways towards achieving targets. This process has been applied using system dynamics modelling to estimate business-as-usual versus different future scenarios to evaluate their performance on the SDG indicators (Collste et al. 2017; Allen, Metternicht, Wiedmann, and Pedercini 2021). Whilst such a process is useful in broadly comparing future scenarios, it is computationally-expensive, potentially reducing its use within decision-making processes, especially in developing countries where capacities and resources are scarce.

With the specific aim of developing a resource-light sustainability assessment that can be used in less developed countries, recent research studies developed decision-support methodologies and tools that combine possible and desirable scenarios to assess and evaluate these on their performance on SDG targets under a range of probable

scenarios (Adshead et al. 2019; Fuldauer et al. 2019). Together, these research studies operationalised the conceptual understanding of how certain sectors influence SDG target achievement at the scale of sectors' assets. The specificity of the asset-scale helped provide a direct entry-point into decision-making, whilst the development of accompanying decision-support tools together with stakeholders allowed building capacity (Fuldauer et al. 2019). Most recently, such asset-based research studies have been expanded to account for key limitations in the literature, including: a) considering a range of sectors and services to meet socio-economic needs; b) accounting for cross-sectoral interdependencies; and c) formally aligning national planning with the SDG targets and the *mitigation* component of the Paris Agreement (Adshead et al. 2021). Yet, despite calls for translating such strategic national decision-making approaches with spatial information and climate risk and adaptation (Adshead et al. 2021), limited to no integration between national-scale formalised SDG and adaptation assessments has been documented.

2.2.4 Formalised climate adaptation assessments

This section reviews the range of formalised adaptation assessments that have been advanced in the scholarly literature to guide adaptation decisions. These include climate risk assessments, probabilistic and deep uncertainty methods to deal with uncertain futures, as well as national-scale spatial adaptation assessments that help underpin adaptation decision-making in practice.

The different types of assessments differ in their goals and the theoretical frameworks they build upon, and ultimately may result in different adaptation responses (Fünfgeld et al. 2011). Top-down assessments are most often utilised to assess the potential impact of climate change on sectors or regions, thereby identifying mainly bio-physical adaptation needs and options. In contrast, bottom-up assessments begin at the local scale and determine the vulnerability of different communities and address socio-economic responses (Dessai et al. 2004). Policy-based assessments use policies as a starting point and assess those for their effectiveness under climate change (UNDP 2004). In practice, most assessments combine elements of top-down, bottom-up, and policy-based approaches. They typically also combine elements of adaptation needs based

on bio-physical, environmental, social, institutional, private sector, and resource capacity considerations (Noble et al. 2015). As this thesis is concerned with integrating adaptation with sustainable development, in particular with meeting socio-economic needs and protecting critical ecosystem services, the focus of the methodologies developed in this thesis lies on bio-physical and environmental adaptation, on which sustainable development ultimately depends.

Climate adaptation assessments can guide decision-making

Climate adaptation assessments have become institutionalised as a common means by which to assess bio-physical and environmental adaptation needs and to guide respective adaptation decisions at the national-scale (Byrd et al. 2000; Jones et al. 2014), especially for high and medium frequency hazard events as discussed in Chapter 2.1. Climate adaptation assessments involve the formal analysis of adaptation needs, as well as an assessment of adaptation options to reduce climate risk (Noble et al. 2015).

Climate risk is often framed as a risk management problem with unique challenges (King et al. 2015; Sussman et al. 2014; Weaver et al. 2017). Failure to consider climate risk now can multiply risks from other stressors, and lock in future decisions and impacts across all other sectors (Ranger et al. 2012). To account for the importance of acting now, this thesis adopts the iterative framework developed by the IPCC for scoping risks and objectives; assessing adaptation needs and evaluating options; and implementing options and reviewing decisions (Jones et al. 2014). This thesis focuses in particular on the steps of assessing adaptation needs and evaluation options, acknowledging that implementation and decision reviews are also critical components of adaptation.

Dealing with uncertain futures in adaptation assessments

Traditional risk assessments based on reductive approaches and historic data of probabilities have been considered less appropriate under conditions of uncertain futures, as is the case with anthropogenic climate change (Funtowicz et al. 1990; Funtowicz et al. 1993; Stirling et al. 2009; Stirling 2010). Authors in the field have instead advocated for risk assessments that consider decision-making under uncertainty approaches (Hallegatte et al.

2012). These include probabilistic methods, which aim to quantitatively assess uncertainty in probabilistic terms (such as real-time flood forecasting) (Todini 2004; Young et al. 2014) and deep uncertainty methods that deliberately avoid probabilistic representations of uncertainty (such as robust decision-making or info-gap methods) (Simpson et al. 2016).

Probabilistic decision-making analyses include accounting for the range of possible scenarios of the future, including the use of probability distributions over these possible scenarios. A set of options with corresponding expected losses and costs are compared to identify optimal decisions that maximise the net benefit, which is often characterised in economic terms. Costs and benefits can be distributed over time by discounting future streams and costs and benefits to present values (Simpson et al. 2016). Thereby, a typical probabilistic decision-making analysis includes: a) estimating the probability of occurrence of hazard variables (e.g. wave height), b) relating these to the consequences of hazards (e.g. dike overtopping during a flood event), c) estimating the damage caused (i.e. the benefit of avoided damage), and d) comparing alternative options to reduce expected risk and associated costs (Hall et al. 2008).

Such probability-based methods are still the main tool for risk-based decision-making, as they can be easily incorporated in normative decision-making frameworks and provide objective evidence for policy decisions (Pidgeon et al. 2009). Yet, critics have pointed out a number of limitations, which include: i) the difficulty in precisely quantifying the probabilities of future scenarios of climate, especially in the context of anthropogenic climate change (Kalra, Hallegatte, et al. 2015; Wilby et al. 2010; Hallegatte 2009), ii) the focus on economic optimisation approaches (Leach et al. 2010), which may not only lock-in future impacts, but which are also impracticable in valuing non-market benefits and costs of adaptation options, as is the case with nature-based adaptation options (Seddon et al. 2021).

Writers on deep uncertainty methods instead advocate for considering a wide range of future scenarios of climate and socio-economic changes (Hallegatte 2009; Dessai et al. 2009). Amongst the most used deep uncertainty methods is robust decision-making, which enables identification of options that perform robustly, i.e. acceptably well, across a wide range of future states (Lempert et al. 2007; Lempert et al. 2013; Lempert et al. 2010;

Kalra, Groves, et al. 2015; Groves et al. 2007). Other deep uncertainty methods allow decision-makers to better assess tipping points, path dependencies, as well as sequence adaptation interventions over time (Haasnoot et al. 2012; Haasnoot et al. 2013; Wise et al. 2014). Whilst such deep uncertainty methods are useful tools to underpin adaptation decisions in the context of future uncertainty, their application is data and resource-intensive (Ranger et al. 2012). This may hamper their applicability to national adaptation planning, particularly in developing countries where data availability is limited and capacities for detailed application of deep uncertainty methods may be more constrained (United Nations International Strategy for Disaster Reduction 2009).

National-scale spatial climate adaptation assessments

With the aim of moving forward on adaptation rather than being constrained by the data-, resource-, and capacity- intensive methods to deal with uncertainties of future climate change, scholars have advocated for the application of the key concepts that underpin deep uncertainty methods (Ranger et al. 2012). This involves focusing on iterative and continuous needs assessments that are able to respond to new information; on options that are robust, sensible today and likely beneficial in the future; and on the communication of current and likely future risks of such robust options (Wilby et al. 2010).

Spatial climate adaptation assessments are useful tools that account for the key concepts underpinning deep uncertainty methods and which enable communicating climate risks through visual maps. By intersecting climate-change hazard scenarios of different return periods with sectors' assets at high spatial granularity, spatial climate adaptation assessments - based on climate risk modelling - help to inform bio-physical adaptation decisions at the national scale (Dawson et al. 2018; Pant et al. n.d.). Such spatial adaptation assessments have most often been applied to infrastructure sectors at the asset scale, with the use of network science-based models and Geographic Information Systems (GIS), which enable visual representation exposure and risks across sectors (Lewis 2006; D'Agostino et al. 2014). To account for advances on climate adaptation research, spatial climate adaptation assessments have increasingly adopted a broader systems approach: i) they have moved from a physical exposure focus towards the

integration of social vulnerability considerations (Koks et al. 2015), ii) they have moved from accounting for economic asset damages to considering socio-economic service disruptions and wider macro-economic impacts following hazard events (Thacker, Kelly, et al. 2017; Thacker, Barr, et al. 2017); iii) they have advanced from single hazard scenarios and single sector assessments to multi-hazard/ multi-sector studies, increasingly accounting for multiple future hazard scenarios and multi-sector interdependencies (Pant et al. 2013; Thacker, Pant, et al. 2017; Koks, Rozenberg, et al. 2019).

Yet, a number of limitations remain for national-scale spatial climate risk modelling, in particular to inform climate adaptation under the Paris Agreement. First, visual maps resulting from spatial climate risk modelling have rarely been integrated in adaptation commitments under the Paris Agreement. In particular, Khan et al. (2020) highlight how the integration of spatial information would be especially important to operationalise nature-based adaptation options under the Paris Agreement. Yet, the authors find that to date, only 4% of NDCs include a visual map and only one of the 196 NDCs contains actionable maps (Khan et al. 2020). Second, sustainable development targets are rarely integrated with spatial climate risk modelling, which however would be critical to make the case for adaptation across a nation's interdependent socio-economic sectors *and* ecosystems to safeguard all dimensions of a nation's development as well as to transcend conventional adaptation option assessments (e.g. cost-benefit optimisations), which have a tendency to underestimate the non-monetary benefits of nature-based solutions (Nay et al. 2014).

2.2.5 The need for national-scale methodologies and applications

The methodological literature reviewed in this chapter allows for a deeper understanding of the foundations of good decision-making. Good decision-making includes both the importance of putting participatory methods and governance issues at the heart of the decision-making process, as well as formalising this process. Despite the sound formalised assessments developed and applied to guide both sustainability and climate adaptation decisions to date, scope remains to improve upon *integrating* such formalised assessments to better support national decision-makers to inform climate adaptation planning for

sustainable development outcomes. In particular, there are gaps for integrating national sustainable development assessments and spatial climate adaptation assessments in both directions, using sustainable development as an end-point and as a starting point in climate adaptation assessments. This includes the need for the development and application of at least two national-scale methodologies to: 1) better assess the impacts of climate change on sustainable development targets, via a holistic set of socio-economic and ecosystem sectors (climate-first); and 2) to use a sustainable development vision to more holistically evaluate climate adaptation (development-first). There is a need to practically apply such methodologies with real-world data and using participatory methods to provide evidence to align adaptation planning with the SDGs and the Paris Agreement in practice.

The two national-scale methodologies developed in this thesis build upon the existing methodological processes used in national sustainable development and spatial climate adaptation assessments (Adshead et al. 2021; Adshead et al. 2019; Thacker, Barr, et al. 2017; Thacker, Kelly, et al. 2017; Hall et al. 2016). As these existing methodological processes resolve decision-making at the scale of specific assets and have shown to be applicable with more resource-light approaches, they are useful in informing national-scale adaptation decisions in practice, including in less developed countries. Yet, to date these existing methodological processes have largely been conducted separately, and do not account for a holistic set of socio-economic sectors and ecosystems and interdependencies between these. Without explicitly integrating these methodologies, it will not be possible to holistically inform national climate adaptation in line with sustainable development targets.

In developing and applying integrated national-scale methodologies, this thesis adopts common best practices identified throughout this literature review chapter. This includes a formalised approach to guide decision-making that is grounded in evidence. It also involves developing and applying methodologies and tools using participatory methods to provide decision-support. More specific best practices to be adopted in integrated national-scale methodologies are dependent on whether a climate-first or development-first approach is adopted.

Assessing climate change impacts on sustainable development targets

To date, national-scale spatial climate adaptation assessments overlay a range of future climate scenarios with sectoral assets to calculate asset damages, service disruptions, or welfare impacts, which allows informing national adaptation in uncertain futures. Yet, a number of gaps remain that would enable informing where and how to target national adaptation in the context of the global agendas:

- Spatially assessing the impact of multiple climate-change hazard scenarios on all of a nation's socio-economic sectors and ecosystems, including all built and natural environment assets and the services these provide.
- Accounting for interdependent and indirect influences between services in terms of SDG achievement.
- Transcending economic assessments by identifying the SDG impact of an adaptation inaction scenario, thereby making the SDG case for adaptation.
- Adding spatial granularity and specificity to national adaptation planning under the Paris Agreement, especially in the context of the under-represented natural environment.

This thesis addresses these gaps through the development and application of a formalised national-scale, climate-first methodology to support adaptation decision-making in Chapter 5.

Using sustainable development targets to evaluate climate adaptation

National-scale sustainability assessments across sectors have been developed that ground long-term development planning in SDG visions. These assessments quantify a nation's SDG target achievement in terms of sector and asset contributions using a set of indicators, based on conceptual SDG influences. These sustainability assessments have been expanded recently to help evaluate the performance of future possible and desirable scenarios and to align sustainable development targets with the climate mitigation component of the Paris Agreement. Yet, a number of gaps remain that would enable grounding long-term

adaptation planning in SDG visions and align sustainable development targets with the climate adaptation component of the Paris Agreement:

- Spatially evaluating the current performance of a nation's sectors and assets in relation to a sustainable development target vision with the use of performance indicators.
- Quantifying the risk of multiple climate-change hazard scenarios on current SDG target performance at the scale of assets to identify adaptation needs in terms of SDG target progress.
- Using desirable scenarios to identify adaptation options that meet these adaptation needs.
- Evaluating adaptation options in terms of their contribution to SDG targets, thereby transcending economic optimisation assessments.

This thesis addresses these gaps through the development and application of a national-scale, development-first methodology to support adaptation decision-making in Chapter 6.

Collectively, the two national-scale methodologies developed in this thesis provide contributions to the spatial translation of SDG targets and indicators at the asset and service provision scale, thereby enabling the integration of sustainability assessments with spatial climate adaptation assessments. For the first time, the proposed methodologies bring together both built socio-economic sectors as well as the natural environment and its ecosystem services in adaptation assessments. The proposed methodologies adopt a holistic systems approach, thereby explicitly considering interdependencies in achieving the SDG targets. Furthermore, adaptation options and strategies are evaluated in terms of delivering on the SDGs. The proposed methodologies are described using transferable mathematical formulations so that a range of future possible, probable, and desireable scenarios can be integrated. By applying the methodologies in test case studies through participatory methods, they can provide useful insights to support adaptation decision-making in practice.

3

Research sites, methods, and data

The first section of this methods chapter outlines the overarching research design used in this thesis. The second section introduces the test cast studies for the practical application of the national-scale methodologies developed in this thesis (Chapter 5 and 6), whilst the third section summarises the methods and data collection process used in the substantive chapters of this thesis (Chapter 4, 5, and 6).

3.1 Research design

Rather than focusing on methods from a particular discipline, this thesis takes a mixed-methods and an interdisciplinary approach (Midgley et al. 2004). Adopting a mixed-methods and interdisciplinary approach was considered particularly important given the aim of this thesis to integrate the largely separate sustainable development and climate adaptation literature. The deliberate development of a conceptual framework – addressing Research Question 1 – provided a means by which to understand the links between sustainable development targets and climate change impacts at the scale of socio-economic sectors and ecosystems. The conceptual framework allowed for the development and application of national-scale methodologies on spatially assessing the impact of climate change on sustainable development targets (addressing Research Question 2) and on using sustainable development targets to evaluate climate adaptation (addressing Research Question 3).

In light of the applied objectives under Research Question 2 and 3, an action research approach was used, defined here as "developing practical knowledge in the pursuit of worthwhile human purposes" (Reason et al. 2001). The objective was to develop two national-scale methodologies that are sufficiently rigorous in academia, but that can simultaneously be used by government and international organisations to assess or evaluate national adaptation for sustainable development. The action research component of this thesis also justifies including actors from outside academia in the research process with the aim of integrating the best available knowledge, reconciling values and preferences, and creating ownership for problems and potential solutions. Thereby, this thesis adopts Lang et al. (2012)'s approach that participatory research methods are appropriate in helping to address real-world problems. To account for the complexity in decision-making due to conflicting values of decision-makers and unclear solutions in the face of 'wicked problems', the use of an iterative and adaptive stakeholder decision-making methodology (Morgan et al. 1990; Jones et al. 2014) was adopted, as discussed in Chapter 2. The use of an iterative decision-making methodology allows updates to be made as more or new data becomes available and as preferences or criteria change, thereby accounting for possible changes in the future.

3.2 Test case studies for national-scale applications

Whilst the framework developed to answer Research Question 1 is described in conceptual terms and applied globally, the national-scale methodologies developed to answer Research Questions 2 and 3 use a test case approach. The choice of nation as a test case study was based on a number of different considerations. Most importantly and as introduced in Chapter 1, it was considered essential to apply the proposed methodology in a nation facing both sustainable development challenges and severe risks from climate change impacts. In alignment with this thesis' action research component, it was further deemed critical that the national governments of the nations show strong commitments towards achievement of the SDGs and the Paris Agreement and are interested in national adaptation planning aligned with the global agendas. Lastly, the ability to engage with national decision-makers across ministries and sectors was a key consideration

in choosing amongst potential test cases to be able to address all objectives under Research Questions 2 and 3.

Saint Lucia

The proposed national-scale methodology developed as part of answering Research Question 2 was practically applied to the trial case in the Small Island Developing State (SIDS) Saint Lucia for the following reasons. Firstly, as a SIDS, Saint Lucia has been considered among the most exposed nations to hazards, such as storm surges or flash floods, projected to increase in intensity with climate change (The World Bank 2021). Their exposure emerges from their low-elevation and large amounts of critical socio-economic assets located at the coast (Nurse et al. 2014). Secondly, Saint Lucia's national-decision makers were interested in making the case for adaptation for sustainable development, and in assessing hazard exposure across all of their built and natural environment sectors in order to spatially prioritise adaptation measures proposed in the country's National Adaptation Plan (NAP) under the Paris Agreement (Government of Saint Lucia 2018). Thirdly, due to the small size of the country, it was possible to establish contact to all national decision-makers concerned with climate adaptation, sustainable development, and integrated planning across sectors. Such contact was facilitated through a partnership between the University of Oxford with the Government of Saint Lucia and the United Nations Office for Project Services (UNOPS).

Ghana

The proposed national-scale methodology developed as part of addressing Research Question 3 was practically applied in Ghana for the following reasons. Firstly, Ghana has been ranked a nation highly vulnerable to climate change, confronted by re-occurring floods that threaten livelihoods (Mcsweeney et al. 2010). With its population expected to almost double by 2050, the country has also been considered to face important 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 2019b). Secondly, as a developing country with a strong commitment

to adaptation and the SDGs, 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 SDGs is required. The government has developed detailed plans on both the adaptation component of the Paris Agreement as well as on how to achieve the targets of the SDGs, which could be integrated into the research. Thirdly, given its relatively large open-access data repertoire - especially compared to other Sub-Saharan countries - and a partnership between the University of Oxford, the Government of Ghana, and UNOPS, it was possible to collect the relevant data and engage in the national decision-making process.

3.3 Methods and data summary

Given that a detailed overview of the employed methods is provided in each substantive chapter, the aim of this section is to compare and contrast the employed methods across the substantive chapters of this thesis and to provide additional justification not included in the substantive chapters. Table 3.1 provides an overview of the methods used in each of the three substantive chapters.

Table 3.1: Overview of methods used in this thesis.

Method	**Chapter 4**	**Chapter 5**	**Chapter 6**
SDG target content analysis	X		
Evidence mapping of influences	X	X	
Secondary data collection and analysis	X	X	X
Primary data collection and analysis		X	X
Spatial adaptation needs assessment		X	X
Spatial adaptation options assessment			X
Sustainability needs and options assessment			X
Workshops and participatory methods		X	X

3.3.1 Conceptual framework

The development of the conceptual framework – part of addressing Research Question 1 – on the role of sectors in mediating between sustainable development targets and climate change impacts involved a set of three steps. These three steps were based on best practices for conducting adaptation research as proposed by Berrang-Ford et al. (2015), which are described in detail in Chapter 4. In practice, these steps were conducted in an iterative manner. Further, the development of the conceptual framework was conducted in parallel with the development and application of the national-scale methodology, which further shaped the conceptual framework. Thereby, the importance of clearly delineating the scope of the conceptual framework became apparent.

In delineating the scope of the conceptual framework, the development of the conceptual framework drew extensively upon Systems Thinking and Critical Systems Theory (CST) (Ulrich 1996; Midgley 2000). CST contends that it is critical to draw explicit boundaries between what is part of and what is out of a particular construct, because an objective definition of the whole system is not possible. Therefore, boundaries were drawn of the definitions and scope of sustainable development, climate change impacts, and sectors to be included, which might however miss important aspects not included in the boundary scope that could have an impact on the result.

First, the conceptual framework, and this thesis as a whole, adopted a normative definition of sustainable development that utilises the targets of the global SDGs as definitions of sustainable development, whilst acknowledging that these were politically determined and might imperfectly represent sustainable development (McGowan et al. 2019; Le Blanc 2015). Given this normative interpretation of development, the conceptual framework and this thesis more broadly might under-represent some of the critical and bi-directional literature on adaptation-development, including the extent to which past development has shaped vulnerability as well as the extent to which past climatic conditions have shaped development. Whilst the service-centred framing adopted in this thesis incorporates the component of (un)equal access to services - one of the components of both vulnerability and sustainable development -, it does not

consider the more descriptive socio-political processes that have led some nations to be more vulnerable (IPCC 2014a).

Second, the conceptual framework used acute and chronic climatic impact-drivers as defined by the IPCC to differentiate between impacts of climate change. The IPCC scope was used to provide an internationally-accepted scope of climate change impacts, which however might be adapted to the specific context of nations.

Third, a review of 35 land-use classification systems and seven industrial classifications systems was conducted to identify an internationally-defined set of sectors and services. This review showed that the original land-cover/land-use classification categories, updated according to the System of Environmental-Economic Accounting (SEEA), and the International Standard Industrial Classification of All Economic Activities (ISIC) Revision 4 (Anderson et al. 1976; UN 2008) met the criteria for an internationally-defined set of sectors and services best. The range of services provided by socio-economic sectors were explicitly documented through the international sector-service classification (UN 2008), whilst the different types of services provided by ecosystems were collected from a range of sources, as no accepted classification was available (see Chapter 4 for discussion).

Following the three best-practice steps as described in Chapter 4, the conceptual framework was populated with potential influences between sectors and SDG targets (SDG influences), and sectors and climatic impact-drivers (climate influences). Potential *sector-SDG* influences were identified based on content analyses and evidence mapping, following previous studies as described in Chapter 4. Potential *sector-climate* influences were identified based on evidence mapping, using IPCC reports and peer-reviewed journals as the main sources of climate influences, which can be considered a benchmark of good practice. The conceptual framework was subsequently applied with global data on risk from climate change on sectors, which warranted a document review of the best available evidence across different climatic impact-drivers and different sectors. The IPCC's 5thAssessment Report (AR5) was considered the best available evidence base across 12 different climatic impact-drivers and across sectors.

Accounting for potential limitations

Given that the identification of influences used to populate and globally apply the conceptual framework is based on published evidence, the results are contingent on the availability of evidence at the time of the research. Moreover, the process of reviewing the state of knowledge in a specific area is influenced by disciplinary background, author training, and positionality. Author teams determine what research is included or excluded and how to deal with conflicting arguments (Fairclough 2010; Victor 2015). The use of IPCC literature as a key contributor to the evidence mapping in this thesis contains its own limitations. These limitations include, for example, a bias towards peer-reviewed articles that may discount practitioner knowledge (Howarth et al. 2017), a contextual bias, and an under-representation of both cultural factors and indigenous knowledge (Ford et al. 2016). To account for these limitations, grey literature was included in the evidence mapping. Whilst there are issues relating to rigour and credibility in using grey literature in evidence mapping (Benzies et al. 2006), the integration of grey literature was considered important in order to increase the likelihood of determining a comprehensive evidence base. Cultural services – which are often under-represented in climate impact assessments – were explicitly included as services delivered by ecosystems as well as by the 'arts and recreation' sector. The research also included a literature review on the ecosystem sector 'ice, snow and tundra', which is inclusive of Arctic indigenous land and its people. Nevertheless, the evidence underpinning the conceptual framework should be updated with further qualitative evidence, as and when such evidence becomes available, and increasingly account for evidence from marginalised and indigenous peoples as highlighted in Chapter 4.

3.3.2 Methodology development and application

A challenge with designing research that involves methodology development to inform planning includes the testing of the proposed methodology for its effectiveness, due to the absence of a competing parallel plan (Haasnoot et al. 2013). Aligned with best practices on overcoming this challenge (Hansman et al. 2006), this thesis validated the proposed methodologies through real-world applications in test case studies. Moreover,

and in drawing on methods of participatory action research, this thesis aimed to ensure effectiveness of the proposed methodology by valuing the process of the application as much as the product (Dewar et al. 1993; Chatterton et al. 2008). Therefore, a large focus was placed on capacity development and iterative stakeholder engagement throughout the methodology application and the development of accompanying tools.

The iterative application of the methodologies for the two test cases to answer Research Questions 2 and 3 included four phases: 1) scope identification (i.e. identifying key priorities and outlining research aims), 2) data collection, 3) data analysis and interpretation, 4) deliberation. In practice, this process was more elaborate and iterative, as new data sources emerged in the process of data analysis.

Saint Lucia

In the application of the developed national-scale methodology (see Chapter 5) to respond to Research Question 2 to Saint Lucia, the four phases were performed in partnership with the country's recently launched National Integrated Planning and Programme unit (NIPP) based in the Ministry of Finance. The scope of the adaptation work was discussed to involve three climate-change hazards (storm surges, flash floods, and landslides), a multi-hazard, and all of the nation's sectors and assets of both the built and natural environment.

Data was collected throughout the fieldwork period, which involved three visits to Saint Lucia during the period from April 2019 to January 2020. Collection of qualitative data involved information on existing efforts with national adaptation planning in Saint Lucia to date, as well as existing land use policies, which was compiled through key informant stakeholder engagements mainly with the Ministry of Finance, the Ministry of the Sustainable Development, and the Ministry of Planning in April 2019 (see Chapter 5 for details). Quantitative data collection involved: geospatial data on the location of built and natural environment assets, information on the services provided by these assets (e.g. freight flows/ year; passengers/year), climate-change hazard maps, and land-use maps. This data was collected using open source data and a review of documents that had been made available through stakeholders. Stakeholder engagement, facilitated by the Oxford/UNOPS/Government of Saint Lucia collaboration, allowed accessing data

not openly available, manually mapping missing asset data, as well as verifying data of all of Saint Lucia's sectors and assets. Stakeholders were contacted using purposive sampling and the snowballing technique (Patton 2002).

Data analysis included data reduction, display, and initial conclusion drawing by triangulating the data from different sources (Hay 2016). All verified data was used in the climate adaptation needs assessment, which was performed using the QGIS software as well as by writing and running python code. A geospatial decision-support tool was developed based on QGIS and python, because their installation, use, and learning tutorials are free of charge. This tool includes all of Saint Lucia's spatial asset data in standardised format, alongside attribute information such as asset capacity, land-use areas, and poverty information. Further, it includes a user guide to help analyse additional and updated data as and when this becomes available.

Intermediate results from the first round of data analysis were presented and deliberated in the second field work in September 2019, which allowed for iterative data scrutiny, contextual understanding, and stakeholder engagement. Final results were presented to in-country stakeholders together with the NIPP team, including ministers from 11 different departments and 8 infrastructure operators in January 2020. Results were also presented at two Public Service Commission (PSC) meetings, attended by the permanent secretaries of the Infrastructure, Housing, Finance, Economic Competitiveness, Planning, and the Transport ministry. Results from this study were further communicated to the Prime Minister of Saint Lucia. A capacity building workshop on using the geospatial decision-support tool was organised in January 2020 with over 30 participating government stakeholders, published on government television. These interactive workshops, the numerous results presentations, and the one-to-one interactions with the NIPP unit throughout the development and application of the climate adaptation assessment helped underpin the action research component of the thesis.

Ghana

In the application of the developed national-scale methodology to respond to Research Question 3 in Ghana, the four phases were performed together with the Ministry of

Environment, Science, Technology & Innovation (MESTI). The scope of the research involved two climate-change hazards (floods and landslides), a multi-hazard, and three sustainable development performance indicators. The reseach focused on Ghana's energy and transport sectors, which are critical both for sustainable development and climate adaptation, yet have received little attention in Ghana to date. Whilst efforts were made to expand the scope to the water sector, which is also essential for both sustainable development and climate adaptation in Ghana, the lack of national-scale data on water supply points and water demand hampered these efforts.

Data was collected over a 1-year period from June 2020 to June 2021. Owing to the pandemic, data collection involved virtual meetings and workshops with the relevant ministries in Ghana (Ministry of Transport; Ministry of Finance; Ministry of Roads and Highways) as well as numerous organisations and academia (National Disaster management Organisation, University of Ghana etc.) as described in Chapter 6. Qualitative data collection was comprised of understanding existing governance frameworks for adaptation in Ghana, existing and proposed initiatives on adaptation options and implementation, as well as existing long-term sectoral development planning efforts aligned with the SDGs. Quantitative data collection involved gathering: geospatial data on the location of renewable and non-renewable energy assets and Ghana's road network; service provision and population data (e.g. renewable energy generation/ year); and existing hazard maps. Given the difficulties of remote data collection, open source datasets were used and information was georeferenced from published reports and articles in Ghana. Stakeholder engagement, facilitated in-country through the MESTI/Oxford/UNOPS collaboration, allowed verifying and manually adding geospatial data.

Data was analysed using a climate adaptation needs and options assessment, which was performed using the QGIS software as well as by writing and running python code. This python code enables translating Ghana's sustainable development performance indicators at the level of the geospatial asset data collected. A geospatial decision-support tool was developed based on QGIS and python in partnership between MESTI and the University of Oxford. This tool involves a broader set of geospatial assets and hazards compared to those that had sufficient scope to be integrated in this thesis. Similar to the

decision-support tool in Saint Lucia, a practical guidance document was developed to ensure that data can be updated and the data analysis can be iteratively performed.

Results from the analysis were presented and deliberated in three workshops with a Technical Working Group (TWG), which was made up of 11 ministries and institutions in Ghana (see Chapter 6). These workshops were performed remotely, owing to the pandemic. An interactive workshop on using the geospatial decision-support tool was organised in partnership between the University of Oxford, MESTI and UNOPS in August 2021, with over 26 participants. Given that the pandemic made it more difficult to evaluate the usefulness of the adaptation assessment and decision-support tool, it is hoped that collaborations with the University in Ghana and interested stakeholders can further shape the adaptation assessment and tool in the future.

Accounting for potential limitations

Whilst the quantitative methods used in the application of the national-scale methodologies provided numerical assessments that can enhance the decision-making process on adaptation prioritisation across sectors and assets, they are prone to uncertainties and data gaps. Efforts were made to communicate these uncertainties and gaps transparently with stakeholders, for example the uncertainties around future hazard scenarios and gaps on national-scale geospatial asset data, service provision information, or additional chronic climate-change hazards (described in detail in Chapter 5 and 6). Given the uncertainty with regard to the climate-change hazards utilised, the methodologies and tools were developed to account for future scenarios of hazards, for example using different return periods. Moreover, the focus on a climate-change hazard exposure framing may under-represent the long-term challenges that have shaped vulnerability, such as the ongoing effects of marginalisation, power relations, and land rights (Field et al. 2014). Further integration of the results from the national-scale methodology applications with more extensive social vulnerability indicators can help account for this limitation. The methodology application on evaluating adaptation options involved participatory workshops, which were used to identify feasible adaptation options. The outcomes of such participatory workshops are dependent on who is included and excluded, as well as

who is heard in stakeholder engagements. Whilst care was taken to engage stakeholders from different backgrounds, including academia and NGOs, to reduce potential negative impacts of exacerbating power dynamics and gender inequalities, further qualitative research is needed to update and extend the discussion on adaptation implementation, both in Saint Lucia and Ghana. Thereby, the presented results from the national-scale methodology applications to Saint Lucia and Ghana should be considered as a first estimate of adaptation prioritisation in the context of the SDG targets that can guide further detailed assessments at local scale.

4

Conceptualising links between sustainable development and climate change impacts

This chapter addresses Research Question 1: *How can the links between global sustainable development targets and climate change impacts be conceptualised at a scale useful to inform adaptation*? This chapter develops a conceptual framework to link a holistic set of 22 ecosystems and socio-economic sectors with all SDG targets and 12 climatic impact-drivers to understand the effects of these drivers (climate change impacts) on sectors. The framework is populated with evidence on potential sector-SDG and sector-climate influences. A global application demonstrates the value of the framework, which is discussed more widely in the context of considerations to better target national adaptation in alignment with the SDG targets.

This chapter was submitted as a journal paper to Nature Communications with the title 'Climate change impacts on sustainable development goals, and national adaptation responses' in June 2021. The chapter has subsequently been revised, addressing reviewers' comments under the new title 'Targeting climate adaptation to safeguard and advance the Sustainable Development Goals'. The chapter was co-authored with Scott Thacker, Robyn Haggis, Francesco Fuso Nerini, Robert Nicholls, and Jim W. Hall, who gave methodological advice, contributed to some of the analysis, and provided comments to the text and figures. All data that support the findings of this chapter, including Supplementary Tables 4.1-4.2, are described below. Chapter 4 Supplementary Information Tabs 1-4 are attached to this thesis and available at: https://doi.org/10.5281/zenodo.5643953.

Abstract

The international community has committed to achieve 17 Sustainable Development Goals (SDGs) by 2030 *and* to enhance climate adaptation under the Paris Agreement. Despite the potential for synergies, aligning SDG and climate adaptation efforts is inhibited by an inadequate understanding of the complex relationship between SDGs and adaptation to various impacts of climate change. Here we propose a framework to conceptualise *how* ecosystems and socio-economic sectors mediate this complex relationship. Adopting a sector scale provides a more nuanced understanding of the impacts of climate change on *all* 169 SDGs targets. Global application of the framework reveals that adaptation of wetlands, rivers, cropland, construction, water, electricity, and housing in the most vulnerable countries is urgently required to safeguard achievement of 68% of SDG targets from near-term climate risk by 2030. We discuss how our framework can help align National Adaptation Plans with SDG targets, thus ensuring that adaptation is contributing to, rather than detracting from, sustainable development.

4.1 Introduction

In 2015, the world's governments committed to achieve 169 targets under the global Sustainable Development Goals (SDGs) *and* to engage in adaptation planning under the Paris Agreement on Climate Change. Success in delivering on these two commitments will heavily depend on decision-makers to effectively plan and implement synergistic action between the SDGs and climate adaptation (UN 2019). Yet, despite numerous calls to align national climate adaptation with sustainable development (UNFCCC 2012), these calls have not yet led to action (Zhenmin et al. 2019). To date, only four of twenty existing National Adaptation Plans (NAPs) mention the SDG targets (Supplementary Table 4.1).

Aligning SDG targets and climate adaptation is inhibited by siloed global and national governance. Another obstacle is the inadequate understanding of the complex relationship between SDG targets and climate adaptation at a useful scale to inform decision-making in practice. Most national governments organise and implement adaptation plans at the sector-scale (such as infrastructure, health, ecosystems etc.) (Supplementary Table 4.1). Whilst the research community has investigated the broad relationships between the SDGs, the impacts of climate change, and climate adaptation at both the level of all the 17 SDGs (Masson-Delmotte et al. 2018) and the 169 SDG targets (Fuso Nerini et al. 2019), it has not yet provided an actionable framework to understand these complex relationships at the scale of sectors of society, the economy, and the environment. Without a systematic of these complex relationships at the sector-scale, it is not possible to exhaustively align national adaptation plans with SDG targets or to account for the indirect and interdependent sectoral effects of how SDG targets are affected by different impacts from climate change. Yet, it is these indirect and interdependent sectoral 'domino' effects on SDG targets (Reichstein et al. 2021) that are likely to have the greatest potential for future catastrophes (Renn et al. 2019), and, inversely, allow for the greatest SDG benefits from adaptation.

In this paper, we aim to address these gaps by proposing a sector-scale framework for targeting adaptation. The framework builds on previous studies that mapped: a) potential influences (also referred to as 'interlinkages' in the literature) between specific

sectors, such as water or energy, and the SDG targets (Fuso Nerini et al. 2018; Lynch et al. 2020; Singh et al. 2018; Thacker et al. 2019; Velis et al. 2017; Vinuesa et al. 2020; Wood et al. 2018), b) influences between specific climatic impact-drivers, such as floods or chronic warming, and sectors (Carleton et al. 2016; Challinor et al. 2018; Field et al. 2014; Yokohata et al. 2019), and c) interdependencies across SDGs and SDG targets (Lusseau et al. 2019; McGowan et al. 2019; Nilsson et al. 2018; Pradhan 2019; Pradhan et al. 2017). These previous studies have provided a conceptual basis for targeting practical action towards SDG target achievement (Adshead et al. 2019) and climate adaptation decisions (Izaguirre et al. 2021). Yet, they have largely been conducted separately, and have focussed on a selected set of SDG targets, sectors, and climatic impact-drivers, thereby reducing their potential to holistically inform national adaptation plans in alignment with sustainable development.

4.2 A framework for targeting adaptation to safeguard and advance SDG targets

Our framework integrates and expands upon previous studies to conceptualise the complex relationships amongst all 169 SDG targets, 12 different acute and chronic climatic impact-drivers, and a holistic set of 22 ecosystems and socio-economic sectors (Figure 4.1, Framework conceptualisation). These sectors represent the three pillars supporting sustainable development: environmental, social, and economic (Purvis et al. 2018; WCED 1987) and are based on international classifications (Anderson et al. 1976; Bogaart et al. 2019; UN 2008)

Using content analyses and evidence mapping, we populate our framework with potential influences (Figure 4.1, Evidence mapping). For each sector, we first identified and mapped evidence of the influences between each sector and SDG target, differentiating by *direct*, *indirect*, and *interdependent SDG influences* (for definitions see Supplementary Table 4.2). Second, we mapped evidence of the influences between each sector and each climatic impact-driver, differentiating by *climate influences on supply*: a) 'land/natural resources' (e.g. affecting natural biodiversity), b) 'physical capital' (e.g. affecting factories/offices), c) 'labour' (e.g. affecting workers or productivity), and on d) *demand*

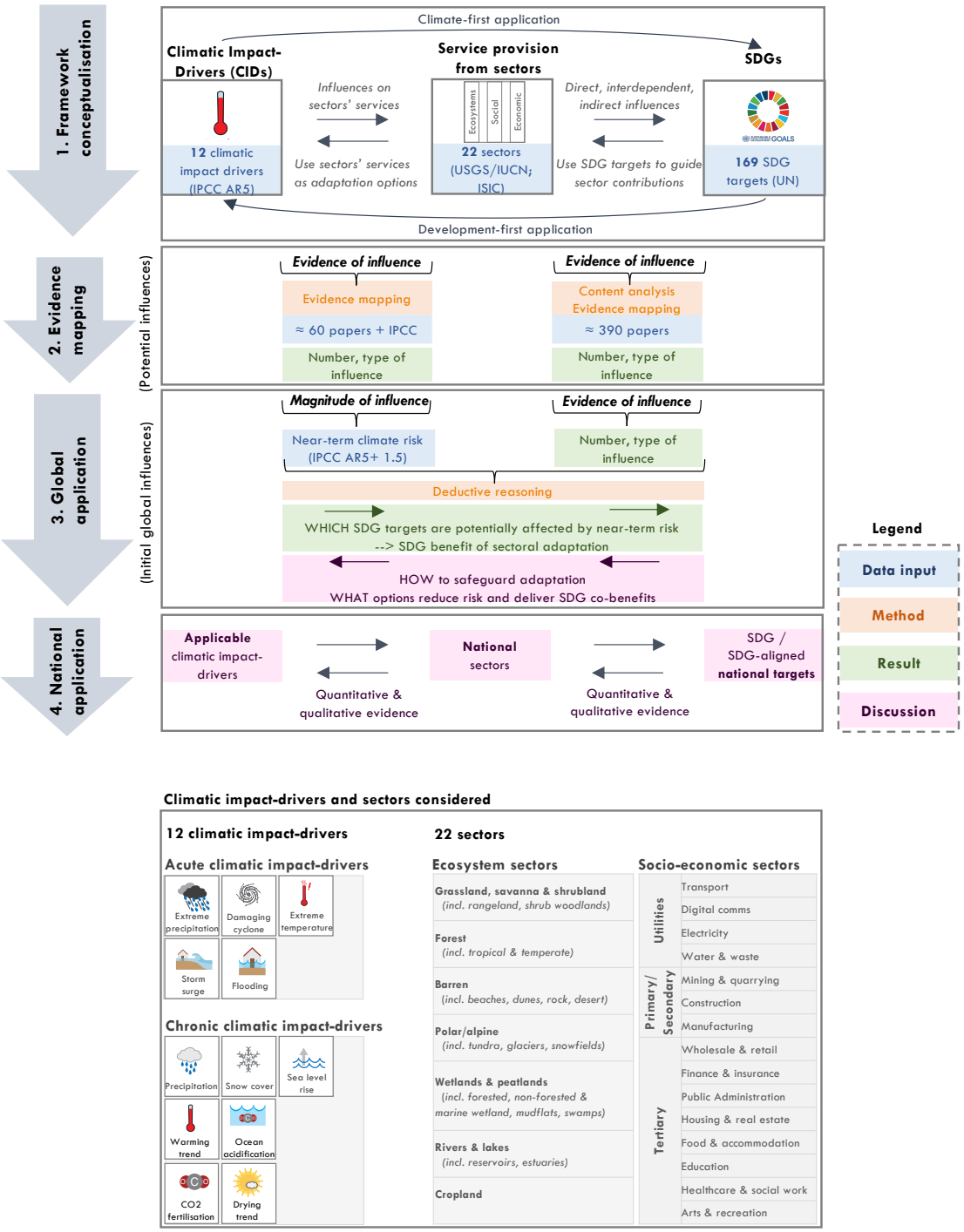


Figure 4.1: Conceptualisation and application of our framework for targeting adaptation, which focuses on the role of sectors in mediating between SDG target achievement and climatic impact-drivers. The sector classification is used to simplify the presentation and does not represent any hierarchy of sectors. We acknowledge the grey boundaries between sectors, and have performed the analysis at the level of services provided by these sectors.

(e.g. affecting electricity demand). We refer readers to the Methods section and to Supplementary Information (SI) Tab 2.1-3.2 for a record of all influences, evidence, and word strings used.

We demonstrate how it is possible to build upon these potential influences with the best available global data on *near-term sectoral risk*, which exemplifies one potential application of our conceptual framework (Figure 4.1, Global application). Near-term sectoral risk refers to the probability and magnitude of climatic impact-drivers affecting sectors by the 2030s (aligned with the SDG timeline), defined based on the Intergovernmental Panel on Climate Change' Fifth Assessment Report of Working Group II (IPCC AR5) (Field et al. 2014). Based on deductive reasoning, we link results from near-term sectoral climate risk to sector influences on SDG targets, which allows quantifying how many SDG targets are potentially affected by near-term sectoral risk (see SI Tab 4).

We discuss how our analysis of the types of SDG and climate influences can help tailor adaptation to safeguard SDG targets, deliver SDG co-benefits *and* reduce sectoral risk. Yet, national governments typically tailor adaptation plans according to their national circumstances and interpret the SDGs and Paris Agreement based on their level of development, climate risk, and contextual factors. We show how applications of our framework that consider nations' differences in resources and geography provide first insights and practical guidance to align adaptation planning with SDG targets and help leave no one behind (Figure 4.1, National application).

4.3 Influences among sectors and SDG targets

Ecosystems and socio-economic sectors can *directly* influence SDG targets, based on the concept that these sectors provide services critical for development (Bateman et al. 2020; Thacker et al. 2019; Wood et al. 2018; EEA 2018). This first step of identifying potential influences involved content analyses of whether an SDG target is directly described in terms of the services a sector provides (see Methods and see SI Tab 2.1 for a detailed overview of the services provided by each sector). Natural or semi-natural ecosystem 'sectors' include grasslands, savannas & shrublands, forests, rivers & lakes, wetlands & peatlands, barren, polar/alpine, and croplands. Depending on contextual

factors, each ecosystem sector can provide a certain set of regulating (flood protection or carbon sequestration), provisioning (food, water, energy or medicines), supporting (habitat), and/or cultural services (heritage, recreational) that are critical for sustainable development. Collectively, we find that all ecosystems directly influence 24% of all 169 SDG targets via the multitude of services they provide (Figure 4.2, direct total). Beyond targets under SDG14 ('life below water') and SDG15 ('life on land') that explicitly mention ecosystems (Blicharska et al. 2019), 12 additional goals are described in terms of the services that ecosystems provide.

Socio-economic sectors, which include utilities, primary/secondary, and tertiary sectors, also provide services that are critical for achieving SDG targets. Utility sectors (electricity, transport, water) provide infrastructure services that can directly influence 17% of SDG targets, primary/secondary sectors (manufacturing, mining, construction) provide services that can directly influence 8% of targets, and tertiary sectors (public administration, education, healthcare, amongst others) provide critical services that can directly influence 72% of targets (Figure 4.2, direct total). Compared to any other sector, the tertiary public administration sector directly influence most targets through the governance services it provides (47% of SDG targets). Identifying the influences amongst sectors and SDG targets enables researchers and decision-makers to relate action and investments on improving service provision to SDG target achievement.

We distinguish ecosystems or socio-economic sectors for practical reasons, acknowledging that multiple sectors act *interdependently* to provide services. For example, water services can be provided both by river & lake ecosystems and by the water utility sector. Similarly, ecosystem services such as flood protection can complement or substitute physical infrastructure services, whilst socio-economic governance services enable equitable ecosystems management. Additionally, cultural services permeate through and across all sectors (Díaz et al. 2018). We consider *interdependencies* in direct SDG influences by accounting for whether sectors provide *unique*, *cross-sectoral*, or *substitutable* contributions to SDG target achievement (Figure 4.2, magenta, turquoise, and green shading). We find that whilst 41% of SDG targets are described in terms of a single sector's service only (*unique* influence), 30% of targets mention multiple sectors'

services (*cross-sectoral* influence) and 12% are described in terms of a sector's service that can be substituted by a different sector (*substitutable* influence). Identifying these types of interdependencies for each SDG target allows decision-makers to understand whether SDG target achievement is solely dependent on action within a single sector (*unique* influence) or whether target achievement can benefit from action across more than one sector (*cross-sectoral, substitutable* influence). In this context, our finding that targets across a total of 13 goals are directly described in terms of both ecosystems and socio-economic services provides novel insight into the essential role ecosystems play in directly complementing and substituting socio-economic service provision in efforts towards sustainable development.

Ecosystems and socio-economic sectors can also *indirectly* influence SDG targets. *Indirect* SDG influences are defined as cases whereby a sector's service is not directly mentioned in the target's description, but for which published evidence indicates SDG target links. For example, we find evidence that ecosystem restoration indirectly creates job creation benefits in relation to SDG8 ('decent work') (Edwards et al. 2013). We identify on average four times more indirect SDG influences than direct ones (Figure 4.2, grey shading). The ratio between indirect and direct SDG influences is highest for targets under SDG8 ('decent work'), SDG5 ('gender equality'), SDG4 ('education'), and SDG16 ('peace'). To ensure a decent work environment, a gender-equal world, quality education, and peaceful living therefore does not directly emerge from scaling up sectoral investments. It requires explicit attention to these issues across various sectors. Similarly, we find the ratio between indirect and direct SDG influences is highest for the mining, manufacturing, digital communications, and transport sector. Achieving sustainable development benefits in these sectors therefore requires explicit attention to the 'hidden' influences in order to maximise the full potential of sectoral investments for sustainable development outcomes.

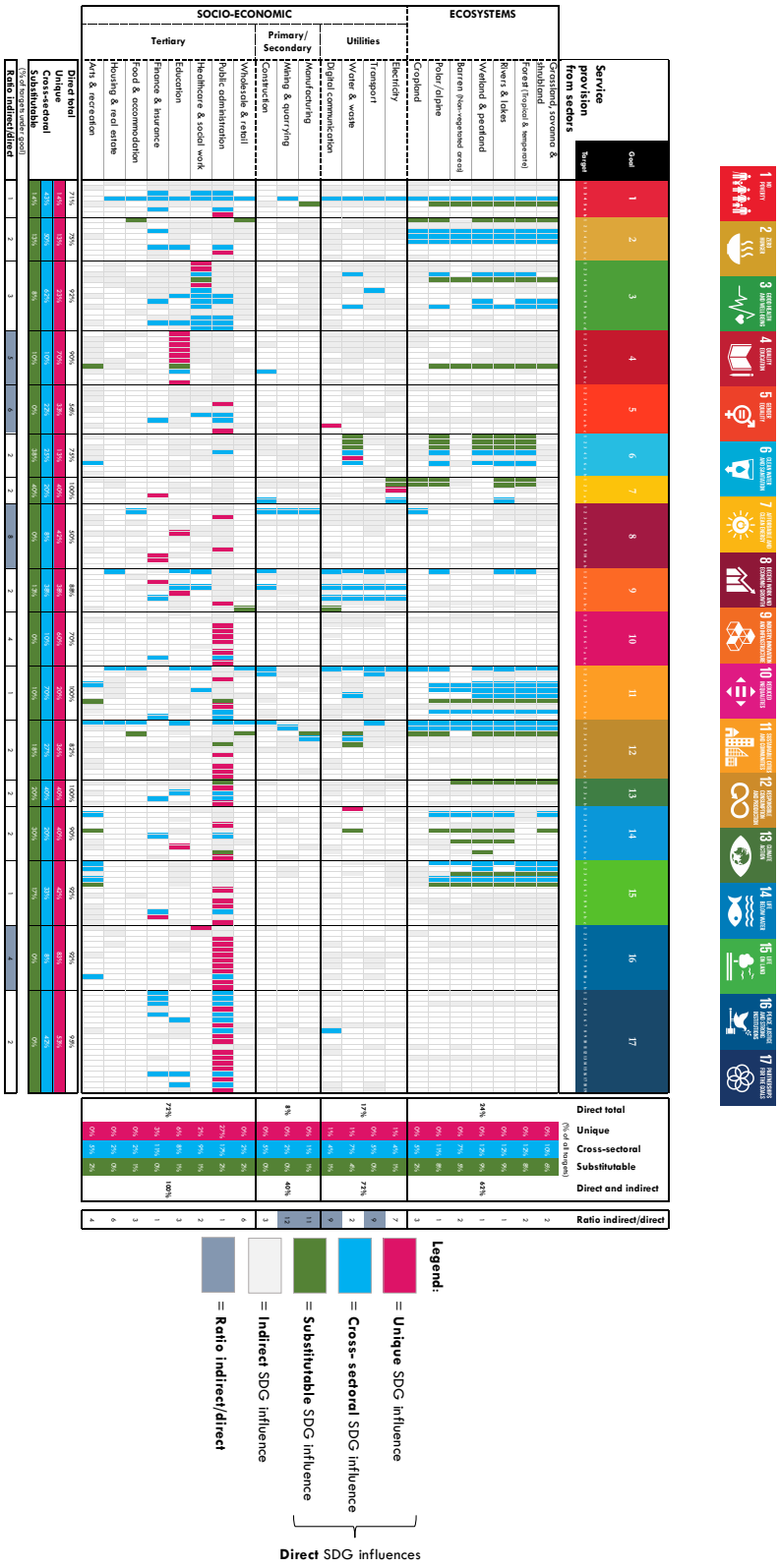


Figure 4.2: Ecosystems and socio-economic sectors influence SDG targets. Each rectangle represents one SDG target: magenta shading denotes a unique, blue a cross-sectoral, and green a substitutable direct influence. Grey indicates an indirect SDG influence.

4.4 Influences among climatic impact-drivers and sectors

There is amble evidence of the influences between climatic impact-drivers and sectors. Our evidence review reveals that acute climatic impact-drivers can threaten all 22 considered sectors through impacts on the supply of, or demand for, sectors' services (Figure 4.3, red shading). Chronic climatic impact-drivers predominantly affect sectors negatively via impacts on 'land/natural resources', with some regional positive effects (Figure 4.3, red and blue shading). For example, chronic warming is projected to reduce agricultural yields globally, but may increase yields in northeast China and the UK (IPCC 2014b).

Yet, the risk emerging from these climatic impact-drivers is highly context-dependent. It is largely based on the magnitude and frequency of the *hazard* (a climatic impact-driver with negative consequences) within a certain area, the *exposure* of sectors to the hazard, the *vulnerability* of the sector to continue to provide its services when exposed to a hazard (a sector's *sensitivity*), and the *vulnerability* of the population using the sector's service (*adaptive capacity*) (see Supplementary Table 4.2 for definitions). Sectors where service provision is already poor, declining, or endangered from other stressors are likely to be more vulnerable to additional impacts of climate change. Similarly, poorer societies are less capable to recover from climate-induced losses by means of diversification of incomes, amongst other factors (Koks et al. 2015). Acknowledging the difficulty and complexities with any global evidence of climate-sector influences, we apply the *near-term sectoral risk ranking* from IPCC AR5 (Field et al. 2014). We identify that all acute chronic climatic impact-drivers and three chronic ones (the warming trend, ocean acidification, and the drying trend) cause highest near-term risk to six sectors and the services these provide. These climate-sensitive sectors include rivers & lakes, wetland & peatland, cropland, electricity, water & waste, construction, and housing & real estate.

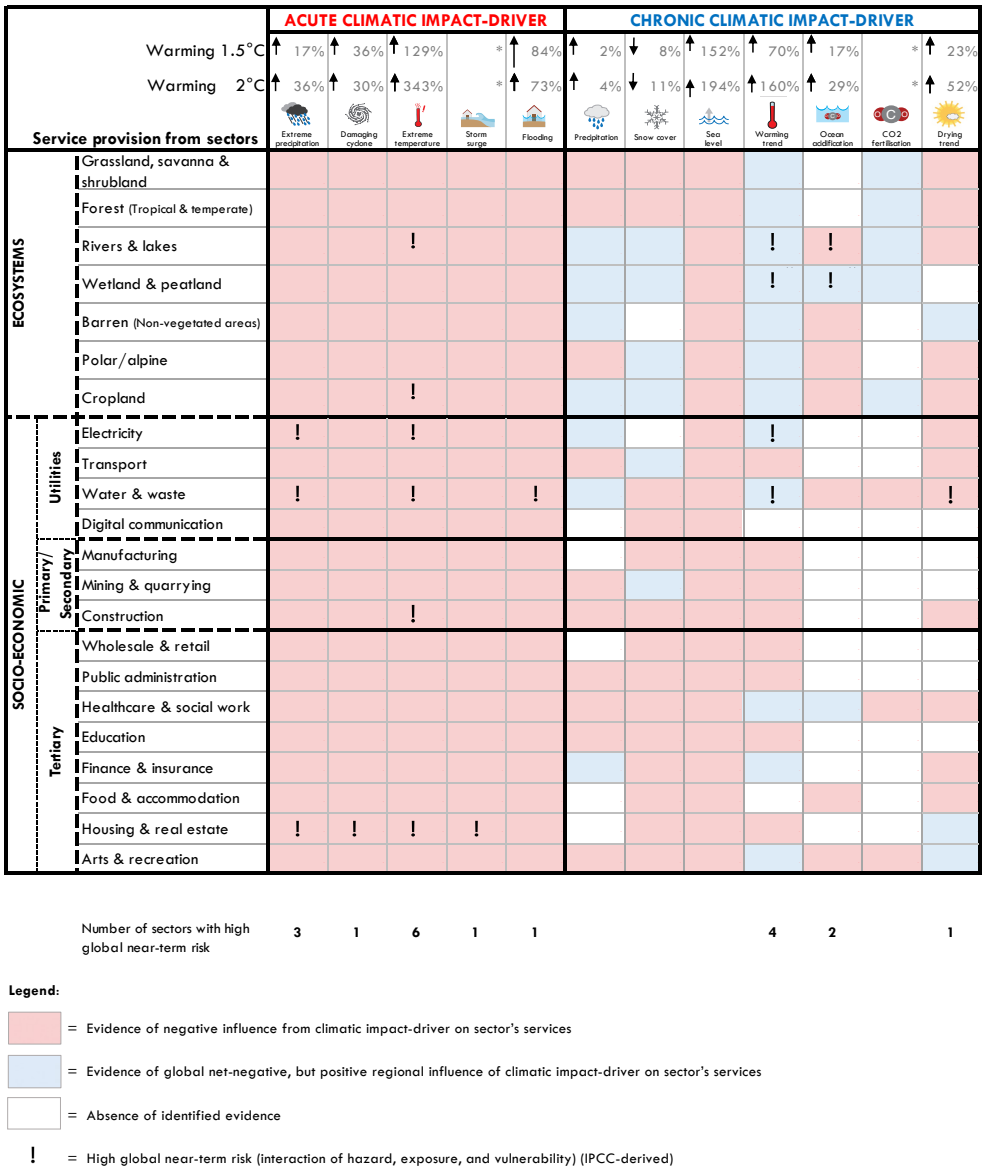


Figure 4.3: Ecosystems and socio-economic sectors influenced by climatic impact-drivers. Red shading denotes evidence of a negative effect, blue shading highlights evidence of a potential positive effect. Percentages for climatic impact-drivers signify changes in frequency under a 1.5 and 2°C scenario (see SI Tab 3.3). The symbol * suggests that no quantified evidence was identified. Exclamation marks represent high near-term risk based on IPCC AR5 TS.4.

4.5 SDG targets influenced by impacts of climate change

Based on deductive reasoning, we integrate: (i) sector-SDG influences, and (ii) sector-climate influences. This allows us to identify that achievement of 141 of 169 SDG targets (83%) can potentially be *directly* undermined by any acute climatic impact-driver

(Figure 4). Chronic climatic impact-drivers, which have either negative or regionally positive effects, can threaten 37% more SDG targets than they can support through opportunities. Combining potential *direct* and *indirect* SDG influences, we find that achievement of all 169 SDG targets can be affected by any climatic impact-drivers. These results demonstrate the value of considering sectors as mediators between SDG targets and impacts of climate change: adopting a sector-scale approach provides a more nuanced understanding of the impacts of climate change on the SDGs as compared with recent literature in the field (Fuso Nerini et al. 2019).

An understanding of the magnitude of climate change impacts on SDG targets inversely provides insight into the SDG benefits of adapting climate-sensitive sectors. When planned and governed well, adapted ecosystems can help safeguard 62% of all 169 SDG targets, adapted utility infrastructure can help safeguard 72% of targets, adapted primary/secondary sectors can help safeguard 40% of targets, and adapted tertiary sectors can help safeguard *all* SDG targets. Notably, 21% of potentially climate-sensitive targets require adaptation across ecosystems *and* socio-economic sectors.

Based on IPCC AR5's global data on near-term sectoral risk, the seven sectors at highest near-term risk can *directly* hamper achievement of 36% of SDG targets (Figure 4.4, exclamation marks). Especially affected is achievement of SDG2 ('end hunger'), SDG6 ('clean water'), SDG7 ('energy'), SDG9 ('innovation and infrastructure'), SDG11 ('sustainable cities'), SDG12 ('responsible consumption and production'), and SDG14 ('life under water'), where a minimum of half of the targets under the respective SDG are directly influenced by one or more of the seven sectors (see Supplementary Information Tab 4 for target-level results). When considering both *direct and indirect* SDG influences, near-term climate risk on the seven sectors can undermine 68% of SDG targets across all 17 goals. Focussing adaptation on these seven sectors this decade is therefore critical to safeguard achievement of 68% of SDG targets by 2030.

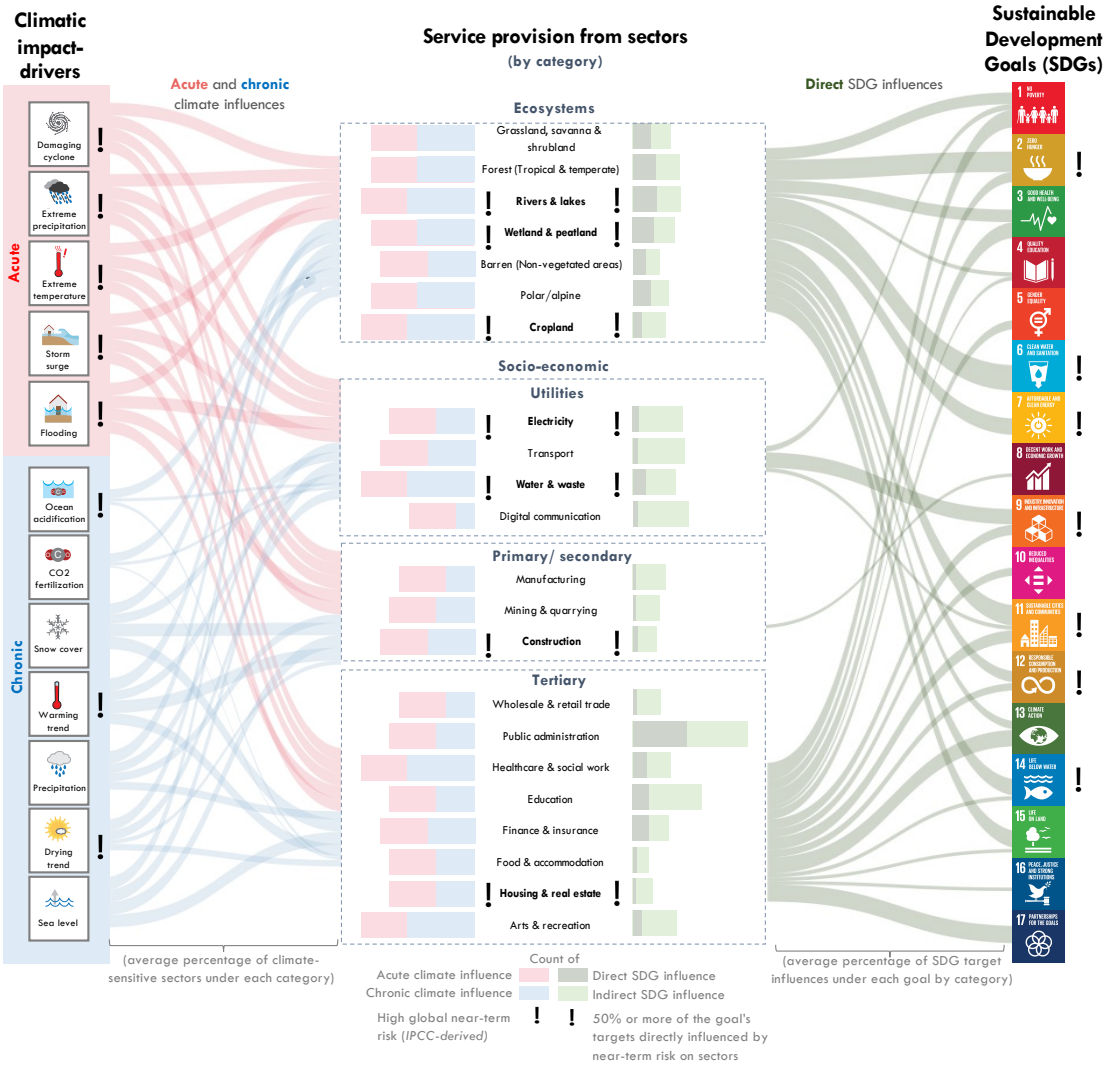


Figure 4.4: Framework linking sectoral risk from climatic impact-drivers to SDG target achievement. From left to right: Percentage of sectors under each category (ecosystems, utilities, primary/secondary, tertiary) influenced by acute and chronic climatic impact-drivers (red and blue lines), quantity of influences of acute and chronic climatic impact-drivers on sectors (red and blue bars), quantity of direct and indirect influences between sectors and SDG targets (dark and light green bars), and the percentage of SDG targets under each goal directly influenced by each sector category (green Sankey lines). Exclamation marks denote high global near-term risk.

4.6 Discussion

4.6.1 Tailor adaptation to safeguard and advance SDG targets

Our understanding of types of influences can help work backwards from the SDGs to specify: 1) where and how to adapt sectors to safeguard SDG target achievement, and 2) what type of sectoral adaptation option might reduce climate risk *and* advance SDG target

co-benefits, which we describe in the context of our global near-term sectoral risk findings.

In tailoring adaptation to safeguard SDG targets, we apply our findings of how sectors influence targets (*unique, cross-sectoral, substitutable, indirect*). For SDG targets that are directly influenced by a single climate-sensitive sector, adaptation can focus *uniquely* on that sector. In the absence of information on where risk on sectors is highest, adaptation of the climate-sensitive public administration sector, which is responsible for implementing just policy, can *uniquely* safeguard most SDG targets (27%) as compared to other sectors (Figure 4.2, magenta shading).

For SDG targets that are influenced by different climate-sensitive sectors, *cross-sectoral* adaptation is needed. Compared to other sectors, we find that adaptation of the climate-sensitive public administration sector and ecosystems can safeguard most SDG targets through *cross-sectoral* contributions (17% and 12% of SDG targets, respectively), where each service provides an independent contribution to target achievement (Figure 4.2, turquoise shading).

For SDG targets that are influenced by climate-sensitive sectors that provide *substitutable* functions, decision-makers have more options in their choice of where to adapt. We find that protecting or enhancing ecosystem services - including rivers & lakes, forests, and wetlands & peatlands - can safeguard 10%, 8%, and 8% of SDG targets, respectively, through substituting climate-sensitive socio-economic services (Figure 4.2, green shading).

In tailoring adaptation to reduce risk *and* to advance SDG target co-benefits, we differentiate by the three components of risk: *hazard*, *exposure*, and *vulnerability* (see Extended Data Figure 4.2). Firstly, decision-makers might focus adaptation on geographic areas projected to experience more frequent/severe *hazards*. Hazard-based adaptation options often involve scaling up ecosystems' adaptation services, such as restoring wetlands that reduce flood severity (Chausson et al. 2020). Our influence findings show that scaling up ecosystems' adaptation services, especially when implemented in a manner that maximises potential indirect influences, has the potential to advance up to

105 SDG target co-benefits (see Supplementary Information Tab 3.1). As such hazard-based options often focus on geographic areas, they can help protect more than one sector against hazards.

Secondly, decision-makers might tailor adaptation to address the *exposure* of a sector ('land/resources', 'physical capital', 'labour') or the demand for its services (Supplementary Information Tab 3.2). For example, we identified evidence that outdoor-working agricultural 'labour' (agricultural workers) is mainly exposed to extreme temperature, whilst agricultural 'physical capital' (machinery, factory) is mainly exposed to floods. Therefore, decision-makers might choose working hour policies as an adaptation option to reduce exposure of 'labour', and land-use policies to reduce exposure of 'physical capital'. Given that exposure-based adaptation options focus on location-adjustments, substituting service provision away from exposed sectors may be a suitable adaptation option to reduce exposure.

Thirdly, decision-makers may tailor adaptation based on which populations or sectors are most *vulnerable* to hazard exposure. For example, poor agricultural workers who are already working under insecure arrangements or with little access to diversified resources have less capacity to adapt, and agricultural factories that have been built without resilient designs may be more sensitive to intense floods. As vulnerability-based adaptation options often focus on ensuring continued service provision to already vulnerable populations or climate-sensitive sectors in the face of hazard exposure, vulnerability-based adaptation may be a suitable adaptation option especially in cases where sector's service provision cannot be substituted and/or hazard exposure cannot be reduced. Considering the hidden indirect SDG influences of vulnerability-based adaptation options can help ensure potential SDG co-benefits are realised. In practice, hazard, exposure, and vulnerability-based options are often implemented in tandem, and are likely to be most effective for near-term hazards of high probability and relatively low impact (Mechler et al. 2014).

In light of our global near-term sectoral risk findings, we identify that safeguarding those SDG targets affected by multiple climate-sensitive sectors - especially under SDG2 ('end hunger'), SDG9 ('innovation and infrastructure'), SDG11 ('sustainable cities'), and SDG12 ('responsible consumption and production') - necessitates *cross-sectoral*

adaptation to multiple climatic impact-drivers. Nature-based Solutions (NbS), which include scaling up ecosystem protection or restoration in a specific geographic area (Cohen-Shacham et al. 2016), can provide the required cross-sectoral adaptation services and protect against numerous climatic impact-drivers simultaneously (*hazard-based)*. If they respect cultural rights and support biodiversity, NbS also deliver cultural and regulating services that advance sustainable development co-benefits (Seddon et al. 2021).

To globally safeguard the near-term climate-sensitive targets under SDG6 ('clean water') and SDG7 ('energy') with many *substitutable* influences, decision-makers may focus adaptation on sectors that provide multiple services in order to maximise SDG co-benefits. For example, achievement of SDG6 ('water') could be safeguarded by prioritising protected river & lake or wetland & peatland ecosystems less exposed by chronic warming to substitute for, or complement, climate-sensitive dams (*exposure-based*). Such substitutable or complementary action can also safeguard the regulating and cultural services provided by these ecosystems whilst building both social capital and adaptive capacity through community-based ecosystem management (Reid et al. 2013).

Some SDG targets, especially under SDG11 ('sustainable cities') and SDG14 ('life under water'), are influenced by climate-sensitive sectors that provide globally *non-substitutable* services in safeguarding wellbeing (Cohen et al. 2019). For example, rivers & lakes and wetland & peatland ecosystems provide regulating air purification as well as natural and cultural heritage services that are globally non-substitutable in their contribution to targets under SDG11 and SDG14. These regulating and cultural services are already threatened by other non-climatic stressors, evidenced by the declining contribution of ecosystems' regulating and cultural services to the SDGs over time (IPBES 2019). Therefore, to help safeguard SDG targets influenced by non-substitutable ecosystem services, adaptation might be best placed to reduce the vulnerability of these highly productive and non-substitutable ecosystems through management and conservation, amongst other options (*vulnerability-based*).

4.6.2 Reflections and considerations in applying the framework

Adaptation decision-making is a complex and multifaceted challenge. Yet, governments and development organisations must urgently make decisions on adaptation that intersect with different dimensions of development (Adger et al. 2018). To avoid maladaptive outcomes, decisions on adaptation should not only reduce risk, but also safeguard and advance sustainable development (Eriksen et al. 2021; Schipper et al. 2020). Although both research and real-work experience underscores the criticality of better understanding the complex relationships between SDG targets and climate change impacts to inform adaptation in alignment with sustainable development (Le Blanc 2015), this understanding has been incomplete and inconsistent to date. Our proposed framework based on sector-SDG and sector-climate influences provides a starting point to navigate these complexities. Yet, its application requires a number of considerations:

First, is the sector-SDG and sector-climate influence positive or negative? Negative sector-SDG influences might reveal opportunities to reverse trends and scale up SDG contributions. For example, negative influences from manufacturing services on child labour may be reversed by enforcing employment regulations, thereby creating positive indirect influences on SDG8 ('decent work'). Where negative SDG influences result from weak national or regional governance procedures, as is the case with child labour in the manufacturing sector, global partnerships and international transparency can help guide sectoral sustainability outcomes whilst maximising the unique and cross-sectoral SDG benefits of good governance. Similarly, positive climate-sector influences, such as increased agricultural crop yields under warming trends, might be exploited in a way to scale up sectoral service provision that benefits the poorest (SDG1 'poverty').

Second, is the current magnitude of the influence direction strong or weak? A strong sector-SDG influence (the SDG target is near full achievement based on a sector contribution) coupled with a strong sector-climate influence (sector is at high risk from climate change) suggests adaptation must be targeted to safeguard existing SDG progress. Conversely, a weak sector-SDG influence with a strong sector-climate influence (low baseline progress on SDG targets influenced by climate-sensitive sectors) suggests future

SDG investments must be climate-resilient. An analysis of substitutable SDG influences may help guide how to replace climate-sensitive with more resilient services.

Third, how robust is the influence, now and into the future? Sectoral adaptation might be targeted to reduce climate risks and advance SDG co-benefits across those influences with highest robustness first (e.g. focusing on near-term sectoral risks attributable with high confidence), whilst creating iterative processes to monitor and assess less robust influences.

Fourth, where are gaps in our understanding of sector-SDG and sector-climate influences, including interdependent influences? Missing evidence for influences can help identify research gaps, but might also provide clues on existing sustainability or climate-resilience efforts or network effects that are effective. Assessing self-reinforcing and cascading interdependent influences is critical to start to understand trade-offs and synergies amongst climate risks, sectors, and SDG targets, evidence of which is limited but emerging (Koks, Rozenberg, et al. 2019; Simpson et al. 2021; Yokohata et al. 2019).

Fifth, is the influence bi-directional? A sector can demonstrably influence SDG targets, whilst working backwards from an SDG vision might provide useful insights on non-existing influences, guiding future research. Similarly, climate change may influence a sector for which risk-reduction efforts may be infeasible. This is the case with some degraded ecosystems that have reached adaptation limits (Klein et al. 2014), rendering risk-reduction options largely impossible. In other cases, risk-reduction efforts might be SDG beneficial despite a lack of existing climate influences, as is the case with strengthening the socio-ecological resilience of non-substitutable ecosystem services.

The aim of the application of the conceptual framework will determine which of these considerations is particularly important, and how so. Climate-first applications of our framework can help researchers and decision-makers assess and quantify impacts of climate change on sectors and its interdependent influences on SDG targets, as demonstrated in a recent assessment in Saint Lucia (Adshead, Roman, et al. 2020; Fuldauer et al. 2021). Such climate-first applications help make the case for sectoral adaptation, transcending economic adaptation assessments.

Development-first applications ground climate adaptation in an SDG vision. By working backwards from national development targets, it is possible to evaluate the extent to which SDG target progress is already met, and how sector adaptation provides the largest SDG safeguarding gains, as demonstrated in a recent assessment in Ghana (Fuldauer, Adshead, et al. n.d.). Similarly, development-first applications can guide where and how future SDG investments require climate-resiliency considerations.

Sector-first applications can support infrastructure planners, land-use managers or other sectoral decision-makers to better tailor adaptation. This includes identifying where sectoral action can maximise positive SDG target influences, minimise negative ones, *and* reduce potential climate risks across different hazards. Opportunities for cross-sectoral coordination can be teased out, both in advancing SDG target outcomes and in reducing risk.

4.6.3 Towards coordinated global and national efforts

Our global application demonstrated one potential application of the framework. It enabled an initial understanding of the sign and magnitude based on a climate-first application of the potential impacts of near-term climate risks on the SDG targets, which helped make the case for sectoral adaptation. Whilst the global application used the best available global evidence on the magnitude of sector-climate influences across a range of climatic impact-drivers, it was hampered by a limited scope of sectors, and missing evidence on the current sign and magnitude of sector-SDG influences, including how adaptation options have resulted in positive and/or negative SDG target impacts (see Limitations). Further, the global application in this paper highlighted some initial bi-directional influences to guide a development-first application of the framework, which would however benefit from further qualitative and quantitative evidence to inform sustainable adaptation.

Building a more substantive global evidence base requires researchers to collect and document the bi-directional sector-SDG and sector-climate influences. Currently, however, this data mainly remains isolated in siloed departments and national contexts. Building on efforts such as the Inter-Sectoral Impact Model Intercomparison Projet (ISIMIP) (Frieler

et al. 2017), globally unified reporting standards and global databases that bring together data across disciplines and sectors can help overcome this challenge. Opportunities provided by machine learning also have an important role to play. Machine learning can pinpoint where evidence of influences is missing, and help dynamically update the ever-increasing evidence base of sector-SDG and sector-climate influences in global platforms.

Differences in geography and resources make it difficult and risky to apply generalised, global influences across highly diverse countries. In some countries, application with national quantitative data on hazard scenarios, sectoral service information (Conway et al. 2019; Adger et al. 2018; Carleton et al. 2016), and quantified SDG linkages (Adshead et al. 2019) might be possible. Given the focus of this framework on a holistic set of internationally classified sectors, further integration with input-output models (Koks, Thissen, et al. 2019) could enable quantifying the cascading effects across sectors in influencing sustainable development outcomes. Multi-criteria decision analysis can help simulate the reliability, multifunctionality (Bateman et al. 2020), and potential maladaptation consequences (Seddon et al. 2020) of nature-based solutions alongside engineering-based adaptation options (Jones et al. 2012) in the context of sustainable development.

In more data- or resource-scarce countries, the framework might be used as a more formalised process to aid participatory discussions on which hazard, sectors, and SDG linkages exist, resulting in qualitative scoring of adaptation priorities. Potential adaptation options can be discussed in multi-stakeholder workshops to identify where and how adaptation can advance synergistic, and reduce negative, SDG target outcomes.

Yet, unless the voices of local, marginalised, and indigenous peoples are explicitly accounted for, any application of the proposed framework will fail in delivering sustainable development outcomes. The most successful applications of the framework will promote citizen buy-in from those already most left behind, account for issues of equity, fairness, and justice (Masson-Delmotte et al. 2018), and consider the non-substitutable value of ecosystems in multifunctional landscape approaches (Kremen et al. 2018). When such applications are also grounded in living data systems and use the

best available science, they can play an important role in developing dynamic climate adaptation plans that 'leave no one behind'.

4.7 A call for scaling up sustainable climate adaptation

To date, calls for aligning climate adaptation with the SDGs have failed to deliver action (Zhenmin et al. 2019). We have demonstrated that without targeted climate adaptation action across sectors, achievement of *all* SDG targets is being threatened by the impacts of climate change. As more nations around the globe revise their adaptation plans and commitments under the Paris Agreement, there is an urgent need for an actionable framework to help align national adaptation plans with SDG targets. If planned and governed well, application of our proposed framework can help stir the action needed to ensure that adaptation is contributing to, rather than detracting from, sustainable development.

4.8 Methods

The conceptualisation and application of this research followed a set of three best-practice steps for conducting and synthesising adaptation research as proposed by Berrang-Ford et al. (2015) (see Supplementary Information Tab 'Contents' for detailed description of each step and Extended Data Figure 4.5 for visualisation). These three best-practice steps were applied to increase the methodological transparency and rigour in synthesising adaptation research. The first step involved contextualising the research problem and identifying a conceptual approach to develop the conceptual framework. Search terms and inclusion and exclusion criteria were formulated to populate the framework with existing evidence. The second step involved searching, screening, and cataloguing published evidence. This evidence was then characterised through descriptive statistics in the third step, which included 'mapping' the quantity of sector-SDG and sector-climate influences for each sector. These steps were applied with IPCC-derived global data on near-term sectoral risk from 12 climatic impact-drivers and can be further applied at the national scale.

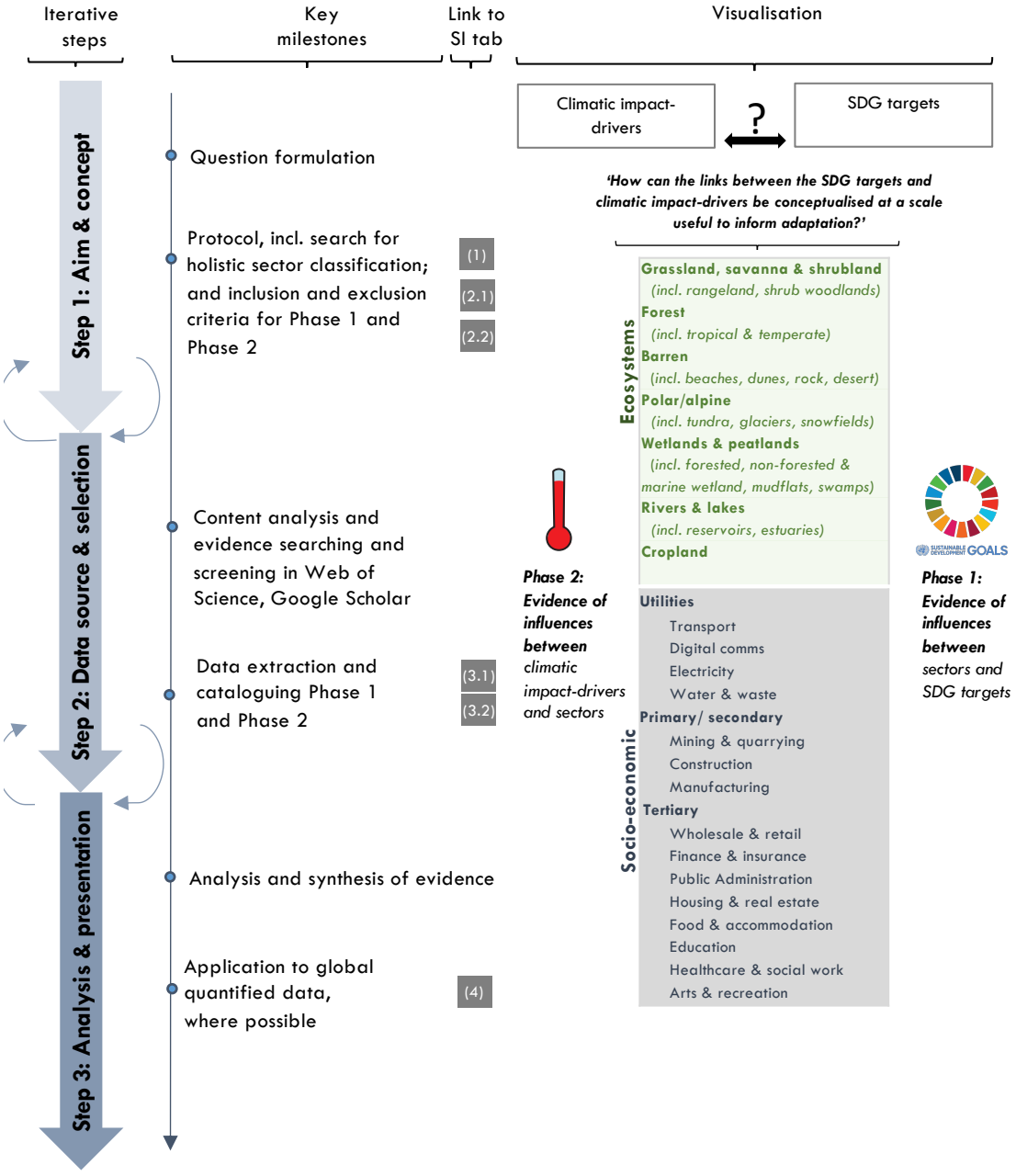


Figure 4.5: Conceptualisation and application of our framework for targeting adaptation. SI refers to Chapter 4 Supplementary Information Tab in excel format.

Step 1: Aim & concept

The aim of this research was to develop a framework for conceptualising the complex relationship between achievement of sustainable development targets and different impacts of climate change in order to provide a direct entry point for decision-makers to target adaptation. Acknowledging the complexities and ambiguities in conceptualising

sustainable development and climate adaptation, we adopted normative definitions of the two concepts in the context of the global SDGs and the Paris Agreement[1].

Previous literature has identified that providing direct entry points for decision-makers at different scales (global, national, public and private sector, academic modelling) requires the role of an intermediary (Conway et al. 2019). The following set of criteria were considered useful to determine such an intermediary in the context of the SDGs and the Paris Agreement:

1. mentioned in nations' sustainable development plans, Nationally Determined Contributions (NDCs), and National Adaptation Plans (NAPs),
2. action within the intermediary can influence SDG target achievement and the adaptation component of the Paris Agreement (as an 'operator') and is influenced by the 'stimulus' of climatic impact-drivers (as an 'exposure unit' or 'receptor'), following an existing framework on adaptation (Eisenack et al. 2012),
3. mappable, i.e. allows for a quantitative, GIS-based translation,
4. globally applicable, i.e. consistent with international accounting standards, such as the System of Environmental Economic Accounting (SEEA) and global modelling standards to allow comparison across nations.

We used a holistic set of 22 ecosystems and socio-economic 'sectors' as an intermediary, because nations' development and climate adaptation plans are typically organised in terms of sectors and because sectors are both essential for achieving the SDGs and affected by climatic impact-drivers. Given the physical dimension of climatic impact-drivers, we based our choice of ecosystems and socio-economic sectors on the original land-cover/land-use classification categories by USGS (Anderson et al. 1976), which was developed using strict criteria to ensure mappability (i.e. spatial units are geographically exclusive and exhaustive). As the USGS classification was the first classification of land-cover/land-use, a range of global land cover classifications build on it, making it

[1]These normative definitions represent the best globally available compromise between the scientifically necessary and the politically possible response to address sustainable development and climate change, thereby reflecting a multiplicity of concerns and interests (Kanie et al. 2019; Le Blanc 2015).

globally applicable (Bogaart et al. 2019). In addition, geospatial data for the terrestrial and freshwater categories is available at high resolution (Bogaart et al. 2019). We updated the USGS classification categories according to the SEEA-updated USGS categories of major ecosystem types (Bogaart et al. 2019), which also align with the ecosystem types developed by the International Union for Conservation of Nature (IUCN) (see Supplementary Information Tab 1). We further disaggregated USGS' classification of 'built-up land' by socio-economic sectors, using the International Standard Industrial Classification of all economic activities (ISIC Rev 4) (UN 2008). ISIC was considered an internationally-used classification of socio-economic sectors that allows for integration of open-source spatial data and that is consistent with international accounting standards.

Given that the value of a sector is determined by the services it provides over its life (Dasgupta 2020), our analysis focused on the concept of ecosystem and socio-economic services (Bateman et al. 2020; Thacker et al. 2019; Wood et al. 2018). We explicitly catalogued the range of services provided by each of the 22 ecosystems and socio-economic sectors, based on international classifications where possible (see Supplementary Information Tab 1 and 2.1). We identified a total of 35 different services provided by all ecosystem sectors, and a total of 32 different services provided by all socio-economic sectors. We grouped ecosystem sectors based on where they provide the same services, acknowledging that the quantity or quality of service provision may differ within the same sector (e.g. tropical forests provide much larger mitigative services compared to temperature forests, but both tropical and temperature forests are grouped under the 'forest' sector). For socio-economic sectors, we applied the services provided by each sector as stated in ISIC Rev 4. Recognising that the grouping of services into single entity sectors masks important differences between sectors and across different national accounts, it nevertheless provided a useful means by which to present and discuss findings that are transferable and that can be expanded upon in national applications.

We populated our framework using content analyses and evidence mapping through two main phases (see Supplementary Information Tab 2.1-3.2 for definitions, specific inclusion and exclusion criteria and a detailed catalogue of the literature evidence).

(Phase 1) Content analysis and evidence mapping: Sector-SDG influences, differentiating by type of influence

For each of the 169 SDG targets and each of the 22 sectors, we analysed and catalogued influences by answering the following questions:

Direct SDG influence: 'Using the official UN wording of the SDG targets, is the SDG target directly described in terms of the services provided by the sector'? (search terms included the wording of SDG targets and the sector's services as described in Supplementary Information Tab 2.1 and 3.1). For example, target 11.6 "By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to *air* quality and municipal and other *waste management*" is directly described in terms of the 'purification of *air'* services provided by forests, and the '*waste management'* services provided by the water & waste sector.

Interdependent SDG influence: 'For each SDG target directly described in terms of the services provided by a sector, how many sectors' services are mentioned in the description of the SDG target?'

- If '1', classify as '*unique SDG influence'*. A unique influence is identified when an SDG target is described solely in terms of one sector's service, in other words, the sector provides an independent, singular contributions towards SDG target achievement. For example, target 16.3 "Promote the rule of *law* at the national and international levels" is uniquely influenced by (i.e. directly described in terms of only) the '*law enforcement'* services provided by the public administration sector. This function cannot be substituted by the services of another sector.
- If '2' or more, 'does each sector provide a different service towards SDG target achievement?'
  - If 'Yes', classify as '*cross-sectoral SDG influence'*. A cross-sectoral influence is identified when a sector's service provides independent, cross-sectoral contributions towards achievement of an SDG target. For example, target 11.4 "Strengthen efforts to protect and safeguard the world's *cultural* and *natural* heritage" is described in terms of both '*cultural* heritage' services from the

arts & recreation sector as well as '*natural* heritage' services from a range of ecosystem sectors, including the forest sector. Both services are needed to ensure target achievement.

- If 'No', classify as '*substitutable SDG influence'*. A substitutable influence is identified when sectors provide a service that can be substituted by another sector. In such a case, various sectors provide the same service towards SDG target achievement, presenting decision-makers with a choice of how to safeguard target achievement in the face of impacts from climate change. For example, target 6.1 "Achieve universal and equitable access to safe and affordable drinking *water*", can be influenced by the *water* provision services directly abstracted from either rivers & lakes *or* from water & waste utilities.

Indirect SDG influence: 'Is there published evidence that achievement of the SDG target can be indirectly influenced by the services provided by the sector?' (search terms included the wording of SDG targets and the sector's services, as described in Supplementary Information Tab 2.1 and 3.1). An indirect influence is identified where the SDG target is not described specifically in terms of the service that a sector provides, but for which published evidence indicates that improving the quality or quantity of the service provided by a sector can enhance the achievement of the target, following the definition of Thacker et al. (2019). For example, target 5.2 "Eliminate all forms of violence against all women and girls [. . .]" can be indirectly influenced by the healthcare & social work sector, as there is evidence that improving the quality of healthcare services, especially drug addiction services, can reduce violence (Swartz et al. 1998). Indirect influences include cases whereby there is published evidence that improvements in environmental management, fair provision or better governance can support achievement of the target. It excludes cases of second-order interdependencies: for example, there is no indirect influence between the mining & quarrying sector and SDG target 11.1 ("Ensure access to housing") because only a second-order influence could be identified: mining & quarrying supports the provision of minerals, which are then used in construction of shelter for housing (see Supplementary Information Tab 3.1 for all inclusion and exclusion criteria).

(Phase 2) Evidence mapping: Sector-climate influences, differentiating by type of influence

We categorised 12 climatic impact-drivers, as defined by the IPCC AR5 (Field et al. 2014), into acute (extreme) and chronic (slow-onset) climatic impact-drivers (Supplementary Information Tab 2.2). For each of the 12 climatic impact-drivers and each sector, we analysed and catalogued influences for the following questions:

Climate influence: 'Is there published evidence that the climatic impact-driver can negatively or positively influence the quantity or quality of the services provided by the sector via impacts on 'land/natural resources', 'physical capital', 'labour') or 'demand'?' (search strings included the wording of the climatic impact-drivers, various strings for supply and demand factors, and the sector's services as described in Supplementary Information Tab 3.2).

- If 'Negative', encode as '-', include the type of impact, and include confidence of the published evidence if available.
- If 'Positive, encode as '+', include the type of impact, and include confidence of the published evidence if available.

If reference is made to 'coastal infrastructure', any socio-economic sector is considered to be potentially affected. If the literature makes reference to 'extreme events', the following climatic impact-drivers are included: extreme precipitation, damaging cyclone, extreme temperature, flooding, storm surge. Climate influences exclude evidence in which climatic impact-drivers can result in economic market readjustments (e.g. increased prices due to shortage of supply following extreme impacts) (see Supplementary Information Tab 3.1 for all inclusion and exclusion criteria).

Step 2: Data source & selection

The content analysis for the direct sector-SDG influences used the wording of the SDG targets and the services of each sector (see search strings in Supplementary Information Tab 2.1). The search for scientific evidence for the indirect sector-SDG, and the sector-climate influences involved three different stages (in order of search): 1) Tier 1 journals,

2) IPCC assessments and special reports (including 'Global Warming of 1.5°C' (Masson-Delmotte et al. 2018), 'AR5' (Field et al. 2014), 'Climate Change and Land' (IPCC 2019), other peer-reviewed articles, and pre-prints, and 3) 'Grey literature' (reports from international organisations, national and subnational agencies). The search for evidence was first performed through Web of Science, which was chosen given its high speed of inclusion of related articles and the inclusion of preprints. Second, a google search was used to identify evidence, especially to capture stage 3 evidence ('Grey literature'). English was used for the evidence search, as it is the most employed language and considered the international academic language (Bailey et al. 1986).

The evidence for each influence was screened against the predetermined definitions and the inclusion and exclusion criteria. In the case of ambiguous influences, these were reviewed and discussed amongst the author team until a consensus was reached, following the process adopted in previous studies (Fuso Nerini et al. 2019; Thacker et al. 2019). If more than one piece of evidence was available, the most recent publication was included for each influence type. All evidence was catalogued in Supplementary Information Tabs 3.1 and 3.2. The search for evidence aimed to gain a view on whether *potential* influences exist rather than a systematic review of all published evidence. We did not conduct a meta review of the evidence to characterise the quality of the evidence, but hope to mitigate this aspect through our prioritised search in different stages, using the most recent available evidence, and embedding confidence intervals where available. We discussed how potential influences could be realised in practice with evidence on actual or projected influences in different settings (see Section 'Reflection and considerations in applying the framework').

Step 3: Analysis & presentation

The sector-SDG influence findings from the content analysis and evidence mapping were characterised through descriptive statistics, both at the sector and SDG target level. At the sector-level, we summarised the quantity of sector-SDG influences in terms of absolute numbers and percentages of SDG targets (Figure 4.1). At the SDG target level, we summarised the number of sectors that can potentially influence that SDG target as well

as the type of influence (direct, indirect, interdependent). To provide useful implications for decision-making, we further summarised results through aggregating sector results at the scale of four categories: ecosystems, utilities, primary/secondary, and tertiary sectors (Figure 4.1). For the sector-SDG influences, we did not assess the magnitude of influences, because such information was not available at the global scale across all ecosystems and socio-economic sectors, and is highly context-specific. Global indicator data to measure the magnitude of SDG target achievement exists (Schmidt-Traub et al. 2017), but this is determined by the availability of data across all nations, does not capture the contribution of sectors as described in this paper, and does not allow accounting for indirect and interdependent influences.

For the sector-climate influences, we described the number of potential negative or positive influences from each climatic impact-driver on each sector (Figure 4.3). We summarised how climatic impact-drivers influence each *supply* factor ('land/natural resources', 'physical capital', 'labour') or *demand* for each sector (see Supplementary Information 3.2).

Unlike for the SDG influences, global data on the magnitude of influences from different climatic impact-drivers on sectors was available. We therefore applied global data from IPCC AR5's key sectoral risk ranking (Table TS.4) (Field et al. 2014), the best globally available ranking of risk across 12 different climatic impact-drivers and sectors. We used near-term sectoral risk to align with the 2030 SDG timeline. A sector was marked as being at high near-term risk if IPCC AR5's Table TS.4 (Field et al. 2014) identifies the sector (or the sector's services, as worded in Supplementary Information Tab 2.1) as being at *high* or *very high* risk of the specific climatic impact-drivers with *current adaptation levels* and *high confidence* (see Supplementary Information Tab 4 for results).

Based on deductive reasoning, we combined sector-SDG target (Phase 1) and sector-climate influences (Phase 2) in order to compute how each SDG target can be affected by climatic impact-drivers via effects on sectors' services (a climate-first application of the conceptual framework). For example, if there was published evidence of a negative effect of chronic warming on cropland-based food production, we computed the number of SDG targets directly and indirectly influenced by cropland-based food production.

We repeated this step with our IPCC-derived global data on the magnitude of near-term sectoral risk to identify the potential SDG targets influenced by those sectors' services at near-term climate risk (see Supplementary Information Tab 4).

We further applied findings from Phase 1 and Phase 2 to discuss how to tailor adaptation to SDG targets and to different components of climate risk. To tailor adaptation to SDG targets, we worked backwards from those SDG targets influenced by sectors at near-term risk from climatic impact-drivers to discuss whether these specific SDG targets are influenced by unique, cross-sectoral, or substitutable sector contributions. To tailor adaptation to risk, we differentiated by the three factors that make up risk as defined by the IPCC (see Supplementary Table 4.2).

Limitations and future work

Sector scope. There are many ways that sectors and services can be classified, a main determinant of the proposed conceptual framework and influences presented in this paper. Due to the inherent complexity of sectors across environmental, social, and economic dimensions, there is no universally accepted representation. Each representation reflects different worldviews (Le Blanc 2015). To provide a framework that can be operationalised and is transferable across nations, we based our sector classification on an original land-cover/land-use and international accounting classification adopted by most nations and global entities. Instead of focusing on impacts on sectors, one might also focus on systems of receptors, as discussed in the literature (Conway et al. 2019). We opted for the internationally-classified set of sectors, given our expectation that the framework can be applied with international and national accounting data across ecosystems and socio-economic sectors (see SEEA (Bogaart et al. 2019)). Yet, this internationally-based physical and mainly economic framing may mask cultural or nation-specific categorisations of indigenous peoples or marine ecosystems. As the influence analysis in this paper (Step 2) focused on the service-level, future work could group the service-level influences under different sector categories in ways that considers national differences. Future work is also required to better conceptualise the full range of services provided by each sector, especially in the context of ecosystems for which service allocation is

complex (Smith et al. 2017) and which often varies across spatial and temporal scales (Bateman et al. 2020). Whilst ISIC provides a globally-applicable overview of services linked to socio-economic sectors, no such international classification for ecosystems and the specific services these provide is available to date (Bateman et al. 2020). Future work can update the ecosystem categories and the services these provide accordingly, for example using the SEEA classification currently being developed.

Climate change scope. We defined climatic impact-drivers based on IPCC's AR5. We aimed to mitigate the absence of 'wildfire' (Smith et al. 2020) as a climatic impact-driver by including those influences whereby fires are exacerbated by droughts under the 'drying trend' influences, recognising that 'wildfire' might fall under the acute, rather than the chronic, climatic impact-driver category.

Sustainable development scope. We utilised the SDG targets to provide a globally accepted framework of defining sustainable development in normative terms, recognising that the targets are a political compromise rather than a scientific representation of all dimensions of sustainable development (Kanie et al. 2019). Our proposed framework is largely dependent on the wording used within each SDG target to determine direct sector influences. This focus on wording implies that the influence findings are affected by the often qualitatively delineated target descriptions that reflect the results of negotiations in intergovernmental contexts as opposed to science (Le Blanc 2015). Yet, by focusing on the SDG target - rather than indicator - descriptions, we hope to address critiques of the use of indicators that are limited by globally available datasets (Diaz-Sarachaga et al. 2018). Further, the target focus broadens the scope, applicability, and the potential range of sectoral action (investments, policies, infrastructures) to influence the SDGs.

Analysis. The majority of the analysis presented in this paper is based on evidence mapping of influences (direct influences are based on content analysis). Whilst for some sector-SDG influences or climate-SDG influences there might not be published evidence yet, we used existing and published evidence to ensure findings are replicable and supported. It is possible for existing literature to make erroneous inferences on influences, especially when based on grey literature. Some sector-SDG or sector-climate influences might be under-researched. We aimed to mitigate this aspect by reviewing

several grey literature studies for each influence and by discussing any potential issues or ambiguities with the authors of this paper, which span a range of disciplines and topical expertise (including geography, engineering, social science, ecosystems & biodiversity, infrastructure, climate risk analysis, SDG target mapping, and climate adaptation). Yet, further research is required that uses the analysis on sector-SDG and sector-climate influences presented in this paper as a basis for more comprehensive systems analyses based on reinforcing or self-reinforcing loops, meta-analyses, or as inputs into systematic assessments. A systematic assessment could characterise the quality, quantity, and geographic focus of each influence. Additional data can help move from associative influences to quantitative causal inferences (Lusseau et al. 2019), which may result in more specific policy implication.

Sectors can have severe negative influences on SDG targets. Whilst we do not specifically assess negative influences or negative trade-offs amongst sectors, our analysis provides an indication of *potential* sector-SDG influences. These potential influences are often reversible, where a potential negative influence is - in the case of weak governance frameworks or corruption - also a positive influence. Future research should explicitly assess negative interdependent influences, for example by evaluating the impact of socio-economic sectors on ecosystem service provision. Previously established interaction scales that range from indivisible, reinforcing, to counteracting, or cancelling SDG target links (Nilsson et al. 2018; Nilsson et al. 2016) could also be applied to sector-SDG, sector-sector, and climate-SDG influences to better identify the full range of positive and negative influences, including those for which more research is required.

Global application. With respect to our global application, the identification of near-term climate risk on sectors is based on the best available evidence of global sectoral near-term risk from the IPCC AR5 (Field et al. 2014). Whilst IPCC AR5 considers a holistic set of climatic impact-drivers and multiple sectors, it is unclear to what extent a holistic set of sectors has been used in the sectoral risk assessment. Importantly, we acknowledge that the public administration sector and its governance services might not have been considered a sector, largely under-estimating the range of SDG targets potentially affected. Future work can apply the framework to an updated overview of

global sectoral risk that is explicit about the range of sectors it includes, such as for example IPCC's AR6 or other global studies.

The global application presented in this paper mainly focused on a climate-first application of the framework. Whilst the discussion highlights how it is possible to work backwards from SDGs via sectors to reduce climate risk and deliver SDG co-benefits, further research can complement the analysis with a better understanding of: i) how SDG targets guide sector action or service provision, and ii) how different adaptation options can reduce risk from acute and chronic climatic impact-drivers and contribute to the SDG targets. This is particularly important in order to understand how leverage points not related to service provision - such as politics, people, culture, or technology – are required for SDG target achievement and climate adaptation. Further expansion of the framework that accounts for the climate *mitigation* potential of different sectors in reducing impacts of climate change could enable the framework to be used to identify climate-compatible (both low-carbon and resilient) pathways.

Supplementary Tables

Supplementary Table 4.1: Overview of SDG targets and indicators integrated in National Adaptation Plans (NAPs), status: February 2021. See Methods for Supplementary Table 4.1 below. *St. Vincent and the Grenadines.

Continent	Country	Year of NAP	1: NAP mentions SDGs	2: NAP mentions targets of SDGs	3: NAP mentions SDG indicators
	Burkina Faso	2015			
	Cameroon	2015			
	Ethiopia	2019			
Africa and Middle East	Kenya	2017			
	Togo	2018			
	Sudan	2016			
	Palestine	2016			
Asia	Sri Lanka	2016			
Pacific	Fiji	2018			
	Kiribati	2020			
	St. Lucia	2018			
Caribbean	St. Vincent*	2019			
	Grenada	2019			
	Brazil	2016			
	Colombia	2018			
	Chile	2017			
Latin America	Guatemala	2019			
	Paraguay	2020			
	Suriname	2020			
	Uruguay	2019			

Legend:

‘No mention

‘Some mention’

‘Clearly mentioned in the context of a single sector’

‘Clearly mentioned for more than one sector’

Methods for Supplementary Table 4.1:

We searched each NAP using the following search terms (based on the status of NAPs under the following link: https://www4.unfccc.int/sites/NAPC/Pages/national-adaptation-plans.aspx in January 2021; SI refers to Supplementary Information Tab)

1: NAP mentions SDGs

- 'Some mention': SDGs, Sustainable Development Goals, Agenda 2030
- 'Clearly mentioned in the context of a single sector': SDGs, Sustainable Development Goals, Agenda 2030 & one sector: either agriculture, forest, water, energy, (other sectors as specific in (Supplementary Information Tab (SI) 2.1)
- 'Clearly mentioned for all main sectors': SDGs, Sustainable Development Goals, Agenda 2030 & more than one sector name, cross-cutting, cross-sectoral

2: NAP mentions the targets of the SDGs

- 'Some mention': SDG targets, development targets, sustainable development targets, Agenda 2030 targets
- 'Clearly mentioned in the context of a single sector': SDGs, Sustainable Development Goals, Agenda 2030 & one sector: either agriculture, forest, water, energy, (other sectors as specific in SI 2.1)
- 'Clearly mentioned for all main sectors': SDGs, Sustainable Development Goals, Agenda 2030 & more than one sector name: agriculture, forest, water, energy, (other sectors as specific in SI 2.1), cross-cutting, cross-sectoral

3: NAP mentions SDG indicators

- 'Some mention': SDG indicators, SDG targets, development targets, sustainable development targets, Agenda 2030 targets
- 'Clearly mentioned in the context of a single sector': SDG indicators, SDG targets, development targets, sustainable development targets, Agenda 2030 targets & one sector: either agriculture, forest, water, energy, (other sectors as specific in SI 2.1)
- 'Clearly mentioned for all main sectors': SDGs, Sustainable Development Goals, Agenda 2030 & more than one sector name: agriculture, forest, water, energy, (other sectors as specific in SI 2.1), cross-cutting, cross-sectoral

Supplementary Table 4.2: Definitions used within the chapter. SI = Supplementary Information.

Term		Definition (and examples)	Source
Services provided by sectors (ecosystem services: n=35)		Services provided by ecosystems: -Regulating (e.g. flood protection), -Provisioning (e.g. food, water, or medicines), -Supporting (e.g. habitat), and -Cultural services (e.g. heritage, recreational)	USGS / IUCN (SI Tab 2.1)
(socio-economic services: n=32)		Services provided by socio-economic sectors: -Infrastructure services (e.g. electricity, transport) -Primary/secondary services (e.g. manufacturing) -Tertiary services (e.g. law enforcement, education)	ISIC Rev.4 (SI Tab 2.1)
SDG influence	Unique	The SDG target is described in terms of a single sector's service only. This contribution cannot be substituted by the services of another sector.	Thacker et al. (2019)
	Cross-sectoral	The SDG target is described in terms of multiple sectors' services, where each sector's service provides an independent contribution to the SDG target.	
	Substitutable	A substitutable SDG influence is identified when an SDG target is described in terms of sector's service that can be substituted by a different sector.	
	Indirect	An indirect influence is identified where published evidence indicates that improving the quality or quantity of the service provided by a sector can enhance the achievement of the target	
Climatic impact-driver (n=12)		Acute climatic impact-drivers include: Cyclones; Extreme precipitation; Extreme temperature; Storm surge; Flooding Chronic climatic impact-drivers include: Ocean acidification; CO2 fertilization; Snow cover; Warming trend; Precipitation; Drying trend; Sea-level rise	IPCC AR5 (SI Tab 2.2)
Risk		Risk is defined as risk from climatic impact-drivers. The factors that make up risk include: a) climate-change hazards – the probability and severity of a climatic impact-driver event; b) exposure - the land/resources, physical capital, labour located in a hazard-prone area; c) vulnerability – the sensitivity of a sector to climatic impact-drivers and the capacity of a population/ society to deal with a hazardous impact.	IPCC Special Report on Oceans (2019)
Near-term risk		Near-term risk refers to key sectoral risk of climatic impact-drivers and is defined based on a function of hazard (high probability/large magnitude), persistent exposure and vulnerability in the 2030s (aligned with the SDG timeline). A sector is considered at high near-term global risk (according to IPCC AR5), if sector or its services, as worded in SI Tab 2.1 is at high/very high risk with current adaptation levels and high confidence.	IPCC AR5 IPCC 1.5 (SI Tab 4)

5

Assessing climate change impacts on sustainable development targets

This chapter addresses Research Question 2: *How can the impacts of climate-change hazards on sustainable development targets be spatially assessed to inform national adaptation?* In addressing this question, this chapter develops and applies a national-scale methodology that operationalises the conceptual framework developed in Chapter 4 using climate-change hazards as a starting point (climate-first approach). The national-scale methodology spatially assesses impacts of climate-change hazards across all a nation's sectors and assets, and how these impacts propagate and interact to influence SDG targets. The methodology it applied to the small island Saint Lucia using transferable algorithms and real-world data. This application helps make the case for adaptation to safeguard sustainable development outcomes and is used to support decision-makers with the evidence on where and how to prioritise adaptation under the Paris Agreement in alignment with the SDGs.

This chapter was published as a journal paper in Global Environmental Change with the title 'Informing national adaptation for sustainable development through spatial systems modelling' in October 2021. The chapter was co-authored with Scott Thacker, and Jim W. Hall, who provided methodological advice, comments, and edits to the text and figures. All data that support the findings of this chapter, including Supplementary Tables 5.1-5.5, are described below. Chapter 5 Supplementary Information Tab 1 is attached to this thesis and available at: https://doi.org/10.5281/zenodo.5643953.

Abstract

Acute climate-change hazards, such as floods or storm surges, can affect a nation's built and natural environment assets that are critical for development and achievement of the Sustainable Development Goals (SDGs). To reduce the impacts of such acute climate-change hazards and safeguard development, national decision-makers require evidence on where and how hazards affect SDG achievement to better inform adaptation. Here, we develop a systems methodology that spatially models the impacts of climate-change hazards across a nation's entire built and natural environment assets and its interdependent influences on the SDG targets to inform national adaptation. We apply our methodology in Saint Lucia through a participatory approach with decision-makers across government ministries, academia, and the private sector. Results reveal that acute climate-change hazards can affect half of Saint Lucia's assets across 22 sectors, which can influence 89% of all SDG targets. Application of our methodology provided evidence on where and how to prioritise adaptation, thereby helping to add spatial granularity to 52 measures under Saint Lucia's National Adaptation Plan (NAP) as well as specificity on how limited capacity for cross-sectoral coordination can be directed to safeguard SDG targets. Adaptation does not necessarily imply investing in physical asset protection: results show the need to protect critical natural environments which provide important adaptation services to the built environment. As more nations develop and revise their NAPs and Nationally Determined Contributions under the Paris Agreement, strategic planning across sectors – as demonstrated in Saint Lucia – will be critical to facilitate adaptation that safeguards SDG achievement.

5.1 Introduction

Over the past decade, the international community has committed to a number of ambitious global agreements, including on eliminating poverty, tackling climate change, and halting the loss of biodiversity. In 2015, UN member countries adopted the Sustainable Development Goals (SDGs), which bring together a broad spectrum of social, economic and environmental goals to be achieved by 2030. Since its adoption, progress towards achievement of the 17 SDGs and its 169 related targets has been realised (Schmidt-Traub et al. 2017). Yet, this progress is increasingly being threatened by the impacts of climate change, including intensifying acute hazards such as extreme flash flood or storm surge events (Fuso Nerini et al. 2019; Gomez-Echeverri 2018).

Safeguarding national SDG progress in the face of increasing climate-change hazards requires adaptation, defined as the processes and actions to adjust to experienced or anticipated impacts of climate change (Magnan et al. 2016; Morgan et al. 2019; UNFCCC 2016a). Through the global Paris Agreement, 197 nations pledged to engage in adaptation, which includes a commitment to submit national adaptation strategies via Nationally Determined Contributions (NDCs) and to re-state National Adaptation Plans (NAPs). Whilst such national commitments have been recognised as a critical vehicle to ensure adaptation (Preston et al. 2011), they have also been criticised for merely re-stating existing strategies and thereby failing to: i) make a convincing national case for adaptation, ii) prioritise proposed adaptation measures, and iii) embed adaptation within the broader sustainable development agenda (Hardee et al. 2009; Termeer et al. 2012; UNFCCC 2012). Further, and despite numerous calls to recognise the interconnected relationship between national commitments under the Paris Agreement and the SDGs, only 22 out of 173 published NDCs mention the SDGs (Fuso Nerini et al. 2019) and only 4 of 20 NAPs mention SDG targets (Fuldauer, Thacker, Haggis, et al. n.d.). Yet, linking climate adaptation with the specificity of the SDG targets provides an opportunity to make the case for adaptation, prioritise adaptation measures, and to embed adaptation within the sustainable development agenda. To capitalise on this opportunity, this paper proposes a systems methodology to provide national-decision makers with the evidence

to inform and prioritise adaptation in the context of sustainable development, using the SDG targets as a globally agreed-upon means of conceptualising sustainable development. As more nations revise and develop their NDCs and NAPs, this evidence will be an important step to ensure that adaptation both reduces the impacts of climate-change hazards and safeguards the SDGs.

Simultaneously reducing impacts of climate-change hazards and safeguarding the SDGs requires a granular understanding of the climate-SDG relationship at the national scale. Research to date has outlined the broad relationship between climate-change hazards and the SDGs at the level of the 17 SDGs (IPCC 2018) and the level of the 169 targets (Fuso Nerini et al. 2019). To provide additional granularity to inform adaptation, research has also conceptualised a 'climate-SDG' framework (Fuldauer, Thacker, Haggis, et al. n.d.). This framework describes socio-economic sectors (the built environment) *and* ecosystem sectors (the natural environment) as mediators between impacts from climate-change hazards and each of the 169 SDG targets. These sectors provide essential socio-economic or ecosystem services, such as energy, healthcare or flood protection, which are necessary both for mediating climate-change hazards and achieving the SDGs. Whilst very useful, the conceptual framework must be spatially translated and operationalised at the national scale in order to be used to inform adaptation in practice.

Well-established methods exist to assess the impacts of acute climate-change hazards on sectors, which can be represented spatially at the asset scale (Aerts et al. 2014; de Sherbinin 2014; Schneiderbauer et al. 2020). Such spatial assessments typically superimposes the footprint of hazard events of certain magnitudes and duration on that of a sector's assets, and then assigns economic, service provision, macro-economic or welfare information to these assets. This assignment in turn enables modelling: i) potential direct economic damages to assets (Koks, Rozenberg, et al. 2019), ii) potential service and customer disruptions caused by a climate-change hazard (Thacker, Barr, et al. 2017), iii) cascading macro-economic consequences (Koks 2018; Koks, Thissen, et al. 2019; Willner et al. 2018), and iv) socio-economic welfare impacts (Hallegatte, Bangalore, and Vogt-Schilb 2016; Verschuur et al. 2020). Application of such spatial assessments has provided valuable information for the evaluation of bio-physical adaptation options to

reduce impacts from hazards, such as where to focus flood insurance coverage or flood protection (Koks, Rozenberg, et al. 2019). These spatial assessments have increasingly been applied to multiple hazards and multiple and interdependent assets (Hall et al. 2016), including at the national scale (Dawson et al. 2018). However, to date, applications of such assessments focus on socio-economic sectors and assets of the built environment. Although climate assessments have been conducted for specific natural environments (Briner et al. 2012; Kirchner et al. 2015), few studies spatially assess impacts of climate-change hazards across a holistic set of both built and natural environment assets at the national scale, and none has been conducted in the context of the SDG targets or explicitly linked to national adaptation commitments under the Paris Agreement.

The goal of this paper is to fill the abovementioned gaps and develop and apply a systems methodology that spatially assesses the impacts of acute climate-change hazards on a holistic set of a nation's built and natural environment assets, and identifies the ways impacts may interact to influence the SDG targets to better inform adaptation under the Paris Agreement. This differs from previous work on three separate research strands: i) *non-spatial* advances on linking climate-change hazards to SDG targets via sectors (Fuldauer, Thacker, Haggis, et al. n.d.), ii) *spatial* advances on assessing the impact of climate-change hazards on some sectors and its service disruptions (Hall et al. 2016; Pant et al. 2017; Thacker, Barr, et al. 2017) as well as spatial advances on SDG indicator progress (Xu et al. 2020), and iii) *interdependencies* between built environment sectors and assets (Adshead et al. 2021; Hall et al. 2019) and between SDGs (Nilsson et al. 2016; Pradhan et al. 2017). For the first time, we integrate these three separate research strands and expand them to include a holistic set of built and natural environment sectors and assets and their interdependencies, acknowledging that there are also social and human assets as well as important political and power dynamics involved in adaptation, which are outside the scope of this paper. Nevertheless, the innovative contribution of this paper to the current literature is twofold. The proposed systems methodology for the first time provides insights into the assessment of acute climate-change hazard on SDG targets at high spatial granularity, thereby transcending current economic damage assessments. Second, an application of the methodology using multiple climate-change hazards, all

of a nation's built and natural environment sectors and assets, and all 169 SDG targets enables national decision-makers to: i) make the case for adaptation, ii) inform where and how to prioritise bio-physical adaptation against acute climate-change hazards and thereby specify where and how to focus limited existing leadership and resources to tackle the challenge of cross-ministerial and cross-sectoral coordination, and iii) help develop or revise NDCs and NAPs under the Paris Agreement.

The remainder of the paper is organised as follows: Section 5.2 summarises our proposed systems methodology. We introduce an application of this methodology in Section 5.3, which focuses on the small island of Saint Lucia that is characterised by a particular set of climate and development challenges. Section 5.4 presents the results of this application to inform adaptation, followed by a discussion of practical and methodological implications in section 5.5. We conclude with reflections on the systems methodology and its application in section 5.6.

5.2 Methodology

Our proposed systems methodology involves three steps: a) systems impact modelling to spatially assess impacts from acute climate-change hazards on a nation's entire set of built and natural environment assets and its potential national service disruptions, b) SDG target mapping to estimate the influences of service disruptions on SDG targets, c) using quantified estimates from (a) and (b) to make the case for adaptation, to inform *where* and *how* to prioritise adaptation, and to revise or develop NDCs or NAPs. Each of these steps is carried out through reflexive stakeholder engagement processes, which form the central foundation of the proposed methodology as shown in Figure 5.1.

The proposed methodology is applied for a country at a given point in time, across currently existing built and natural assets. Recognising that the impacts of climate-change hazards on SDG targets have hitherto not been spatially assessed, we aim for a high-level screening and prioritisation of bio-physical adaptation needs across assets by focusing on hazards and exposure. This type of simple and transparent methodology, proposed as an iterative decision-support tool, can be expanded to include a temporal

dimension, direct population demand implications resulting from climate-change hazards, or spatially-disaggregated data on population's adaptive capacity, amongst others.

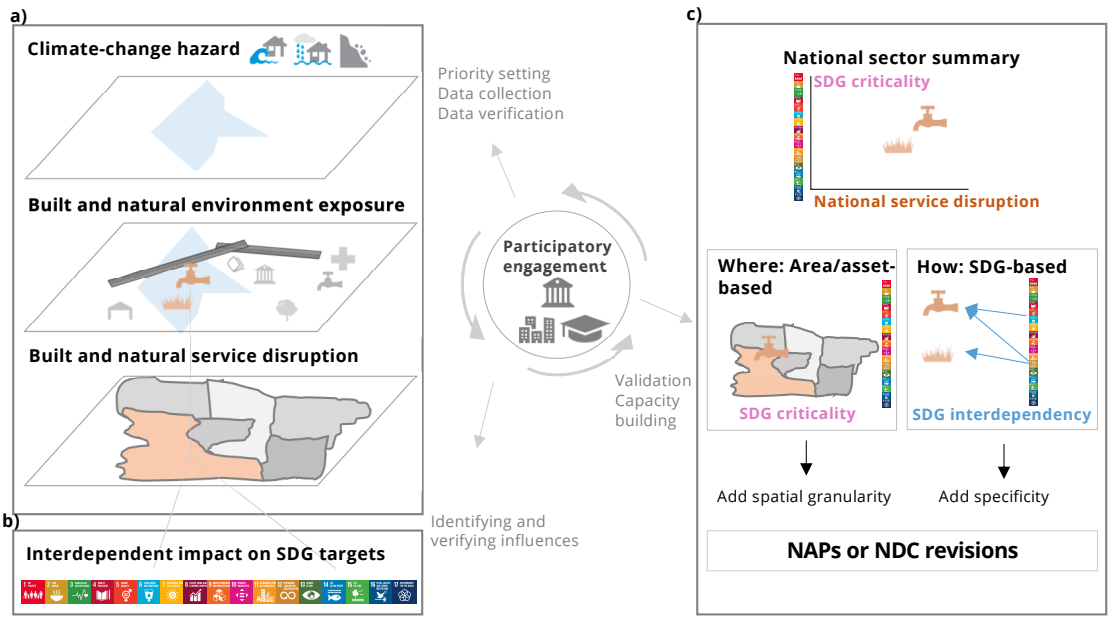


Figure 5.1: Proposed three-step systems methodology for assessing impacts of climate-change hazards on built and natural environment assets and SDG targets, which can inform where and how to prioritise adaptation under NDCs and NAPs. The three steps – a) Systems impact modelling, b) SDG target mapping, c) Informing adaptation – are informed by an iterative participatory stakeholder engagement process.

5.2.1 Step a): Systems impact modelling

Climate-change hazards can bio-physically affect a nation's geographic area, which is made up of assets of the built environment (electricity, transport, healthcare, amongst others) and the natural environment (wetlands, water ecosystems, forests, amongst others) (Fuldauer, Thacker, Haggis, et al. n.d.). Each asset is assigned socio-economic or ecosystem service provision data for a given time period (for example how much electricity is used at each sub-station). Here we use an asset's operating capacity as a proxy to measure service provision and assume that service provision degrades linearly with the loss of an asset. We group assets with the same service provision unit and assign grouped assets to the same sector s.

We represent acute climate-change hazards using indicative hazard maps h of a given return period, duration and magnitude, such as flow volumes and/or flood depth

(see Hall et al. (2016), Pant et al. (2016), and Thacker, Pant, et al. (2017) for detailed descriptions of hazard modelling). We propose using Geographic Information Systems (GIS) to spatially superimpose existing hazard maps, sectors' assets and assigned service provision data (Figure 5.1a). This spatial overlay provides a first order estimate of the **percentage of national service disruption** $D_{s,h}$ for each hazard and sector, which is given by Equation 5.1:

$$D_{s,h} = \frac{\sum_{a=1}^{N} \mathrm{c}_{a_s} - \sum_{a=1}^{N} (\mathrm{c}_{a_s} \times r_{h,a_s})}{\sum_{a=1}^{N} \mathrm{c}_{a_s}} \tag{5.1}$$

where national operating capacity to serve the population's demand for the sector's service is calculated as the sum of the operating capacity c_{a_s} of each individual assets a_s, with N representing the number of assets of sector *s* and where c_{a_s} is measured in the respective sectoral unit (e.g. GWh year^{-1}, yield year^{-1} etc.).

r_{h,a_s} describes the sensitivity of the services provided by asset a_s to hazard h, which is dependent on fragility variables such as the depth of inundation an asset can withstand before it ceases to function (Hall et al. 2019) or an adjustment in potential capacity to provide services following a hazard. r_{h,a_s} can take a value between 1 and 0. If $r_{h,a_s} = 1$, asset a_s is providing its services at full capacity under hazard h, if r_{h,a_s} = 0, asset a_s is providing no service under hazard h.

Systemic or multi-hazards, resulting from hazard/ impact interactions, their simultaneity or co-location, can also be considered under their associated hazard maps h.

5.2.2 Step b): SDG target mapping

The service provided by each of a nation's sector can be linked to society's wellbeing and therefore to one or more of the 169 official SDG targets, where t represents one of the UN's SDG targets in the range 1.1 to 17.21 (Adshead et al. 2019; Fuldauer, Thacker, Haggis, et al. n.d.; Thacker et al. 2019). In cases where a sector's service is directly described in terms of an SDG target, sector s exhibits a direct influence on target t, represented by $I_{s,t}$. $I_{s,t}$ takes a binary value {1,0}: if $I_{s,t}$ = 1, the services provided by sector s are directly described in SDG target t , if $I_{s,t}$= 0, the services of sector s are not directly described in terms of SDG target t.

Sectors of the built and natural environment can also indirectly influence SDG targets. Indirect influences are defined as cases where evidence exists that improving the quality or quantity of the services provided by a sector can enhance SDG target achievement. We use $Ind_{s,t}$ to refer to an indirect influence, which can take a binary value {1,0}.

We propose an **SDG criticality metric** for each sector L_s, defined as the number of SDG targets directly or indirectly influenced by a sector's services, given by Equation 5.2:

$$L_s = \sum_{t=1}^{M} I_{s,t} + Ind_{s,t} \tag{5.2}$$

where M refers to the total number of SDG targets.

This SDG criticality metric provides an estimation of the range of sustainable development dimensions that can be affected by service disruptions of a sector, and that can be safeguarded by adapting the sector's services (Figure 5.1b, magenta shading).

To account for the growing understanding of interdependencies between sectors and SDGs, the literature has conceptualised how sectors' services act in interdependent ways to influence SDG targets (Adshead et al. 2019; Fuldauer, Thacker, Haggis, et al. n.d.). Across all 169 SDG targets, 51 SDG targets are directly described in terms of multiple services from different sectors, i.e. there is a *cross-sectoral* influence. For example, target 9.1 "Develop quality, reliable, sustainable and resilient infrastructure (...)" is described in terms of the services from multiple infrastructure sectors (i.e. $I_{energy,9.1}$ = 1, $I_{water,9.1}$ = 1, $I_{transport,9.1}$ =1, etc.). In contrast, 90 SDG targets are directly described in terms of a single service of a sector, i.e. there is a *unique* influence. For example, target 7.1 "By 2030, ensure universal access to (...) energy services" is described uniquely in terms of energy services ($I_{energy,7.1} = 1$, it follows that $I_{water,7.1}$ = 0, $I_{transport,7.1}$ = 0, etc.). We propose assessing SDG interdependencies by identifying whether each SDG target is influenced by *cross-sectoral* or *unique* influences.

5.2.3 Step c): Informing adaptation

As part of step c), national service disruption of each sector $D_{s,h}$ can be approximated with the SDG criticality metric L_s to identify the range of SDG dimensions potentially

impacted by service disruptions from hazard exposure. This enables a high-level, national-scale summary to make the case for adaptation and to identify which sectors to prioritise for adaptation across hazards (Figure 5.1c, national summary). Based on this national-scale sector summary, it is possible to prioritise specific area and assets, informing *where* to focus adaptation (Figure 5.1c, area/asset-based), as well as to identify SDG interdependencies across exposed sector's services, informing *how* to target adaptation across sectors (Figure 5.1c, SDG-based).

The participatory process of data collection and standardisation across built and natural environment assets embedded in the proposed methodology can in itself support achievement or highlight shortcomings with respect to adaptation measures proposed under NDCs or NAPs. Results from the methodology application on where and how to prioritise adaptation can further be used to add spatial granularity and specificity to NDCs or NAPs, respectively. If no NDC or NAP exists in-country, results can provide high-resolution evidence to develop such strategies or plans.

5.3 Application to Saint Lucia

We apply the proposed methodology to a recent adaptation assessment in the small island of Saint Lucia (Adshead, Fuldauer, et al. 2020). Small Island Developing States (SIDS) have specific contextual and geographical features with respect to sustainable development and are recognised as some of the most vulnerable places to climate-change hazards (Cairns et al. 2013; Kelman et al. 2009). Historic impacts from hazards have highlighted the island's climate vulnerability, with Hurricane Tomas in 2010 resulting in more than USD 330 million damages to sectors of the built and natural environment that underpin Saint Lucia's development. The cost of inaction with regard to future climate adaptation on the island has been estimated at 50% of GDP by 2100 (Government of Saint Lucia 2017b). To facilitate adaptation, Saint Lucia's government has proposed a NAP with a comprehensive set of 271 sectoral and cross-sectoral NAP measures. Yet, implementation and prioritisation of these measures remains poorly informed.

For the application of the proposed methodology, a participatory approach to data collection, verification, and analysis was adopted. Such a participatory approach is

suitable to infrastructure planning in small islands (Fuldauer et al. 2019), as its small size context helps avoid limitations of stakeholder selection and participation, which are common in larger countries (Cairns et al. 2013). Therefore, a large number of stakeholders could be consulted throughout the research process.

5.3.1 Step a): Systems impact modelling

The first step of the methodology application involved collecting and analysing climate-change hazard, asset, and service provision data. Priorities on the types of hazards and assets were ascertained and data was collected and verified in three separate visits to the country through engagement with more than 134 stakeholders across government ministries, academia, and the private sector. These include stakeholders from the Ministry of Finance, Ministry of Physical Development, Ministry of Infrastructure, Ministry of Education and Sustainable Development, Ministry of Economic Development, the Economic Competitiveness Council and the National Emergency Management Organisation, and members of Saint Lucia's national climate change committee, amongst others (Adshead, Fuldauer, et al. 2020).

Climate-change hazard data

Based on stakeholder discussion on priorities, the methodology application covered the three most frequently occurring hazards in Saint Lucia, namely storm surges, flash floods, and landslides. These hazards have also been identified to become more intense or frequent with climate change (Adshead, Fuldauer, et al. 2020; Government of Saint Lucia 2017b). A multi-hazard event was added to account for the growing acknowledgement that hazards are often connected (Raymond et al. 2020; Zscheischler et al. 2018), including in Saint Lucia (Charim 2016).

Following stakeholder discussion and previous literature as described below, we used non-probabilistic hazard maps, because these were available at the highest spatial resolution (10 to 20-metres) and have been used for previous Caribbean assessments. An upper bound was used for each hazard to represent a worst-case scenario. Based on a Caribbean Digital Elevation Map (Charim 2016), we constructed a storm surge

hazard map with a 4-metre inundation scenario, chosen as an average value for Caribbean countries for a 1 in 100-year storm event (Simpson et al. 2010) (Figure 5.2a). A worst-case 1-in-50-year flash flood hazard was taken from Jetten (2016) (Figure 5.2b). A high susceptibility landslide map was obtained from Van Westen (2016) (Figure 5.2c). We acknowledge potential limitations in the scope of hazards considered, which do not include probability or duration information and are not inclusive of chronic, slow-onset climate-change hazards. Therefore, iterative stakeholder engagement and capacity building workshops were put at the heart of this research, as to enable the updating of additional hazards and scenarios into the future.

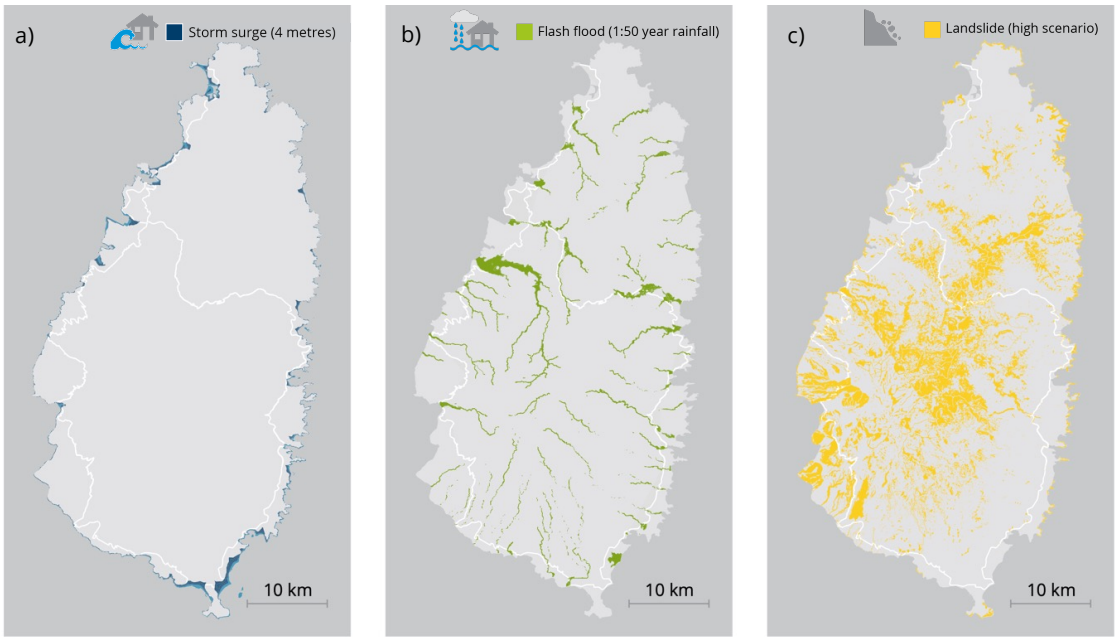


Figure 5.2: Saint Lucia areas exposed to climate-change hazards: a) coastal flooding from a 4-metre storm surge (at a 10-metre resolution), b) flash floods from a 1:50 rainfall scenario (at a 20-metre resolution), and c) landslides from a high susceptibility scenario (at a 20-metre resolution).

Asset and service provision data

The spatial data collected is comprised of 24 sectors, including all 725 Saint Lucia's built and natural environment assets and 2600km of road length as well as service provision data (Supplementary Table 5.1). Where service provision data was unavailable, we used asset count for built environment assets and area for natural environment assets as a proxy.

All data was standardised across sectors, verified and complemented by geo-referencing missing data together with the National Integrated Planning and Programme (NIPP) unit, housed in the Ministry of Finance, as well as from open-source data as described in Supplementary Table 5.2. Based on feedback from the NIPP, we classified sectors into three categories, including built environment infrastructure sectors, built environment socio-economic sectors, and natural environment sectors (Supplementary Table 5.1). Natural environment sectors were extracted from a national land-use map (Forestry Department Saint Lucia 2009) and re-classified as described in Supplementary Table 5.3.

Spatial impact modelling

We superimposed each hazard on each built and natural environment asset under the infrastructure, socio-economic, and natural environment sector category (Figure 5.3) and calculated the potential national service disruption following Equation 1. We assumed that without adaptation, climate-change hazard exposure exceeds existing asset design standards and ecosystem conditions. Therefore, r_{h,a_s} was considered as a binary value $\{0,1\}$. This worst-case assumption was verified as a useful means to inform adaptation planning with NIPP stakeholders, and has been postulated as a useful means to decide on responses in the wider literature (Hinkel et al. 2015). Given that natural assets can withstand climate-change hazards of moderate severity, the adaptation services (such as flood protection or slope stabilisation) provided by natural assets are discussed separately in the results.

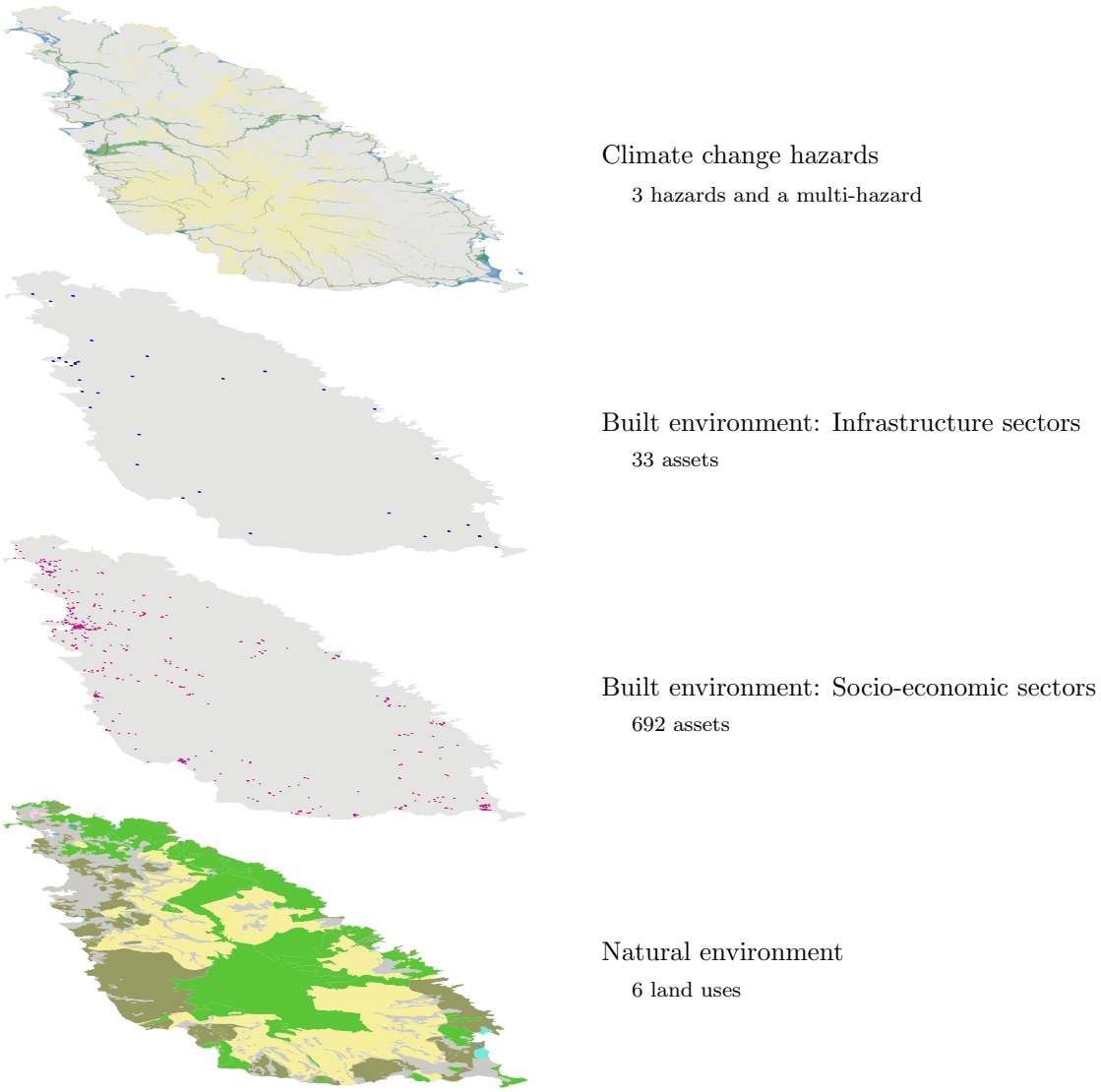


Figure 5.3: Overlaying the spatial footprint of climate-change hazards and of built and natural environment assets in Saint Lucia.

5.3.2 Step b): SDG target mapping

We identified the direct ($I_{s,t}$) and indirect influences ($Ind_{s,t}$) from the services of each of Saint Lucia's 24 sectors on each SDG target as formulated in the official UN documentation, using published information and stakeholder engagement (Supplementary Table 5.1, Supplementary Table 5.4). For each sector, we combined counts of direct and indirect SDG influences to compute the SDG criticality metric L_s according to Equation 2. We identified SDG interdependencies based on direct SDG influences, thereby assessing

whether each SDG target is influenced by a single sector (*unique* influence) or by more than one sector (*cross-sectoral* influence).

5.3.3 Step c): Informing adaptation

We first integrated results from step a) and step b) for each sector and each hazard to arrive at a national-scale summary of which sectors to prioritise. Second, we assessed *where* to focus adaptation using the spatial location of where asset exposure results in the largest service disruption. For assets where service information was not available, we compared the percentage of total assets/area across Saint Lucia's administrative districts, which were provided by the Statistics department during in-country stakeholder engagement. Where possible, we complemented the where analysis with in-country data on the societal implications of service disruption obtained from stakeholder engagement or national documents. Third, we identified *how* to target adaptation by determining how each SDG target is influenced by the services of exposed sectors. Initial results were presented to in-country stakeholders in bilateral meetings, and feedback on missing data and priority locations for adaptation was iteratively incorporated. Stakeholders mainly agreed with the findings of the most hazard-exposed sectors and assets and added further qualitative explanations of past hazard impacts, which allowed for additional verification of the results. Capacity-building workshops on the use of the modelling and accompanying decision-support tool were conducted, which were attended by stakeholders across the NIPP unit as well as 11 ministries, infrastructure utilities, and NGOs. It is hoped that such cross-ministerial and cross-sectoral workshops allow for the updating of data in iterative cycles in the future, which can be led by the cross-ministerial NIPP unit.

Next, we placed our overall results in the context of Saint Lucia's NAP. We extracted Saint Lucia's 271 sectoral and cross-sectoral NAP measures (Government of Saint Lucia 2018) and classified each measure into either a 'groundwork or recognition' measure or a 'tangible action' measure, following Lesnikowski et al. (2013). Hereby, 'groundwork or recognition' measures comprised adaptation research, vulnerability assessments, development of conceptual tools, amongst others. 'Tangible action' measures included specific policy, built or natural environment measures taken in response to climate-change

hazards (see Supplementary Information Tab 1). For the 'groundwork or recognition' measures, we identified how many NAP adaptation measures can be supported through our broad national-scale sector summary via a set of the following activities: raising awareness, academia-government partnerships, data collection, standardisation as well as training on the geodatabase developed as part of this research. For the 'tangible action' measures, we summarised whether the results from our analysis on *where* to prioritise adaptation can provide spatial granularity to the NAP measure. For the 'cross-sectoral' category of Saint Lucia's NAP, we reviewed how many of the proposed NAP measures under this category can benefit from our results on *how* to target adaptation across sectors (Supplementary Information Tab 1).

5.4 Results

The next sections describe the results of the application of our proposed systems methodology in Saint Lucia. We first *summarise* national-scale results across sectors in the context of the SDG targets, thereby differentiating the three sector categories using the colours grey (infrastructure), magenta (socio-economic), and green (natural environment). Second, we highlight the location of exposure and potential service disruption for the most highly exposed sectors within each of the three categories. Third, we present results at the SDG target level. Lastly, we place each of these three specific results in the context of Saint Lucia's proposed NAP measures.

5.4.1 Summary of national exposure results

Across the considered climate-change hazards, we find that the multi-hazard can expose most sectoral assets and the services these provide (see Supplementary Table 5 for full results) (Figure 5.4d, x-axis scale is adjusted for visualisation purposes).

Of Saint Lucia's 33 assets from the infrastructure sector category (grey circles), 80% are exposed to one or more of the three individual climate-change hazards. The freight sector scores highest in terms of exposure to storm surges and flash floods as well as its SDG criticality, potentially affecting 76 targets established in the SDGs (Figure 5.4a and b, grey circles). Even though less than 4% of Saint Lucia's total road length is exposed

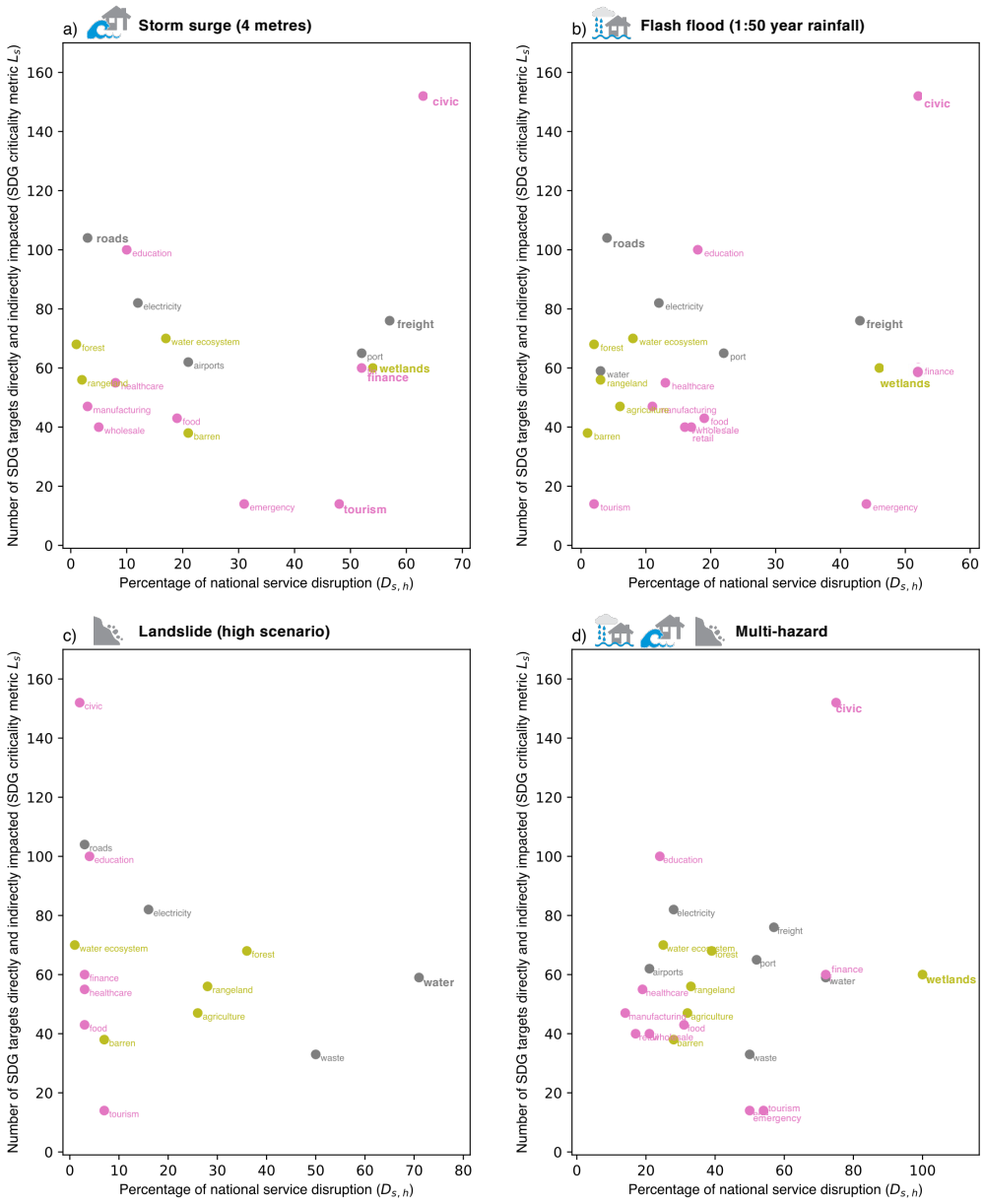


Figure 5.4: National service disruptions across sectors affect SDG targets for: a) storm surge (4-metre), b) flash flood (1:50 year rainfall), c) landslide (high scenario), d) multi-hazard. The x-axis represents the percentage of national service disruption $D_{s,h}$ and the y-axis represents the criticality metric (L_s). The x-axis scale is adjusted for each climate-change hazard for visualisation purposes. Sectors mentioned in the manuscript text are shown in bold.

to either storm surges or flash floods, the road sector exhibits the overall largest SDG criticality, influencing 104 SDG targets (Figure 5.4a and b). With respect to landslides, the water sector is most exposed (Figure 5.4c).

Of Saint Lucia's 692 socio-economic assets, we find that 48% are exposed to one or more of the three individual climate-change hazards. The civic, finance, and tourism

sectors are most exposed to storm surges, with the civic sector showing the largest SDG criticality (Figure 5.4, magenta circles).

Of Saint Lucia's natural environment area of over 600 km^2, more than 50% is exposed to one or more of the individual climate-change hazards. Wetlands are most exposed to storm surges and flash floods, which can affect 60 SDG targets (Figure 5.4a and b, green circles). This exposure can hamper the essential services provided by wetlands, which include habitat provision, amenity value, water purification, and natural flood protection, amongst others. However, the wetlands are likely to withstand inundations of moderate severity and can thus act as natural flood protection to other infrastructure and socio-economic assets concentrated in the area, which is further described in Section 5.4.2.

5.4.2 Area-based hazard exposure in the context of SDG targets

Having identified sectors with the largest score across national service disruption and SDG criticality in Section 5.4.1, this section visualises the location of those sectors' assets. This provides spatial granularity on *where* to focus national adaptation.

Infrastructure sectors

Within the highly exposed freight sector, the exposure of two specific freight assets - two of Saint Lucia's key import terminals - can result in the largest disruption of up to 577,000 tonnes of freight (Figure 5.5). While freight is directly linked to only 2 SDG targets, its indirect contribution across 74 targets is pervasive (Supplementary Table 5). Freight underpins the import of goods and services to the value of 1.7 billion EC dollars yearly, as well as the export of numerous industries that employ more than 25% of the labour force (Central Statistical Office of Saint Lucia2018). Imports include goods such as foods, medicament and fuel for cooking and electricity, which are essential not only for most of Saint Lucia's other industries but also in the immediate aftermath of a hazard. Therefore, freight service disruptions can indirectly impact targets across all 17 SDGs, most notable SDG2 ('end hunger'), SDG7 ('energy'), and SDG3 ('health') (Figure 5.5c), in other words, adapting the freight sector is critical to safeguard these dimensions of development.

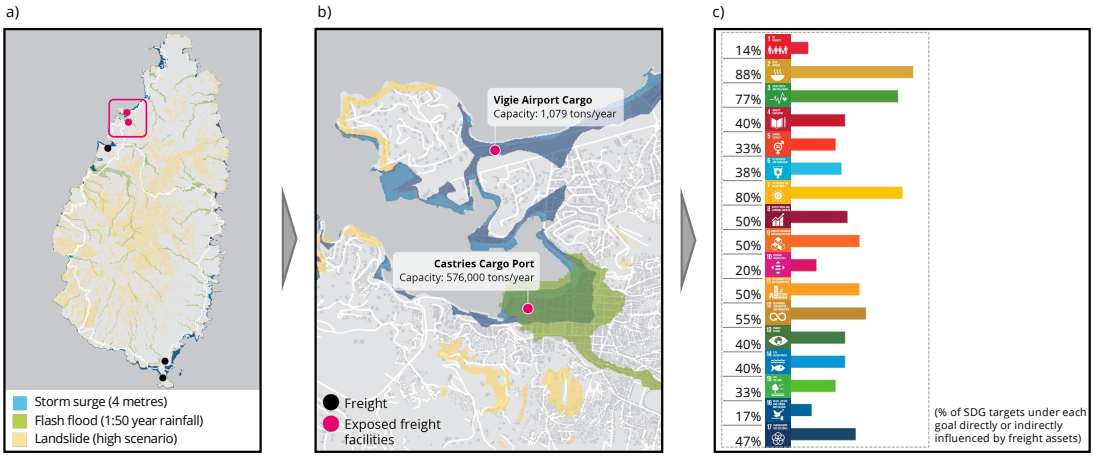


Figure 5.5: Exposure of Saint Lucia's freight assets and potential SDG impacts, where a) shows the exposed freight assets, b) highlights the exposed freight assets with largest service disruption, and c) identifies potential impacts on the percentage of SDG targets within each goal.

Socio-economic sectors

Within the highly exposed civic sector, 90% of civic assets centred within Saint Lucia's capital city Castries are exposed. This can in turn disrupt the critical services civic assets provide, including implementation of government policy, land registration services, or training police and emergency responders to manage disasters (Supplementary Table 5.4), which underpin 152 SDG targets. In addition to the large direct SDG target influences from these services for SDG13 ('climate action'), SDG16 ('peace') and SDG17 ('partnership'), exposure of civic services can indirectly influence targets across all 17 goals, most notably SDG1 ('poverty'), SDG10 ('inequality'), SDG12 ('sustainable production and consumption') (Figure 5.6). Unless adaptation is focused on these civic assets, the critical services provided by the civic sector, such as ensuring adequate governance, may be lost.

Natural environment sectors

Within the highly exposed wetland sector, Saint Lucia's Choc wetland in the North-West is most exposed to climate-change hazards in terms of total area. The Choc wetland exposure can affect 60 SDG targets, most notable targets under SDG6 ('water'), SDG14 ('life under water'), and SDG11 ('sustainable communities') (Figure 5.7). Failure to conserve this wetland and the critical flood protection services it provides can result in increased hazard severity, for example through inundation of the nearby only road linking the North and

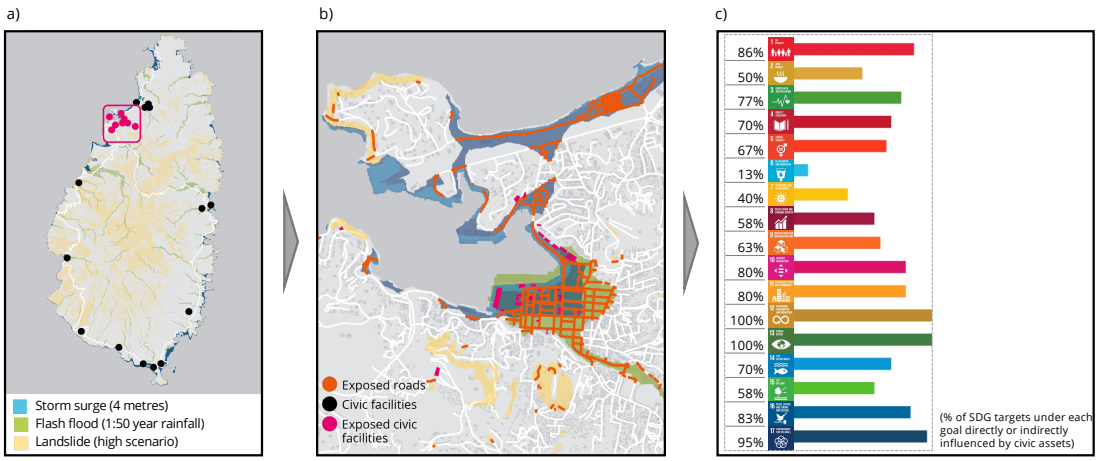


Figure 5.6: Exposure of Saint Lucia's civic assets and potential SDG impacts, where a) shows the exposed civic assets, b) highlights the zoomed-in area of the exposed civic assets, and c) identifies potential impacts on the percentage of SDG targets within each goal.

the South of the island. This link provides access for over 27,000 vehicles per day, and in addition to people movement, enables the transport of cargo, including food, hospital equipment, and fuel. Therefore, the Choc wetland conservation not only safeguards the services provided by the wetland sector, but also those provided by the transport sector.

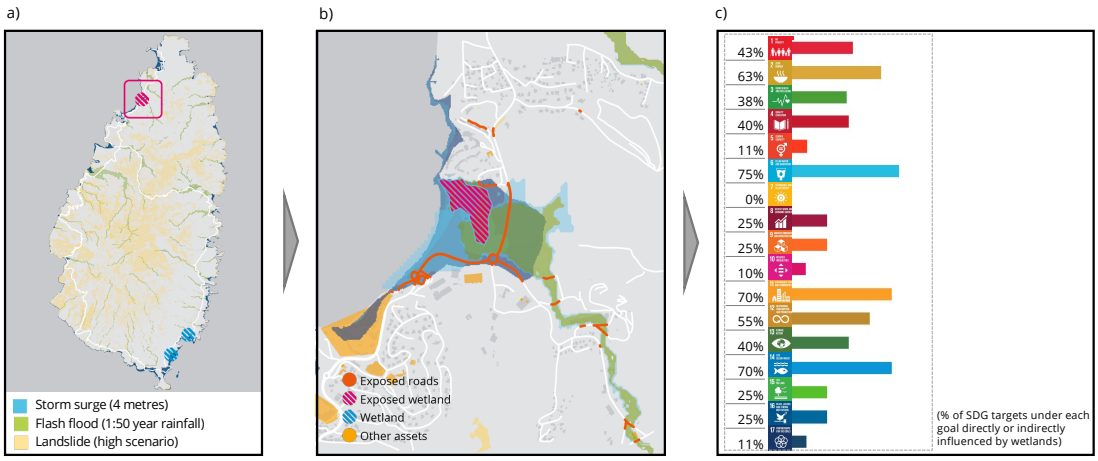


Figure 5.7: Exposure of Saint Lucia's wetlands and potential impact on SDG targets, where a) shows the exposed Choc wetland in Saint Lucia, b) highlights the zoomed-in area of the exposed wetland, and c) identifies potential impacts on the percentage of SDG targets within each goal.

5.4.3 SDG target results

Next, we describe results on the pathways of *how* SDG targets are affected by a set of exposed sectors that act in interdependent ways to directly influence SDG targets.

These types of results can provide insight into the ministerial and sectoral collaborations required to safeguard SDG target achievement.

We find that whilst a total of 69 SDG targets (41%) are influenced *uniquely* by one exposed service of a sector (Figure 5.8, magenta shading), 73 SDG targets (43%) are influenced by exposed services from more than one sector, i.e. through *cross-sectoral* influences (Figure 5.8, darker blue shading represents a larger number of sectors).

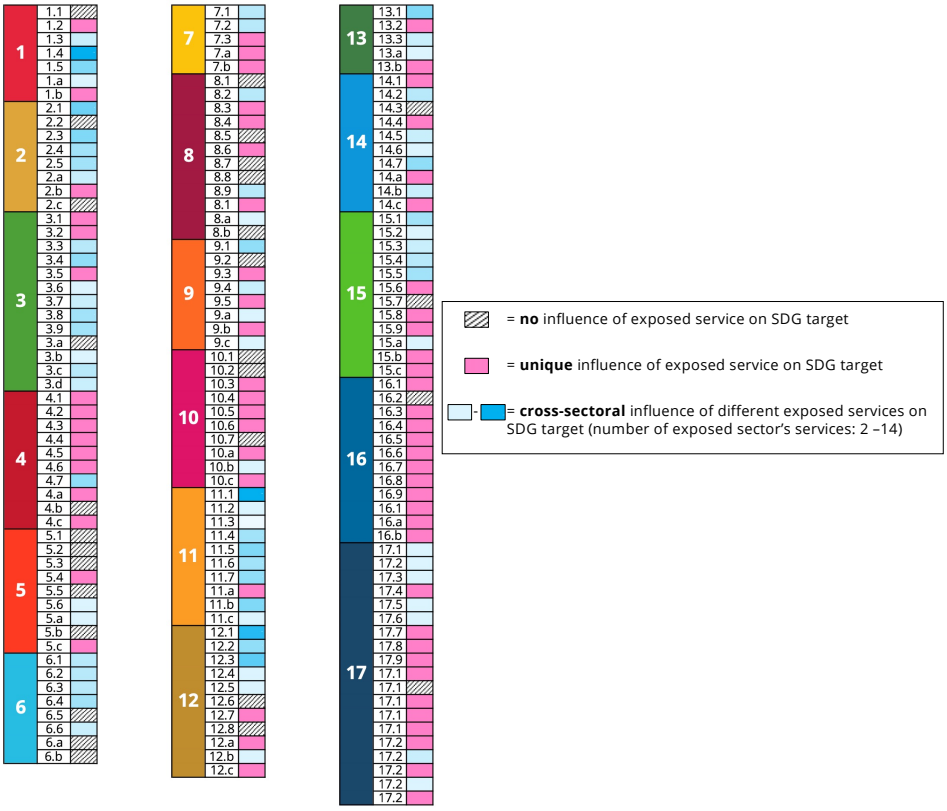


Figure 5.8: Summary of how each SDG target is influenced by, and can be safeguarded from, exposed sectors' services.

Comparing across sectors, we find most *unique* influences for the exposure of Saint Lucia's civic and education facilities. The loss of civic and educational services following a multi-hazard can uniquely affect 46 and 11 SDG targets, respectively (see Figure 5.9 and Supplementary Table 5.1 for unique SDG influences). Therefore, safeguarding those SDG targets uniquely influenced by the civic or education sector requires focussing adaptation within a single sector and its related ministry and stakeholders.

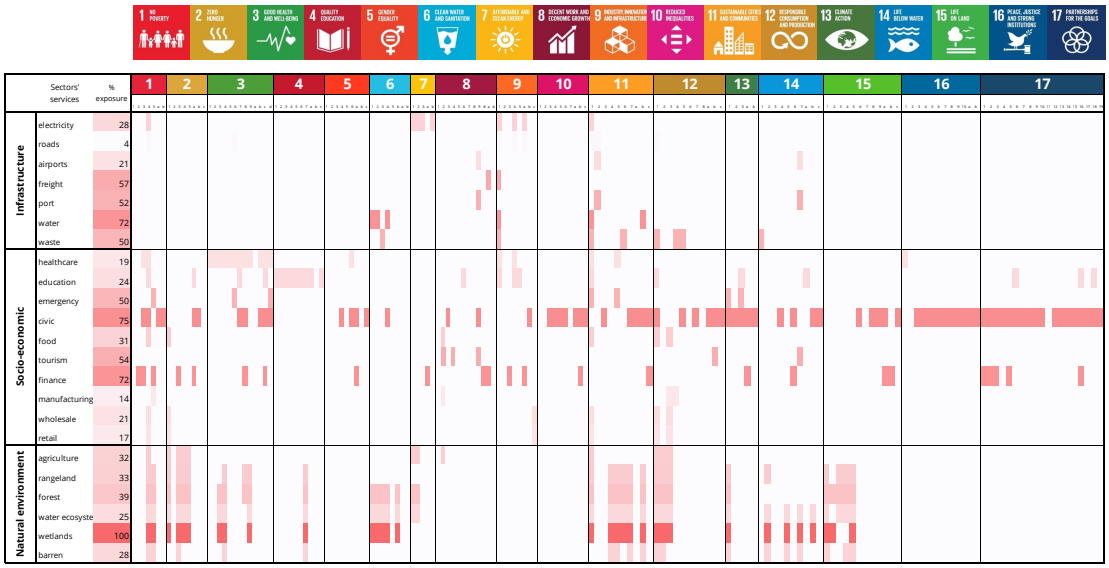


Figure 5.9: Influence of sector's service exposure directly on SDG targets in Saint Lucia. Each rectangle represents one target. Darker red shading denotes higher exposure of sector's services to the multi-hazard.

In contrast, exposure of Saint Lucia's water ecosystems, forests, and civic sectors can have most *cross-sectoral* influences on SDG targets, influencing 35, 33, and 33 SDG targets, respectively (Figure 5.8, Figure 5.9). This suggests that safeguarding those SDG targets influenced through cross-sectoral contributions requires adaptation measures across more than one sector. For example, SDG11.1 "By 2030, ensure access for all to adequate, safe and affordable housing and basic services" is influenced by the services from the largest number of different exposed sectors (14 sectors) (Figure 5.9). Therefore, safeguarding those SDG targets exposed through more than one sector requires cross-sectoral adaptation.

Collectively, we find that the multi-hazard of a combined storm surge, flash floods and landslide event can expose 22 sectors, thereby directly influencing 142 SDG targets in interdependent ways. Especially exposed are the development dimensions of clean energy, sustainable cities, climate action, and global partnerships (SDG7, SDG11, SDG13, and SDG17, with more than 95% of targets under these goals potentially affected by one or more exposed sectors) (Figure 5.10).

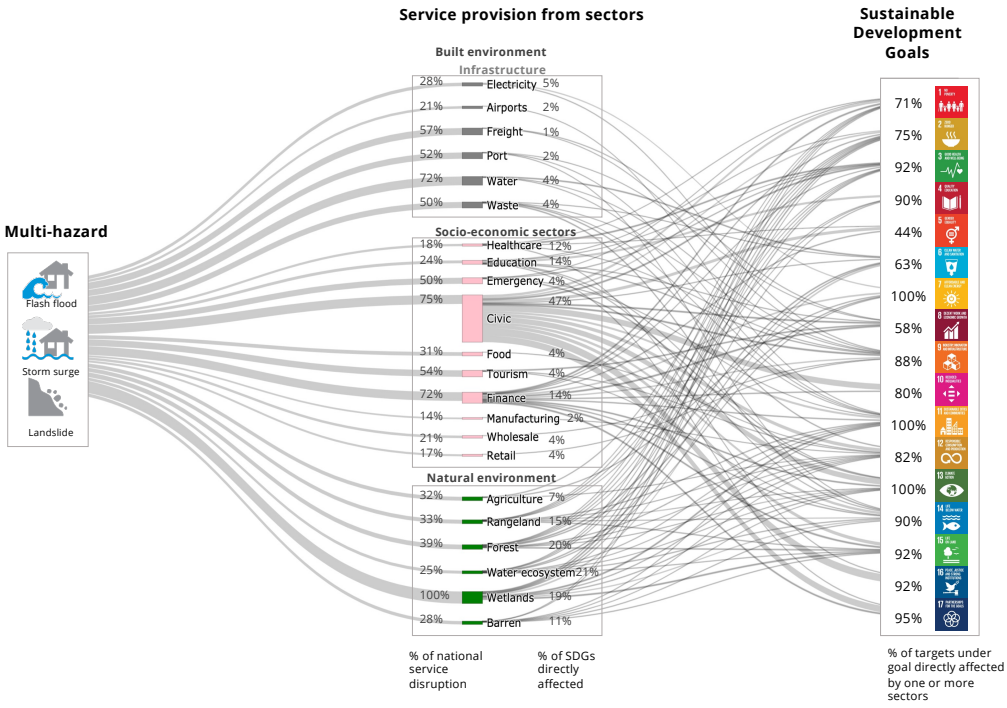


Figure 5.10: Exposure of multi-hazard event of storm surge, flash flood and landslide on services provided by sectors which can be linked directly to SDG targets.

5.4.4 Link to National Adaptation Plan

In comparing the summary, area-, and SDG-based results to Saint Lucia's NAP measures, we identify that the process of the research and stakeholder engagement throughout our proposed national-scale methodology application can help advance 14 of a total of 98 'groundwork & recognition' NAP measures through the following activities: collecting and standardising data across sectors, research-academia partnerships or capacity building workshops, amongst others. Evidently, measures advanced through the methodology application include NAP#6 "Create a new or strengthen an existing portal to centralise climate, environmental and socio-economic data relevant to adaptation" or NAP#11 "Model and map coastal flooding under sea-level rise".

Results from the area-based prioritisation of *where* to focus adaptation can help add spatial granularity to 52 of the 173 broadly formulated 'tangible action' NAP measures. Notably, we find that the results can help add spatial granularity to 13 of 16 (81%) tangible actions under the 'infrastructure and spatial planning' category, 10 of 17 (59%) tangible actions under the 'natural resources' category, and 3 of 6 (50%) tangible actions

under the 'cross-sectoral' category. For example, NAP#189 proposes infrastructural design upgrades, such as strengthening drainage or adhering to building design codes, which we find could be particularly relevant for the highly exposed freight assets in Saint Lucia's capital Castries. Moreover, using ecosystem-based solutions to protect infrastructure from climate impacts (NAP#185) could have wide SDG benefits if focused on Saint Lucia's highly exposed Choc wetland.

Results from the SDG-based prioritisation of *how* to focus adaptation can help add specificity to 11 of 50 NAP measures under the 'cross-sectoral' category. For example, NAP#5 proposes to "establish an autonomous body for the environment including climate change and sustainable development", which we find can have the largest benefit when sub-grouping ministries and sectoral stakeholder based on the types of cross-sectoral efforts required to safeguard affected SDG targets (e.g. efforts across water ecosystems, forests and the civic sector). Moreover, our results on how to adapt to safeguard SDG targets can provide specificity into how to divide groups when conducting training sessions for technical officers (NAP#28) or for private sector representatives (NAP#29) to ensure cross-sectoral contributions to SDG targets.

5.5 Discussion

The proposed methodology provides a new perspective on the complexity of the impacts of climate-change hazards on SDG targets at the granularity required to help national decision-makers inform and prioritise adaptation under the Paris Agreement. Research in the past has qualitatively emphasised that climate-change hazards can affect specific SDGs, with the potential to affect some of humanity's greatest challenges, including health, poverty, hunger, inequality and ecosystem preservation, amongst others (Fuso Nerini et al. 2018; IPCC 2018). However, to date, no research study has spatially assessed the potential impacts from climate-change hazards on all a nation's built and natural environment assets, and identified cascading impacts across SDG targets. Yet, such information is essential to provide national decision-makers with sound evidence to inform where bio-physical adaptation needs are greatest and to better prioritise adaptation under the Paris Agreement. This paper fills this gap by developing a transferable systems methodology.

5.5.1 Practical implications for Saint Lucia

An application of our systems methodology to Saint Lucia has achieved a number of benefits: i) it has helped decision-makers better make the case for national-scale adaptation across sectors, ii) it has provided depoliticised evidence on which sectors or assets to focus on for more detailed adaptation assessments, thereby identifying *where* one might add spatial granularity and prioritise the broadly formulated measures proposed in Saint Lucia's NAP, as well as specifying *how* NAP adaptation measures might benefit from cross-sectoral and cross-ministerial efforts, and iii) the process of data standardisation and capacity building itself has contributed to establishing parts of the groundwork for implementing adaptation in practice. We discuss each benefit in turn.

In Saint Lucia, previous studies have calculated the economic impacts of climate-change hazards, which were mostly attributed to impacts on the tourism and agricultural sector (Simpson et al. 2010). When applying the proposed systems methodology, a different picture of the SDG impacts of climate-change hazards emerges. We find that a multi-hazard event results in the largest exposure for the wetland and civic sectors. Disruption of the critical services provided by the civic sector, including implementing policy and governing most other sectors, can potentially influence most SDG targets (152 targets) across all SDGs. A focus on reducing exposure to protect the civic assets within the capital is important, not least in reducing the island's crime, case backlog, and in improving public perception of safety, which are key focus areas within Saint Lucia's SDG achievement plan (Government of Saint Lucia 2019b). Yet, previously, Saint Lucia's national climate and development documents did not explicitly highlight the importance of the civic sector and the critical services it provides for adaptation. By pinpointing the range of dimension of sustainable development potentially impacted by sectoral service disruptions, the methodology application provided a more holistic rationale for adaptation beyond economic impacts that also accounts for the natural environment.

Results from the application of the methodology enabled priority adaptation locations to be identified, which to date has not been conducted for Saint Lucia's NAP measures. Results also provide a means by which to identify how to focus cross-sectoral efforts to safeguard SDG targets. Whilst Saint Lucia's NAP clearly highlights the importance

of cross-sectoral action, to date it was not clear how to focus limited existing resources and leadership for cross-sectoral coordination to help safeguard development. By adding granularity and specificity to national adaptation planning across sectors, the methodology presented in this paper explicitly responds to critiques of NAPs: it takes a cross-sectoral approach and it helps prioritise adaptation in the context of sustainable development (Hardee et al. 2009; Termeer et al. 2012).

With respect to adaptation implementation, the application of our methodology reinforced previous arguments on the importance of adaptation policy coherence (Naess et al. 2015). Application of our systems methodology in close partnership with Saint Lucia's National Integrated Planning and Programme (NIPP) unit, who are tasked with integrated and cross-sectoral planning, helped to establish parts of the groundwork to ensure future governance and coordination of siloed institutions. The process of data collection, verification, and the capacity building workshops across ministries and sectors, which all formed part of this research, constitute a first step in bringing together ministries and stakeholders that typically work in siloes. Whilst increased cross-sectoral coordination can help overcome one of the factors limiting policy coherence in the context of the global agendas, it is important to highlight that much additional work remains to achieve policy coherence (Kanie et al. 2019). Iteratively updating data and re-applying the proposed systems methodology with new data representing multiple climate and future land-use scenarios as well as additional proposed adaptation measures can assist the NIPP unit in making more informed decisions, thereby depoliticising resource allocation. Such a holistic approach that accounts for the natural environment is essential, especially given our finding of the large role Saint Lucia's natural environment plays in cumulatively influencing more than 70 targets established in the SDGs.

5.5.2 Methodological implications

The choice of methodology to assess impacts of climate-change hazards is extremely important. Most climate-change hazard assessments focus on buildings and populations exposed and identify economic damages, which can provide a biased representation of climate-change hazards by focusing on certain dimensions of development only. An

assessment of impacts across both built and natural environment assets and all dimensions of development provides decision-makers with evidence to better inform bio-physical adaptation across and within sectors, and to revise or develop adaptation commitments under the Paris Agreement.

We propose a first attempt to spatially assess impacts of climate-change hazards on all dimensions of sustainable development by developing a novel methodology that takes into account the potential implications of hazard-induced service disruptions from both built *and* natural environments on the globally agreed-upon SDG targets to better inform adaptation. Thereby, the methodology responds to research calls showing how natural environments can attenuate risks and reduce the reliance on the built infrastructure towards improving resilience (Chester et al. 2020). Given the global acceptance of the SDG framework, the proposed systems methodology can be transferred across nations at varying levels of development and facing a diverse array of development challenges. However, applications of the proposed systems methodology in larger nations might be restrained by data availability on a holistic set of the nation's assets and their services, as well as logistical problems with regard to stakeholder engagement. Strategies to reduce these potential problems could include disaggregating the analysis by a nation's administrative regions, integrating fewer sectors, and/or building on pre-existing cross-sectoral and cross-ministerial efforts.

The allocation of resources is amongst the most difficult process for national governments in adapting to climate change (Allison et al. 2009; IPCC 2012; Tran et al. 2010). Such resource allocation should be informed by an assessment on where adaptation needs are greatest. These needs assessments include bio-physical, social, institutional, financial resource, and private sector engagement needs (Noble et al. 2015). Application of our proposed systems methodology can provide a useful starting point to allocate resources based on where bio-physical adaptation needs are greatest, acknowledging the equal importance of analysing and allocating social, institutional, financial or private sector engagement adaptation needs. Our proposed bio-physical-focussed needs assessment can help national governments: i) identify priority locations among built and natural assets where further detailed research is needed, ii) underpin national budget allocation

across sector and ministry siloes, iii) enable application to adaptation funds, for example as part of the Green Climate Fund.

Furthermore, application of our proposed methodology can help national decision-makers either revise or develop adaptation commitments under NDC and NAP commitments in line with the SDG targets, a broadly unmet requirement to date (Fuldauer, Thacker, Haggis, et al. n.d.; Fuso Nerini et al. 2019). In linking adaptation and development, the methodology responds to calls in the literature for integrated approaches to address climate and development objectives (Gomez-Echeverri 2018; Tran et al. 2010), which are particularly needed in the Global South (Carmin et al. 2012). The process of data standardisation, data sharing, and coordinated workshops across ministries and sectors, which are part of applying the proposed systems methodology, is one initial groundwork step to allow for the coordination required to meet the SDGs (Sachs et al. 2019; Stafford-Smith et al. 2016) and to overcome the difficulty in comparing impacts across sectors and hazards (Fekete et al. 2017; Kappes et al. 2012).

5.5.3 Limitations and future research

The modelling presented in this paper is conditional on assumed and available climate-change hazard, asset and socio-economic/ecosystem service provision data. First, the choice and scope of hazard scenarios largely determines the asset prioritisation results. The available hazard scenarios for Saint Lucia were non-probabilistic and did not include quantified magnitude, duration, or future risk quantifications. Whilst efforts have been made to verify the choice of hazard scenarios with stakeholders and organise capacity building workshops that enable iteratively updating results with new hazard scenarios, these limitations nevertheless suggest that current results do not allow for direct comparison of impact magnitude or duration across hazards and might not capture which assets or areas are at risk of future climate-change hazards. Future work might address these data limitations using the increasing availability of open-source probabilistic hazard scenarios (Ward et al. 2020), dynamically updating models with the most up-to-data datasets, and adding the potential for intensified hazard impacts arising from various types of future complex climate-change risks (Simpson et al. 2021).

Second, the use of the currently existing stock of built and natural assets and the available service provision information has important implications for the results: it does not enable accounting for future changes, urbanisation or afforestation/deforestation efforts, which can alter hazard exposure results. Moreover, the lack of service provision data for natural assets implies that larger natural areas – even if these provide a lower quality of service – might be prioritised in the results described in this paper. Whilst modelling results were sense-checked with in-country stakeholders, future work should aim to model the dynamic nature of current built and natural assets and the services these provide, including their service quality attributes, as well as spatial scenarios of future socio-economic development (Gao et al. 2020).

Third, data limitations and uncertainties did not allow for a quantitative estimate of how asset exposure can result in service disruptions, how long service is disrupted, how failure cascades across built and natural environments, and how a nation's population might respond to service disruptions. Whilst efforts have been made to identify the SDG interdependencies from multiple sectors' service disruptions, future work could extend the analysis in this paper: i) using detailed damage functions for multiple sectors (see Koks, Rozenberg, et al. (2019), ii) integrating cascading failures across interconnected sectors, such as when electricity outages result in other sector's service disruptions (Pant et al. 2014), iii) quantitatively evaluating natural and built environments interactions, including integrating the nature of hydrological and ecosystem corridors which can propagate services disruptions (Palmer et al. 2011), and iv) identifying the differential adaptive capacity of populations in responding to service disruptions given the well-established literature that poorer households are more dependent on publicly provided assets and are often less able to smooth income fluctuations from service disruptions, and thereby suffer disproportional welfare losses from hazards (Verschuur et al. 2020). Scaling up these efforts can improve the results of national-scale applications of the proposed systems methodology, and might eventually help to apply the proposed methodology at the global scale.

The application of the proposed methodology in this paper focused on acute climate-change hazards. The methodology may be further extended to chronic, slow-onset

climate-change hazards, for example by assessing climate-induced changes in asset's operating capacity or service provision potential over time (see Adshead, Fuldauer, et al. (2020) for an example on assessing reduced water storage capacity with climate-change drought scenarios). Further work can also quantify the magnitude of climate-change hazard impacts on specific SDG targets. Such work requires the development of indicators which are able to capture both climate-change hazard impacts as well as a nation's current SDG target progress. To this end, the emerging array of open-source data can play an important role, including that derived from citizen science (Fritz et al. 2019).

We acknowledge that adaptation in the context of sustainable development is a highly complex topic. Adaptation can lead to maladaptive outcomes, especially if it is not embedded in an iterative, reflexive process that works together with marginalised and disproportionally affected households (Eriksen et al. 2021). It is therefore important to recognise that our proposed methodology provides a starting point to identify a high-level prioritisation of bio-physical adaptation needs, and is proposed as a decision-support tool. It is critical to also consider the social, institutional, and political issues of adaptation as well as the uneven distribution of impacts from climate-change hazards and service disruptions on the poorest and the most vulnerable in Saint Lucia (see Adshead et al. (2019)).

Assessments such as this one can be enriched by efforts focusing on the next step of identifying, evaluating, and implementing adaptation measures. Building on this assessment of cross-sector and multi-hazard exposure, we recommend evaluating the costs, effectiveness, SDG co-benefits, and potential maladaptive outcomes of future adaptation measures (Skourtos et al. 2014), thereby aiming to adapt assets currently exposed and keeping longer term options open to account for future uncertainties (Hallegatte 2009; Hinkel et al. 2015). Alongside the need to use deep uncertainty tools to keep infrastructure reliable under climate uncertainty (Chester et al. 2020), research is needed to apply such methods to keep natural environment services reliable under climate uncertainty (Jones et al. 2012). In doing so, community-based adaptation initiatives, especially those integrated with ecosystem-based adaptation, should feature extensively and can be applied to various sectors (Schipper et al. 2014). Relevant indicators must be developed to

measure the success of such adaptation initiatives, building on advances on how successful adaptation initiatives require: i) local approval and ownership, ii) shared access to, and benefits from, adaptation, iii) integration of local realities, and iv) systems-thinking and forward-planning (McNamara et al. 2020). Therefore, implementing adaptation requires understanding existing policy and decision-making processes as well as the political economy context, including issues of power that shape debates and determine outcomes (Naess et al. 2015). Future work on implementing adaptation could benefit from understanding the informal and historical embeddedness of decision-making within sectors, and to use inclusive governance processes and co-learning to improve decision-making in practice (Butler et al. 2016).

5.6 Conclusions

Informing national adaptation in the context of the SDGs is challenging, not least due to the fragmented availability of data and incomplete knowledge of the relationships between climate-change hazards and SDG targets. Such knowledge however is important to provide national decision-makers with the evidence on where and how to prioritise bio-physical adaptation to safeguard SDG targets and better inform national adaptation under the Paris Agreement. This paper puts forward a systems methodology to help address this gap. Focusing on the spatial distribution of a nation's built and natural environment assets, we present a novel systems methodology that spatially assesses the impacts of climate-change hazards on a nation's entire set of assets and its interdependent influences on SDG targets. Insights from the application of this systems methodology can be used as a starting point for spatial planners and national decision-makers to prioritise and allocate appropriate resources across physical assets, apply for global climate funds, and help revise or develop Nationally Determined Contributions or National Adaptation Plans under the Paris Agreement. Application of the proposed methodology in Saint Lucia highlighted the profound bio-physical impacts of acute climate-change hazard across all SDGs and 22 sectors. Ensuring Saint Lucia's continued provision of critical services in the face of climate-change hazards will require sectoral and cross-sectoral adaptation, which may be governed by the island's National Integrated Planning and

Programme unit. The systems methodology presented in this paper can be repeated with hazard maps representing different climate-change scenarios, and may be transferred to other climate-vulnerable nations. Effective and equitable adaptation is now urgently needed to safeguard the achievement of the global agendas, though it requires political will and transcending siloed approaches.

Code availability

All Python source code can be requested from the corresponding author.

Supplementary Tables

Supplementary Table 5.1: Data for the built and natural environment characterisation for Saint Lucia, including direct SDG target influences. Unique influences are represented by those SDG targets only listed as influenced by a single sector. Unless otherwise specified, national service provision data was collected in country in collaboration with UNOPS. References include: a) (IDEA 2008), b) (Government of Saint Lucia 2017b) , c) (SLASPA 2017), d) (Charim 2016), e) (SLUSWMA 2015).

Sector s	**Current national service provision C^s**	**Unit for national service provision**	**SDG targets directly linked to services from sector *s* *t* where $I_{s,t}$ =1.**
Built environment: Infrastructure utility sectors			
Electricity	4.5 * 10^2 [a)]	GWh/year	1.4, 7.1, 7.2, 7.3, 7.b, 9.1, 9.4, 9.a, 11.1
Water	2.2 * 10^7 [b)]	m^3 /year	6.1, 6.2, 6.4, 9.1, 11.1, 11.b
Wastewater	2.8 *10^6 [b)]	m^3 /year	6.2, 6.3, 11.1, 11.6, 12.4
Solid waste	6.0 * 10^5 [e)]	tons /year	6.3, 9.1, 11.1, 11.6, 12.1, 12.4, 14.1
Roads	2,616 [d)]	km of road length	3.6, 9.1, 11.1, 11.2, 11.a
Freight	1.3 *10^6[c)]	tons /year	8.a, 9.1
Port	1.7 *10^6 [c)]	passengers /year	8.9, 11.2, 14.7
Airport	4.6 *10^5 [d)]	passengers /year	8.9, 11.2, 14.7
Built environment: Socio-economic sectors			
Healthcare	114	number of assets	1.3, 1.4, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.b, 3.c, 3.d, 5.6, 9.1, 9.4, 11.1, 11.5, 16.1

Education	189	number of assets	1.4, 2.a, 3.7, 3.c, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.a, 4.c, 8.6, 9.1, 9.4, 9.5, 11.1, 12.1, 13.3, 14.a, 17.6, 17.16, 17.18
Emergency	22	number of assets	1.5, 3.6, 3.d, 11.1, 11.5, 13.1, 13.3
Civic	84	number of assets	1.3, 1.4, 1.a, 1.b, 2.a, 2.b, 3.7, 3.8, 3.b-3.d, 5.4, 5.6, 5.a, 5.c, 6.4, 8.3, 8.9, 9.b, 10.3-10.6, 10.a-10.c, 11.3, 11.7, 11.a- 11.c, 12.1, 12.5, 12.7, 12.a-12.c, 13.1-13.3, 13.a, 13.b, 14.4, 14.6, 14.b, 14.c, 15.6, 15.8, 15.9, 15.a, 15.c, 16.3-16.10, 16.a, 16.b, 17. 1-17.10,17.12-17.19
Manufacturing	35	number of assets	1.5, 8.2, 12.3, 12.4
Wholesale	19	number of assets	1.4, 2.1, 9.c, 11.1, 12.1, 12.3
Retail	12	number of assets	1.4, 2.1, 9.c, 11.1, 12.1, 12.3
Food distribution	247	number of assets	1.4, 2.1, 8.2, 11.1, 12.1, 12.3
Tourism	42	number of assets	1.1, 1.2, 1.4, 1.5, 9.1, 11.1, 11.c
Finance	42	number of assets	1.3, 1.4, 1.a, 2.3, 2.a, 3.8, 3.c, 5.a, 7.a, 8.1, 8.a, 9.3, 9.a, 10.b, 11.c, 13.a, 14.6, 15.a, 15.b, 17.1-17.3, 17.5, 17.16
Natural environment: Ecosystems			
Agriculture	182	km^2	1.4, 2.1, 2.3, 2.4, 2.5, 7.1, 7.2, 8.2, 11.1, 12.1, 12.2, 12.3

Barren (Non-vegetated areas)	1	km^2	1.4, 1.5, 2.3, 3.4, 4.7, 11.4, 11.5, 11.7, 11.b,12.1, 12.2, 13.1, 14.2, 14.5, 14.7, 15.1, 15.4, 15.5
Water ecosystems	0.4	km^2	1.4, 1.5, 2.1, 2.3, 2.4, 2.5, 3.3, 3.4, 3.9, 4.7,6.1-6.4, 6.6, 7.1, 7.2, 11.1, 11.4-11.7, 11.b, 12.1-12.3, 13.1, 14.2, 14.5,14.7, 14.b, 15.1, 15.3-15.5
Forests	205	km^2	1.4, 1.5, 2.1, 2.3, 2.4, 2.5, 3.3, 3.4, 3.8, 3.9,4.7, 6.1, 6.2, 6.3, 6.4, 6.6, 7.1, 7.2, 11.1, 11.4,11.5, 11.6, 11.7, 11.b, 12.1, 12.2, 12.3, 13.1, 15.1,15.2, 15.3, 15.4, 15.5
Wetlands	2 [b)]	km^2	1.4, 1.5, 2.1, 2.3, 2.4, 2.5, 3.3, 3.4, 3.9, 4.7,6.1, 6.2, 6.3, 6.4, 6.6, 11.1, 11.4, 11.5, 11.6,11.7, 11.b, 12.1, 12.2, 12.3, 13.1, 14.2, 14.5, 14.7, 14.b, 15.1, 15.2, 15.5
Rangeland (incl. grassland, savannah, shrubland)	116	km^2	1.4, 1.5, 2.1, 2.3, 2.4, 2.5, 3.4, 3.8, 3.9, 4.7,11.1, 11.4, 11.5, 11.6, 11.7, 11.b, 12.1, 12.2, 12.3,13.1, 14.2, 15.1, 15.3, 15.4, 15.5

Supplementary Table 5.2: Categorisation of Saint Lucia data combined from different sources. Sources without brackets refer to stakeholders engaged during in-country visits. Every geospatial dataset was verified and georectified where necessary with in-country stakeholders together with the National Infrastructure Planning and Programme (NIPP) unit.

Data	**Categorisation (and included sub-categories)**	**Source**
Government-obtained social infrastructure	Emergency (Fire stations)	(Charim, 2016)
	Healthcare (Health centres, pharmacies)	(Charim, 2016)
	Education (Schools)	Ministry of Education
	Tourism (Hotels)	(Charim, 2016)
	Finance (Bank)	Department of Statistics
	Food (Supermarkets)	Department of Statistics
OSM-obtained social infrastructure	Education (School, library, university, college, pre school, childcare, kindergarden)	(OSM, 2020)
	Healthcare (Dentist, hospital, pharmacy, doctors, clinic)	
	Emergency (Youth centre, social facility)	
	Food (Fast food, restaurant, café, marketplace, convenience, supermarket, mall, butcher, bakery	

Civic (Courthouse, prison, townhall government)
Tourism (Restaurant, hotel)
Finance (Bank, money transfer)

Supplementary Table 5.3: Land-use re-classification according to the standard land-use classification (Anderson et al. 1976) based on Saint Lucia's land use classification (Ministry of Agriculture Forestry and Fisheries Saint Lucia, 2002).

Standard land-use classification	**Saint Lucia land uses**
Rangeland (incl. grassland, savannah, shrubland)	Bare Ground/Scrub, Grassland, Other vegetation
Built area	Built-up Area
Forests	Densely Vegetated Farming, Forest reserve, Natural Tropical Forest, Scrub Forest
Agriculture	Intensive Farming, Mixed Farming
Water ecosystem	Ponds
Barren (non-vegetated areas)	Touristic
Wetlands	Mangroves

Supplementary Table 5.4: Overview of sector's services and indirect SDG influences in Saint Lucia. References (Ref) include: a) Ministry of Agriculture Forestry and Fisheries Saint Lucia (2002), b) IDEA (2008), c) Central Statistical Office of Saint Lucia (2018), d) Government of Saint Lucia (2017a). Where no in-country data on the services or indirect SDG influences was available, we used global information based on a previous publication (Fuldauer, Thacker, Haggis, et al. n.d.), indicated by the letter e), which was verified by the NIPP unit where possible.

Sector	Service	Indirect influence	Ref
Built environment: Infrastructure sectors			
Electricity	Energy, electricity, basic service	['1.1', '1.2', '1.4', '1.5', '2.1', '2.2', '2.3', '2.4', '3.1', '3.2', '3.3', '3.4', '3.8', '3.9', '3.b', '4.1', '4.2', '4.3', '4.4', '4.5', '4.6', '4.7', '4.a', '5.1', '5.2', '5.4', '5.5', '5.6', '5.b', '6.1', '6.2', '6.3', '6.4', '6.6', '8.1', '8.2', '8.3', '8.4', '8.6', '8.1', '8.a', '9.2', '9.b', '9.c', '10.1', '10.2', '10.b', '11.2', '11.3', '11.5','11.a', '11.b', '11.c', 12.1', '12.2', '12.3', '12.4', '12.5', '12.c', '13.1', '13.2', '13.3', '14.1', '14.3', '14.b', '15.1', '15.2', '16.1', '16.6', '17.7', '17.8', '17.9', '17.17']	d,e
Roads	Transportation, access to goods and services	['1.1', '1.4', '1.5', '1.a', '1.b', '2.3', '2.4', '2.5', '2.a', '3.2', '3.3', '3.4', '3.5', '3.6', '3.9', '3.a', '3.b', '3.d', '4.1', '4.2', '4.3', '4.4', '4.5', '4.6', '4.7', '4.a', '4.c', '5.2', '5.a', '6.3', '6.4', '6.5', '6.6', '6.b', '7.1', '7.2', '7.3', '7.b', '8.1', '8.2', '8.3', '8.4', '8.5', '8.6', '8.7', '8.8', '8.1', '8.a', '9.3', '9.4', '9.5', '9.c', '10.1', '10.2', '10.3', '10.5', '10.6', '10.7', '11.4', '11.5', '11.6', '11.7', '11.b', '11.c', '12.1', '12.2', '12.3', '12.4', '12.5','12.7', '12.a', '13.1', '13.2', '13.3', '13.a', '13.b', '14.3', '14.5', '14.a', '14.b', '15.1', '15.3', '15.6', '15.7', '15.8', '16.1', '16.3', '16.4', '16.8', '16.9', '16.1', '16.a', '16.b', '17.1', '17.6', '17.8', '17.9', '17.16', '17.17']	b,e

Airports	Passenger transportation, tourism	['2.3', '2.a', '3.1', '3.2', '3.3', '3.4', '3.9', '3.d', '4.3', '4.7', '4.b', '4.c', '5.6', '5.a', '6.5', '6.a', '7.a', '8.1', '8.3', '8.5', '8.6', '9.2', '9.3', '9.5', '9.b', '10.5', '10.6', '10.7', '10.b', '11.5', '11.a', '11.b', '11.c', '12.1', '12.2', '12.a', '13.1', '13.2', '13.3', '13.b', '14.3', '14.7', '14.a', '15.3', '15.8', '16.3', '16.4', '16.6', '16.8', '16.a', '17.1', '17.4', '17.6', '17.7', '17.8', '17.9', '17.16', '17.18', '17.19']	b,e
Freight	Freight transportation, access to goods and services	['1.5', '2.1', '2.2', '2.3', '2.4', '2.5', '2.a', '2.c', '3.1', '3.2', '3.3', '3.4', '3.5', '3.7', '3.8', '3.9', '3.b', '3.d', '4.4', '4.5', '4.6', '4.a', '5.6', '5.a', '5.b', '6.1', '6.2', '6.4', '7.1', '7.2', '7.3', '7.b', '8.1', '8.2', '8.3', '8.4', '8.a', '9.2', '9.3', '9.c', '10.1', '10.b', '11.3', '11.5', '11.a', '11.b', '11.c', '12.1', '12.2', '12.3', '12.4', '12.5', '12.a', '13.1', '13.2', '14.1', '14.2', '14.7', '14.b', '15.2', '15.6', '15.7', '15.8', '16.4', '16.6', '17.5', '17.6', '17.7', '17.8', '17.9', '17.1', '17.11', '17.12', '17.18']	b,c, d,e
Port	Passenger transportation through cruise ports and marinas, tourism	['2.3', '2.a', '3.1', '3.2', '3.3', '3.4', '3.9', '3.d', '4.3', '4.7', '4.b', '4.c', '5.2', '5.6', '5.a', '6.5', '6.a', '7.a', '8.1', '8.3', '8.5', '8.6', '9.2', '9.3', '9.5', '9.b', '10.5', '10.7', '10.b', '11.5', '11.6', '11.a', '11.b', '11.c', '12.1', '12.2', '12.a', '13.1', '13.2', '13.3', '13.b', '14.1', '14.2', '14.3', '14.7', '14.a', '15.3', '15.8', '16.3', '16.4', '16.6', '16.8', '16.a', '17.1', '17.4', '17.6', '17.7', '17.8', '17.9', '17.16', '17.18', '17.19']	b,d, e
Water	Water provision, basic service	['1.1', '1.4', '1.a', '1.b', '2.3', '2.4', '2.a', '3.1', '3.2', '3.3', '3.4', '3.5', '3.6', '3.8', '3.9', '3.b', '4.1', '4.2', '4.3', '4.4', '4.5', '4.6', '4.7', '4.a', '4.c', '5.4', '5.6', '5.a', '6.5', '7.1', '8.1', '8.3', '8.4', '8.5', '8.6', '9.4', '10.1', '10.3', '10.5', '10.b', '11.5', '11.6', '11.a', '11.b', '12.1', '12.3', '12.4', '13.1', '13.2', '13.a', '15.3', '15.5', '17.17']	d,e
Waste water	Wastewater service, sanitation, storm water runoff, basic service	['1.4', '2.3', '3.1', '3.2', '3.3', '3.4', '3.5', '3.9', '8.1', '8.3', '9.2', '9.b', '10.b', '11.3', '11.5', '11.a', '11.b', '12.1', '12.2', '13.1', '14.1', '14.2', '15.1', '16.6']	b,e

Waste	Waste service, basic service	['1.4', '1.a', '1.b', '2.a', '3.b', '4.c', '8.3', '8.4', '8.5', '8.6', '9.4', '10.3', '11.5', '11.7', '11.a', '11.b', '11.c', '12.1', '12.4', '13.3', '13.a', '14.1', '14.2', '15.1', '15.3', '16.8']	e
Built environment: Socio-economic sectors			
Health care	Healthcare services, basic service	['1.1', '1.2', '1.5', '2.1', '2.2', '2.3', '3.a', '4.1', '4.2', '4.3', '4.4', '4.5', '4.6', '5.1', '5.2', '5.3', '5.5', '6.2', '6.4', '6.5', '7.3', '8.1', '8.5', '8.6', '8.8', '8.9', '10.2', '10.7', '11.6', '12.4', '12.5', '12.6', '14.1', '16.2', '16.9']	e
Education	Educational services, basic service	['1.1', '1.2', '1.3', '1.5', '2.1', '2.2', '2.3', '2.4', '2.5', '3.1', '3.2', '3.3', '3.4','3.5', '3.6', '3.a', '3.b', '3.d', '5.1', '5.2', '5.3', '5.4', '5.5', '5.a', '5.b', '6.2', '6.3', '6.4', '6.6', '6.a', '6.b', '7.2', '7.3', '8.1', '8.2', '8.3', '8.5', '8.7', '8.1', '8.b', '9.3', '9.a', '9.b', '9.c', '10.1', '11.3', '11.5', '11.a', '11.b', '12.2', '12.3', '12.5', '12.6', '12.8', '12.a', '13.1', '13.2', '13.b', '14.1', '14.3', '14.5', '15.1', '15.2', '15.3', '15.4', '15.5', '15.c', '16.2', '16.4', '16.5', '16.1', '16.a', '17.7', '17.8', '17.9', '17.19']	d,e
Emergency	Emergency service, disaster risk reduction, resilience, basic services	['1.4', '8.1', '10.1', '10.7', '11.a', '13.2', '17.17']	e
Civic	Implementation of government policy, training police and emergency responders to manage disasters, develop policy, govern society, enforce standards	['1.2', '1.3', '1.5', '1.a', '2.1', '2.a', '2.b', '2.c', '3.1', '3.3', '3.6', '3.7', '3.8','3.9', '3.a', '3.d', '4.2', '4.3', '4.4', '4.5', '4.6', '4.7', '4.b', '5.1', '5.3', '7.2', '7.3', '8.2', '8.4', '8.5', '8.6', '8.7', '9.1', '9.5', '9.a', '9.c', '10.2', '10.4', '10.5','10.6', '10.a', '11.2', '11.3', '11.5', '11.6', '11.a', '12.1', '12.2', '12.3', '12.4', '12.5', '12.6', '12.8', '12.c', '13.1', '13.a', '13.b', '14.1', '14.3', '14.7', '15.1', '15.2', '15.a', '16.7', '16.9', '16.1', '16.a', '17.1', '17.4', '17.9', '17.1', '17.14', '17.15']	d,e

Food	Food services, basic service	['1.2', '1.3', '1.5', '2.5', '2.a', '3.7', '3.c', '4.1', '4.3', '6.2', '6.6', '6.a', '6.b', '7.a', '7.b', '8.3', '8.4', '8.7', '9.4', '9.5', '9.b', '9.c', '10.2', '10.3', '11.4', '11.5', '11.7', '12.4', '12.7', '12.8', '12.a', '14.6', '15.3', '15.5', '15.6', '17.1', '17.14']	e
Tourism	Tourism (incl. yachting, sports, adventure, cultural tourism), recreation	['8.1', '8.2', '8.3', '10.1', '11.a', '12.2', '12.5']	b,d, e
Manu-facturing	Manufacturing of goods and services (mainly food and beverage products, electrical, paper and metal products)	['2.1', '2.2', '2.3', '2.4', '3.1', '3.2', '3.3', '3.4', '3.5', '3.6', '3.7', '3.8', '3.9', '3.a', '3.b', '3.d', '5.b', '6.1', '6.2', '6.3', '6.4', '6.5', '7.2', '7.b', '8.1', '8.4', '9.1', '9.2', '9.4', '9.5', '9.c', '11.1', '11.2', '11.5', '12.1', '12.2', '12.5', '12.6', '12.b', '14.a', '17.1', '17.8', '17.11']	d,e
Wholesale	Wholesale to business	['1.2', '2.2', '2.3', '2.4', '3.1', '3.2', '3.3', '3.4', '3.5', '3.6', '3.7', '3.8', '3.9', '3.a', '3.b', '3.d', '4.4', '4.a', '5.b', '6.1', '6.2', '6.3', '9.2', '9.4', '9.5', '11.2', '11.6', '12.4', '12.5', '12.6', '14.7', '17.7', '17.8', '17.11']	d,e
Retail	Sale to customers	['1.2', '2.2', '2.3', '2.4', '3.1', '3.2', '3.3', '3.4', '3.5', '3.6', '3.7', '3.8', '3.9', '3.a', '3.b', '3.d', '4.4', '4.a', '5.b', '6.1', '6.2', '6.3', '9.2', '9.4', '9.5', '11.2', '11.6', '12.4', '12.5', '12.6', '14.7', '17.7', '17.8', '17.11']	d,e
Finance	Financial services, insurance, basic service	['1.2', '1.3', '1.5', '2.5', '2.a', '2.b', '3.4', '3.5', '3.6', '3.7', '3.8', '3.9', '3.a', '3.b', '3.c', '3.d', '4.1', '4.3', '4.7', '5.1', '6.2', '6.4', '6.5', '6.6', '9.5', '9.b', '9.c', '11.5', '11.b', '12.7', '12.8', '12.a', '14.c', '17.1', 17.11', '17.14']	d,e

Natural environment sectors

Agriculture	Food services, basic service (including bananas, coconut, sugar, cocoa, fruits, herbs, and vegetables, tree crops, horticulture and livestock)	['1.2', '1.3', '2.2', '2.c', '3.1', '3.2', '3.3', '3.4', '3.9', '3.d', '4.1', '4.2', '4.3', '5.a', '6.1', '6.3', '6.4', '6.5', '7.3', '8.1', '8.4', '11.a', '12.4', '12.5', '14.1', '14.3', '14.7', '15.2', '15.3', '15.4', '15.5', '15.8', '16.2', '17.11', '17.13']	d,e
Rangeland (incl. Grassland, savannah, shrubland)	Air purification, habitat provision, water regulation, adaptation services, biodiversity, adaptation services	['1.1', '1.2', '2.2', '3.2', '4.1', '4.5', '5.a', '6.1', '6.3', '6.4', '6.5', '7.1', '7.2', '8.1', '8.4', '8.9', '9.b', '10.1', '11.a', '12.4', '12.5', '12.8', '13.3', '14.1', '14.3', '16.1', '16.4', '16.7', '17.1', '17.3', '17.11']	a,e
Forest	Air purification, habitat provision, water regulation, adaptation services, biodiversity, supply of freshwater, water quality, cultural resource, tourism, slope stabilisation	['1.2', '2.2', '3.1', '3.2', '3.5', '3.b', '4.1', '4.5', '4.6', '4.a', '5.a', '6.5', '7.3', '8.1', '8.4', '8.9', '9.1', '9.4', '9.b', '10.1', '11.a', '11.c', '12.4', '12.5', '12.8', '13.3', '14.1', '14.2', '14.3', '16.1', '16.4', '16.7', '17.1', '17.3', '17.11']	a,b, e
Water ecosystem	Habitat provision, adaptation services, biodiversity, aquaculture, portable water, cultural resource	['1.2', '2.2', '3.1', '3.2', '4.1', '4.2', '4.3', '4.4', '4.5', '4.6', '5.4', '5.5', '5.a', '6.5', '7.b', '8.1', '8.6', '8.8', '8.9', '9.4', '9.b', '11.a', '12.4', 2.5', '12.8', '13.3', '14.1', '14.3', '14.4', '15.8', '16.1', '16.4', '16.7', '17.1', '17.3']	a,b, e

Wetlands	Habitat provision, adaptation services, flood protection, biodiversity, aquaculture, seabed sediment stabiliser, cultural resource	['1.2', '2.2', '3.1', '3.2', '4.1', '4.5', '4.6', '5.a', '6.5', '8.1', '8.4', '8.9', '9.1', '9.b', '10.1', '11.a', '12.4', '12.5', '12.8', '13.3', '14.1', '14.3', '14.4', '16.1', '16.4', '16.7', '17.1', '17.3']	a,b, e
Barren (non-vegetated areas)	Recreation, tourism, habitat provision, public facilities such as restrooms, adaptation services	['5.a', '6.3', '7.1', '7.2', '8.1', '8.9', '9.b', '10.1', '11.a', '12.4', '12.5', '12.8', '13.2', '13.3', '16.1', '16.4', '16.7', '17.1', '17.3', '17.11']	a,e

Supplementary Table 5.5: Overview of results from the application of the proposed systems methodology.

Sectors	Attribute information of all sector's assets		SDG targets and goals influenced by sector's services (count)					Climate-change hazard exposure (Percentage of national service provision exposed)			
	National service provision (C)	Unit for national service provision	SDG targets direct	SDG targets indirect	SDG targets direct and indirect	SDGs direct	SDGs indirect	Storm surge exposure	Flash flood exposure	Landslide exposure	Multi-hazard exposure
Built environment: Infrastructure sectors											
Electricity	454	GWh/year	9	73	82	17	16	12	12	16	28
Roads	2,615,941	km	5	99	104	3	17	3	4	3	0
Airports	456,123	pax/year	3	59	62	3	16	21	0	0	21
Freight	1,349,158	tons/year	2	74	76	2	17	57	43	0	57
Port	1,742,265	pax/year	3	62	65	3	16	52	22	0	52
Water	21,629,274	m3/year	6	53	59	3	17	0	3	71	72
Wastewater	2,838,240	m3/year	5	24	29	3	12	0	0	0	0
Waste	598,360	tons/year	7	26	33	5	17	0	0	50	50
Built environment: Socio-economic sectors											
Healthcare	114	assets	20	35	55	17	17	8	13	3	19
Education	189	assets	24	76	100	17	17	10	18	4	24
Emergency	22	assets	7	7	14	4	7	31	44	0	50
Civic	84	assets	79	73	152	17	17	63	52	2	75
Food	247	assets	6	37	43	17	17	19	19	3	31
Tourism	42	assets	7	7	14	3	4	48	2	7	54

Finance	59	assets	24	36	60	17	17	52	52	3	72
Manufacturing	35	assets	4	43	47	17	17	3	11	0	14
Wholesale	19	assets	6	34	40	17	17	5	16	0	21
Retail	12	assets	6	34	40	17	17	0	17	0	17
Natural environment sectors											
Agriculture	182	km2	12	35	47	17	17	0	6	26	32
Rangeland (incl. Grassland, savannah, shrubland)	116	km2	25	31	56	17	17	2	3	28	33
Forest	205	km2	33	35	68	17	17	1	2	36	39
Water ecosystem	0.4	km2	35	35	70	17	17	17	8	1	25
Wetlands	1.8	km2	32	28	60	17	17	54	46	0	100
Barren (non-vegetated areas)	1.1	km2	18	20	38	17	17	21	1	7	28

6

Evaluating climate adaptation based on sustainable development targets

This chapter addresses Research Question 3: *How can adaptation needs and options be evaluated based on sustainable development targets?* In addressing this question, this chapter operationalises the conceptual framework introduced in Chapter 4 using the SDGs as a starting point (development-first approach). This chapter further builds upon the spatial translation of the SDG targets presented in Chapter 5 by expanding it to the SDG indicator level. Collectively, the chapter develops a methodology that allows national decision-makers to evaluate adaptation to both safeguard existing SDG progress and advance SDG co-benefits. Its application to Ghana's energy and transport sector enables evaluating how much of Ghana's SDG progress can be safeguarded through adaptation, and which adaptation options can maximise SDG target co-benefits.

This chapter was submitted as a journal paper to Global Environmental Change with the title 'Evaluating the benefits of national adaptation to reduce climate risks and contribute to the Sustainable Development Goals' in September 2021. The paper was co-authored with Daniel Adshead, Scott Thacker, Sarah Gall, and Jim W. Hall, who gave methodological advice, contributed to some of the analysis, and provided comments and edits to the text and figures. All data that support the findings of this chapter, including Supplementary Appendix A and Supplementary Tables 6.2-6.4, are described below. Chapter 6 Supplementary Information Tabs 1-3 are attached to this thesis and available at: https://doi.org/10.5281/zenodo.5643953.

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 methodology 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 methodology 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 methodology 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.

6.1 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 et al. 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 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, Thacker, Haggis, et al. n.d.; Zhenmin et al. 2019), national adaptation planning under the Paris Agreement is seldom articulated in terms of its 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.

Climate risk is the combination of three crucial components: i) climate-change hazards: events that may cause loss of life or physical asset damages, ii) exposure: built, natural, or human assets and services located in hazard-prone areas, and iii) vulnerability: the sensitivity of these built, natural, or human assets to be adversely affected (asset vulnerability) as well as the lack of capacity of communities to cope and respond to impacts of climate change (social vulnerability) (IPCC 2019; IPCC 2014a; IPCC 2012). In this context, impacts refer to the consequences of realised climate risks (Masson-Delmotte et al. 2018). With the aim of formalising the process of adaptation decision-making, various adaptation assessments to reduce climate risks have been proposed, including on bio-physical, social, institutional, financial, and private sector engagement adaptation (see Noble et al. (2015) for detailed review of adaptation assessments). Such adaptation

assessments are typically structured around two main phases: I) adaptation needs, which refer to the assets, locations, communities or institutions requiring actions in response to climate risks; and II) adaptation options, which are comprised of the array of measures available and appropriate to address these needs (Noble et al. 2015).

Here, we focus on bio-physical adaptation assessments, acknowledging the equal importance of the other dimensions of adaptation. Bio-physical adaptation needs are typically quantified in terms of the direct economic benefits of protecting physical built or natural assets on which lives ultimately depend, both under current and a range of future climate and socio-economic scenarios. These economic benefits of protecting assets are subsequently compared with the costs of different adaptation options, such as built asset protection or nature-based wetland conservation efforts. Through this two-phase process, bio-physical adaptation assessments evaluate the cost-effectiveness for different combinations of assets and adaptation options, and identify those that cost-effectively and robustly reduce climate risk across numerous future scenarios (Ward et al. 2017; Koks, Rozenberg, et al. 2019; Thacker, Kelly, et al. 2017; Kheradmand et al. 2018). Whilst the high spatial granularity of such assessments is very useful to inform adaptation prioritisation, the focus on economic cost-benefit approaches to reduce climate risk may not adequately represent the range of sustainability benefits of built or nature-based adaptation, such as protecting development progress towards energy access or contributing to biodiversity (Jafino et al. 2021).

To maximise synergies between adaptation and the SDGs in national adaptation needs assessments (Phase I), methods have been developed that 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 is critical to identify adaptation needs with the largest potential to safeguard and contribute to sustainable development.

To account for a broader range of sustainability dimensions in adaptation option evaluations (Phase II), feasibility assessments have been proposed that evaluate a wide range of different adaptation options across social, environmental, geographic, political, and economic dimensions (Singh et al. 2020; Williams et al. 2021). Yet, methods that consider the full range of benefits of adaptation options across various 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). Whilst methods have increasingly been developed to estimate the economic costs and benefits of nature-based options alongside built ones (Menéndez et al. 2020; Beck et al. 2018), 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, Metternicht, Wiedmann, and Pedercini 2019; Allen, Metternicht, Wiedmann, and Pedercini 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 methodology that allows national decision-makers to evaluate the total SDG benefit of adapting specific assets or areas against climate risk (see Figure 6.1). 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 SDG target co-benefits of adaptation options to protect these assets. By placing an SDG target vision at the outset of national adaptation assessments, this proposed methodology incorporates two main contributions. The first is a set of SDG-risk indicators, spatially translated to the asset-scale, which quantify where bio-physical adaptation needs are largest to safeguard a nation's SDG progress. The second is the creation of strategies of adaptation options, from both built and nature-based options, which are designed to meet these adaptation needs and which are evaluated for their ability to deliver SDG target co-benefits. An application of the proposed methodology to Ghana's energy and transport sector provides one important step in helping national decision-makers inform sustainable adaptation in the context of the global agendas, acknowledging 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 6.2 outlines the different steps of the proposed methodology in the context of acute climate-change hazards. Section 6.3 presents the data and materials used in its application to a national adaptation assessment for Ghana's energy and transport sector. Section 6.4 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 6.5 provides concluding remarks.

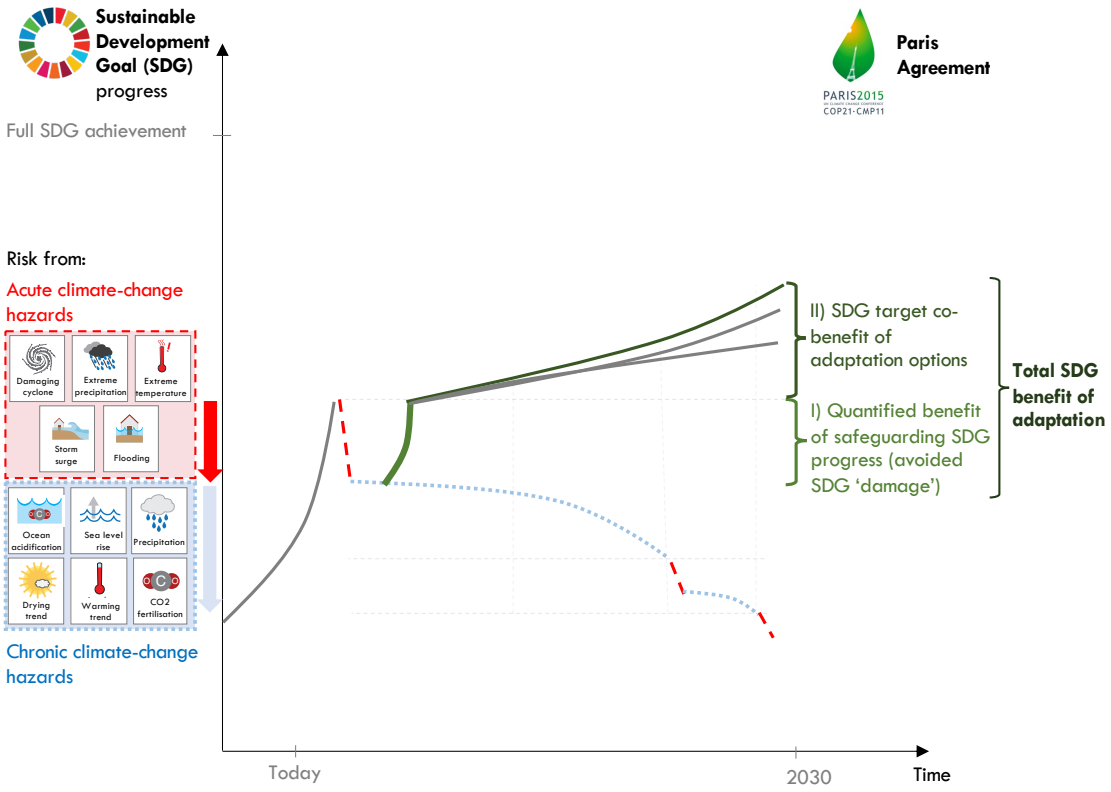


Figure 6.1: Identifying the total Sustainable Development Goal (SDG) benefit of adaptation, which includes: I) the quantified benefit of safeguarding SDG progress against risks from acute and chronic climate-change hazards (red and blue arrows and lines, respectively), in other words, the avoided SDG '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.

6.2 Methodology

Our proposed methodology for integrating SDG targets into the two main phases of national adaptation assessments involves four steps (Figure 6.2): (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 described in more detail (shown in green in Figure 6.2).

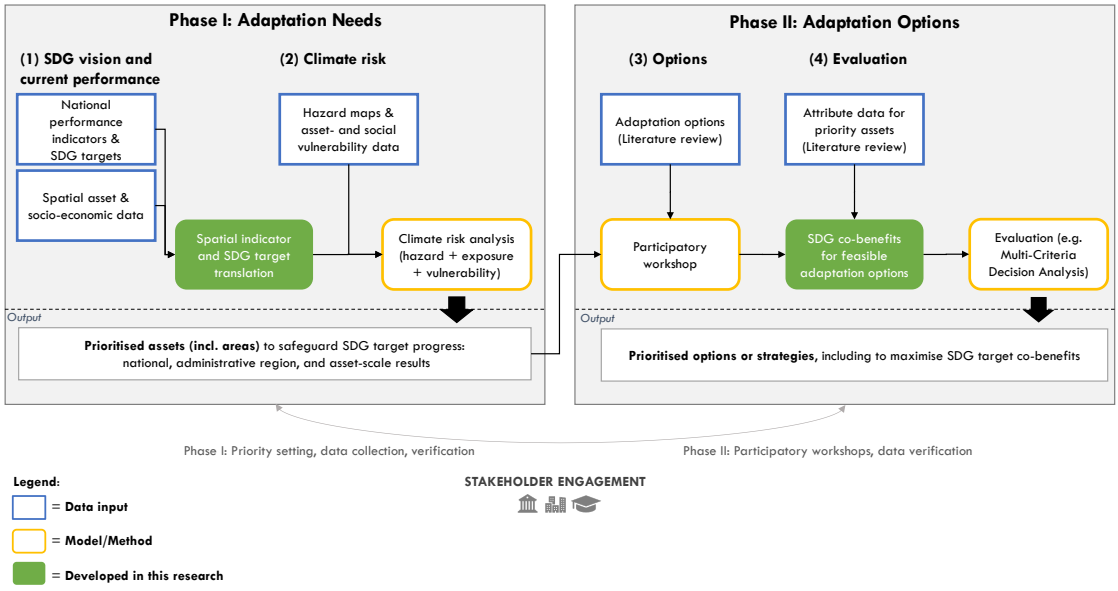


Figure 6.2: Integrating SDG targets in national adaptation assessments.

6.2.1 Phase (I) Adaptation needs

Step (1) SDG vision and current performance

The 169 SDG targets represent a global vision to guide sustainable development. At the national scale, the SDG targets are often operationalised through the formulation of sectoral development plans. 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, Thacker, Haggis, et al. n.d.); 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 service a sector provides, such as energy services. 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 service is provided in relation to desired national target levels. In the context of the three pillars of sustainability, assigning such indicators also requires the consideration of multiple sustainability dimensions which may include economic, environmental, and social dimensions (Allen, Metternicht, Wiedmann, and Pedercini 2019) or security of service provision, environmental, and accessibility dimensions (Adshead et al. 2019).

Previous work has described a framework of setting SDG performance indicators for different sector and sustainability dimensions that allows measuring current progress

towards a desired performance value (Adshead et al. 2019). The definition of a desired performance value in the SDG context may differ substantially depending on a nation's development context, and can be ascertained either through formalised sectoral development plans or in collaboration with stakeholders tasked with national interpretations of the SDG targets. The framework describes how a single performance indicator can be used to quantify progress on the given SDG target for those targets described in terms of a single sector and a single sustainability dimension. 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 overall energy generation mix in relation to a nationally-defined 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 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 accessibility, environmental, and service provision dimension (Adshead et al. 2019).

Here, we expand the above-described 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. By assigning socio-economic data to each asset (e.g. the amount of renewable energy generated by each asset), its contribution to national current baseline performance can be ascertained, which is denoted by a_s. For assets that serve a specific population, their contribution to national baseline performance may be derived by assigning spatially distributed populations to assets (see Thacker, Barr, et al. (2017) and Thacker, Pant, et al. (2017) for details of such techniques). The sum of the contribution of each geospatial 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 Equation 6.1:

$$I_s = \frac{B_s}{O_s}, \quad s = 1, \ldots, N \tag{6.1}$$

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 Equation 6.2:

$$\mathbf{w}_t = [w_{t,s=1}, w_{t,s=2}, \ldots, w_{t,s=N}], \quad t = 1, \ldots, M \tag{6.2}$$

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, Metternicht, and Wiedmann 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 Equation 6.3:

$$Z_t = \sum_{s=1}^{N} w_{t,s} I_s, \quad t = 1, \ldots, M \tag{6.3}$$

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

The 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 enable quantifying adaptation needs in the context of the SDG targets.

Step (2) Climate risk

Spatial climate risk analyses, also termed spatial adaptation assessments, are useful tools to help decision-makers identify and evaluate where and how hazard, exposure, and vulnerability intersect, thereby ascertaining adaptation priorities (IPCC 2014a; 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, Barr, et al. (2017) and Pant et al. (2016) for detailed descriptions of climate risk analysis). 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 $ae_{s,h}$. By summing across the contribution of all exposed assets for a certain sector/sustainability dimensions, it is possible to 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 Equation 6.4:

$$IE_{s,h} = \frac{BE_{s,h}}{O_s} \tag{6.4}$$

where

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

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 6.2.1 (Equation 6.5):

$$ZE_{t,h} = \sum_{s=1}^{N} w_{t,s} IE_{s,h} \quad t = 1, \ldots, M \tag{6.5}$$

6. Evaluating climate adaptation based on sustainable development targets

To provide a more holistic picture of climate risk, both asset- and social vulnerability should be considered alongside hazard exposure (Koks et al. 2015). Asset vulnerability can be integrated in the hazard exposure calculation using a sensitivity parameter $r_{a,s,h}$, which represents the sensitivity of asset a_s 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 0 refers to the asset ceasing to function under hazard h and 1 refers to the asset fully functioning under hazard h. Social vulnerability can, amongst other factors, be conceptualised using proxy indicators that capture factors such as a population's 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), and 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 can be assigned a social vulnerability value based on the social vulnerability proxy of the administrative region/district that asset serves. This in turn allows identifying administrative regions/districts and associated assets that provide the largest contribution to the indicator at-risk score $IR_{t,h}$ and SDG target at-risk score $ZR_{t,h}$.

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 assessments 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.

6.2.2 Phase (II) Adaptation options

Step (3) Options

No single adaptation option exists 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).

An initial literature and document review allows determining 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 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 feasibly be implemented in a given country.

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 potential direct and indirect influences of adaptation options on SDG targets, based on previously published service-SDG influences (Fuldauer, Thacker, Haggis, et al. n.d.). A systematic understanding of the potential influences of adaptation options before these are implemented can help decision-makers identify means to maximise positive influences and minimise potential trade-offs.

Previous work has identified how sectors of the built environment provide manufacturing, infrastructure, and social services that influences 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, Thacker, Haggis, et al. n.d.). 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 for a detailed step-by-step overview of the proposed co-benefits method and Supplementary Information Tab 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, 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 by an adaptation strategy – can represent a further performance metric during such evaluations. It 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)

6.3 Application to Ghana

6.3.1 Research design and test case

The proposed methodological contributions are applied to a recent adaptation assessment in Ghana (Adshead et al. n.d.). Ghana is strongly committed to contribute to global efforts towards sustainable development and to reduce the growing climate change impacts across sectors (Asante et al. 2015). Ghana's National Development Planning Commission was mandated to prepare medium and long-term (40-year) development plans to guide governmental efforts towards sustainability (Abubakari et al. 2018). Similarly, 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).

A participatory approach to data collection and analysis was adopted, which is essential for improving adaptation practice in developing countries (Conway et al. 2014) and which has been successfully applied to national infrastructure planning (Fuldauer et al. 2019; Adshead et al. 2021). A large proportion of key stakeholders and experts was consulted throughout a one-year research period, including from individuals across over 20 ministries and institutions, most notably including: Ministry of Environment, Science, Technology and Innovation (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; and the Centre for Remote Sensing and Geographic Information Services (CERSGIS). 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 to ensure data collection as well as data and result verification. The specific data collected and methods used in the Ghana application of the proposed methodology for Phase I and II are described in the following paragraphs.

6.3.2 Phase (I) Adaptation needs

With the aim of identifying an SDG vision, national performance indicators, and desired performance values under step (1) of the proposed methodology, the following key national development documents were reviewed: 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 the Africa SDG-aligned target year 2047 were identified, which were reduced to three performance indicators for which high-resolution geospatial data were available in Ghana 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 6.2).

The scope of geospatial asset and related socio-economic data utilised in this assessment included all currently existing assets for the specified sectors, as well as assets which are due to be completed by the end of 2021 (see Supplementary Table 6.3). Data confidence with each of these data values was encoded into an accompanying decision-support tool and database, which also details the methods used to assign baseline performance values spatially (see Supplementary Information Tab 2 for details).

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 6.3). 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 6.2.1, 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 methodology 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 as well as under a future timeline (2050) based on a regional climate projections under the A1B scenario (NADMO 2015). 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 Figure 6.3. 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 $\{0,1\}$. Social vulnerability data was integrated using data on the inverse of the adaptive capacity data at the level of the 216 districts and the current population numbers per district, which were subsequently assigned to the

respective energy or transport assets (see Supplementary Table 6.3 and Supplementary Information Tab 2 for details).

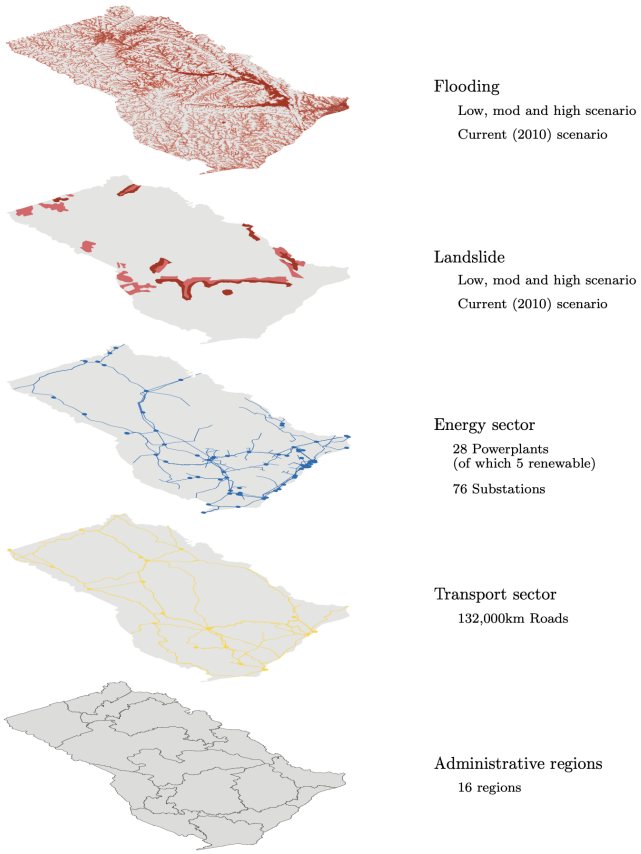


Figure 6.3: Superimposing the spatial footprint of climate-change hazards on spatial data across different sectors in order to derive results at the national, regional, and asset-scale.

6.3.3 Phase (II) Adaptation options

In order to derive proposed and suggested adaptation options under step (3) of the proposed methodology, 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 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. In total, 12 options were considered feasible by stakeholders for the assessed sectors (Supplementary Table 6.4).

Using the set of 12 feasible adaptation options for the considered sectors, the SDG co-benefit analysis method under step (4) of the proposed methodology 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 Tab 3).

6.4 Results

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.

6.4.1 Phase (I) Adaptation needs

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' (Figure 6.4). 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 equation 6.1, 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.

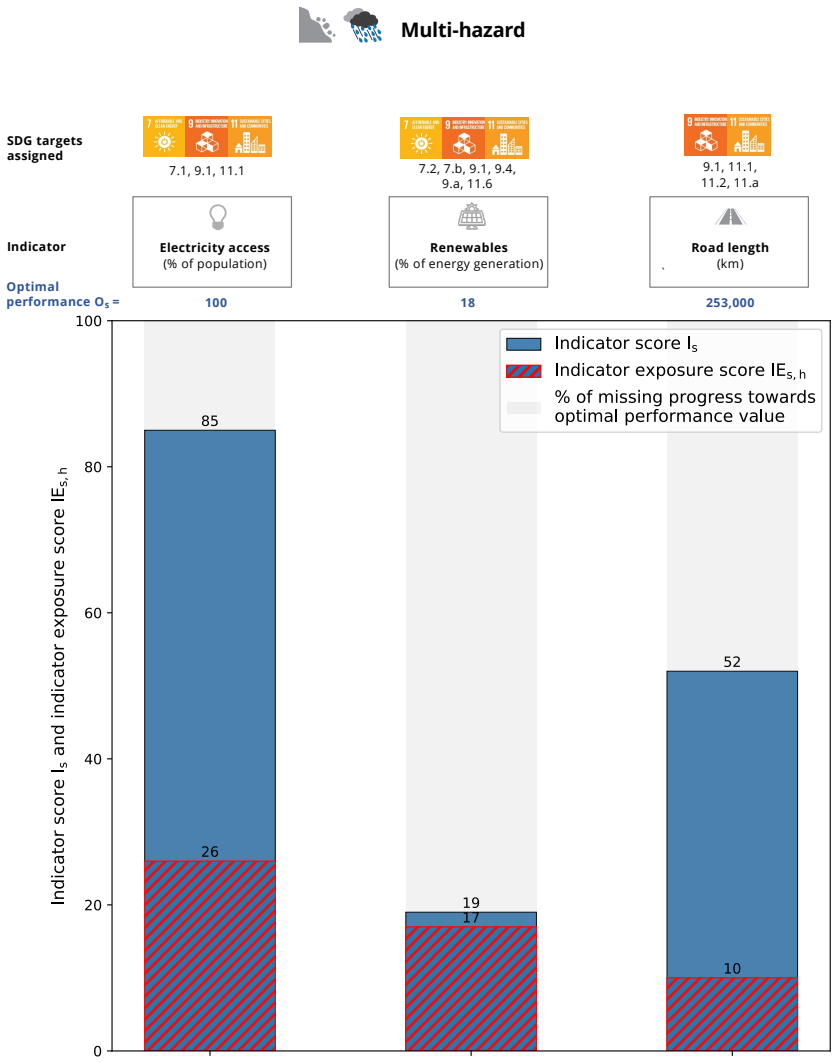


Figure 6.4: National performance indicator scores and national performance indicator scores exposed to multi-hazard.

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% (Figure 6.4) - 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% (Figure 6.4), 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 $ZE_{t,h}$) (Figure 6.5).

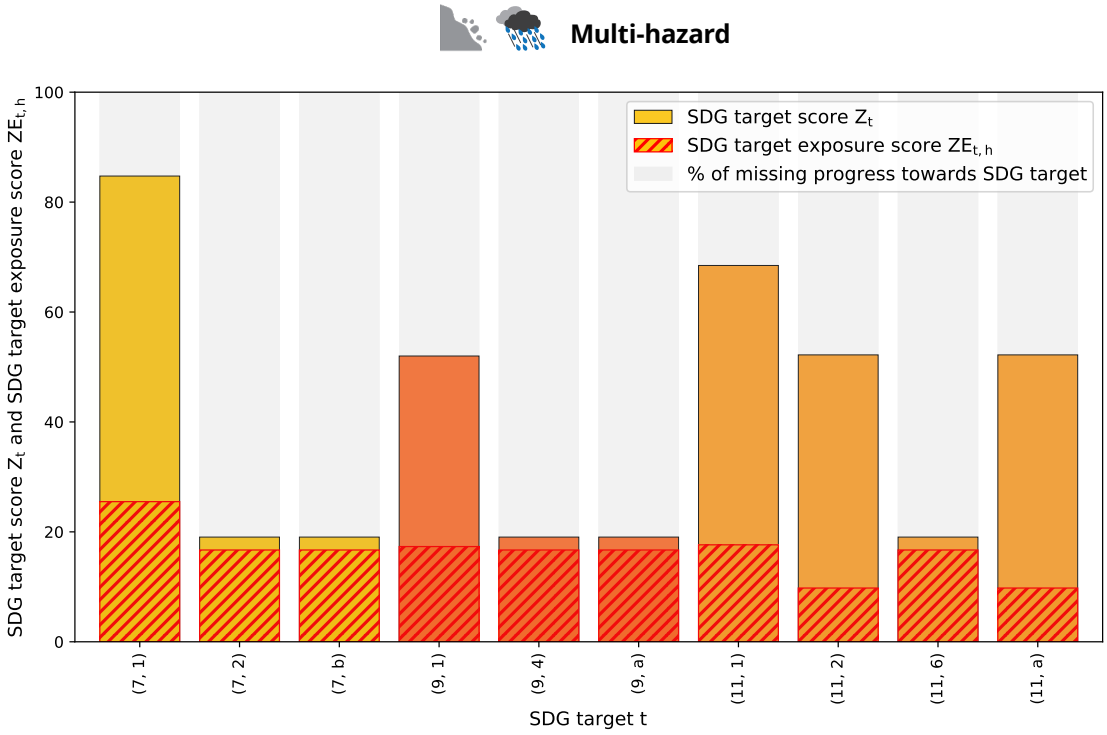


Figure 6.5: SDG target score, and SDG target score exposed to multi-hazard.

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 on sustainable development with regard to energy and transport.

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.

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 (Figure 6.6a). 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 (Figure 6.6b). When also considering the social vulnerability component of climate risk (Figure 6.6c), 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.

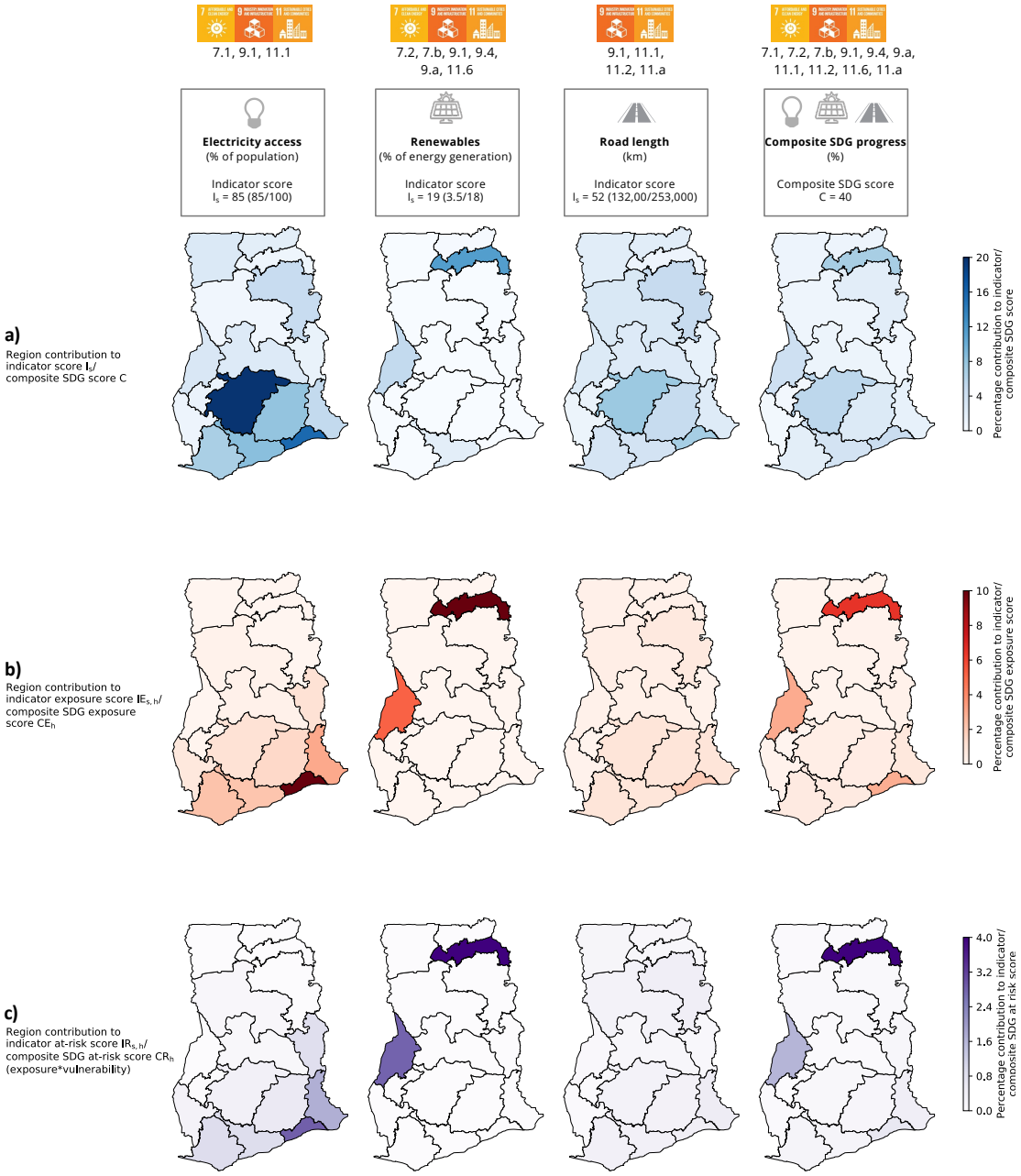


Figure 6.6: Spatial translation of adaptation needs in the context of three national performance indicators and a composite SDG score in Ghana, with the contribution of administrative regions to a) indicator and composite SDG score, (b) indicator and composite SDG exposure score, (c) indicator and composite SDG at-risk score.

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. Figure 6.7a-c shows the specific assets that play the largest role in safeguarding indicator progress at-risk, while Figure 6.7d shows those with largest contribution to composite SDG progress 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 Tab 2 for prioritised assets).

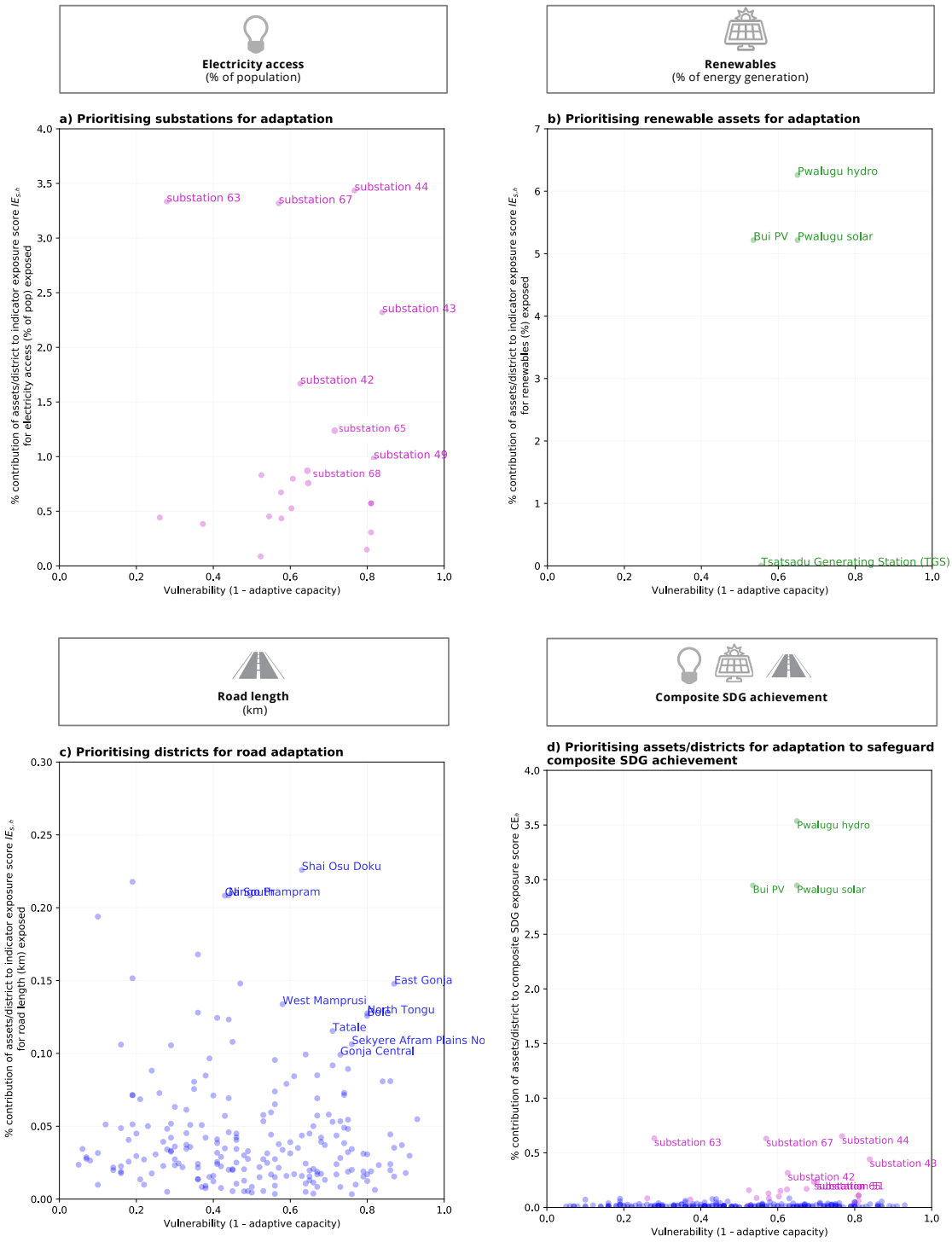


Figure 6.7: Prioritising assets to safeguard largest progress on the indicator and composite SDG target scores against climate risk, where (a)-(c) show asset contributions to indicator at-risk scores $IR_{t,s}$ and (d) shows asset contributions to composite SDG at-risk score CR_t (d). Axis scaled for visualisation purposes.

6.4.2 Phase (II) Adaptation options

A participatory workshop with the TWG and key national stakeholders resulted in the identification of a set of economically, technically, and politically feasible adaptation options to protect Ghana's prioritised Phase I assets against floods and landslides (Table 6.1). 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, combining built and nature-based adaptation options for the Phase I prioritised assets to meet the identified adaptation needs across sectors and across hazards.

Table 6.1: Overview of adaptation strategies which include combinations of adaptation options for prioritised assets (see Supplementary Information Tab 3 for application of co-benefits method to proposed adaptation options and links to specific prioritised assets).

Strategy	Hazard	Options	Sector(s)
Built	Flood	Elevation of assets	All
	Flood	Re-enforcing road structure	Road
	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, Energy: generation
	Flood	Urban green areas and trees	Road, Energy: distribution
	Landslides	Natural slope stabilisation	Energy: distribution
Combined SDG	Flood	Sponge city and urban drainage	All
	Flood	Construct temporary barriers	All
	Flood	Urban green areas and trees	Road, Energy: distribution
	Flood	Protection of riparian vegetation	All
	Landslides	Natural and built slope stabilisation	Energy: distribution

The relative performance of the built– versus nature-based strategy differs in relation to the total count of SDG co-benefits (see Figure 6.8). Whilst the built strategy can have SDG co-benefits across a total of 62 of 169 SDG targets, these co-benefits increase to 102 SDG target co-benefits under a nature-based strategy. The additional 65% of SDG target co-benefits by the nature-based strategy can be attributed to the multifunctionality 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 stabilisations 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 Figure 6.8a versus Figure 6.8b).

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.

6.5 Discussion

The methodological contributions developed here provide a systematic process by which to integrate national performance indicators and SDG targets quantitatively within spatial adaptation assessments. Conceptual research in the past has emphasised that adaptation has the potential to theoretically influence a range of SDG targets (Fuso Nerini et al.

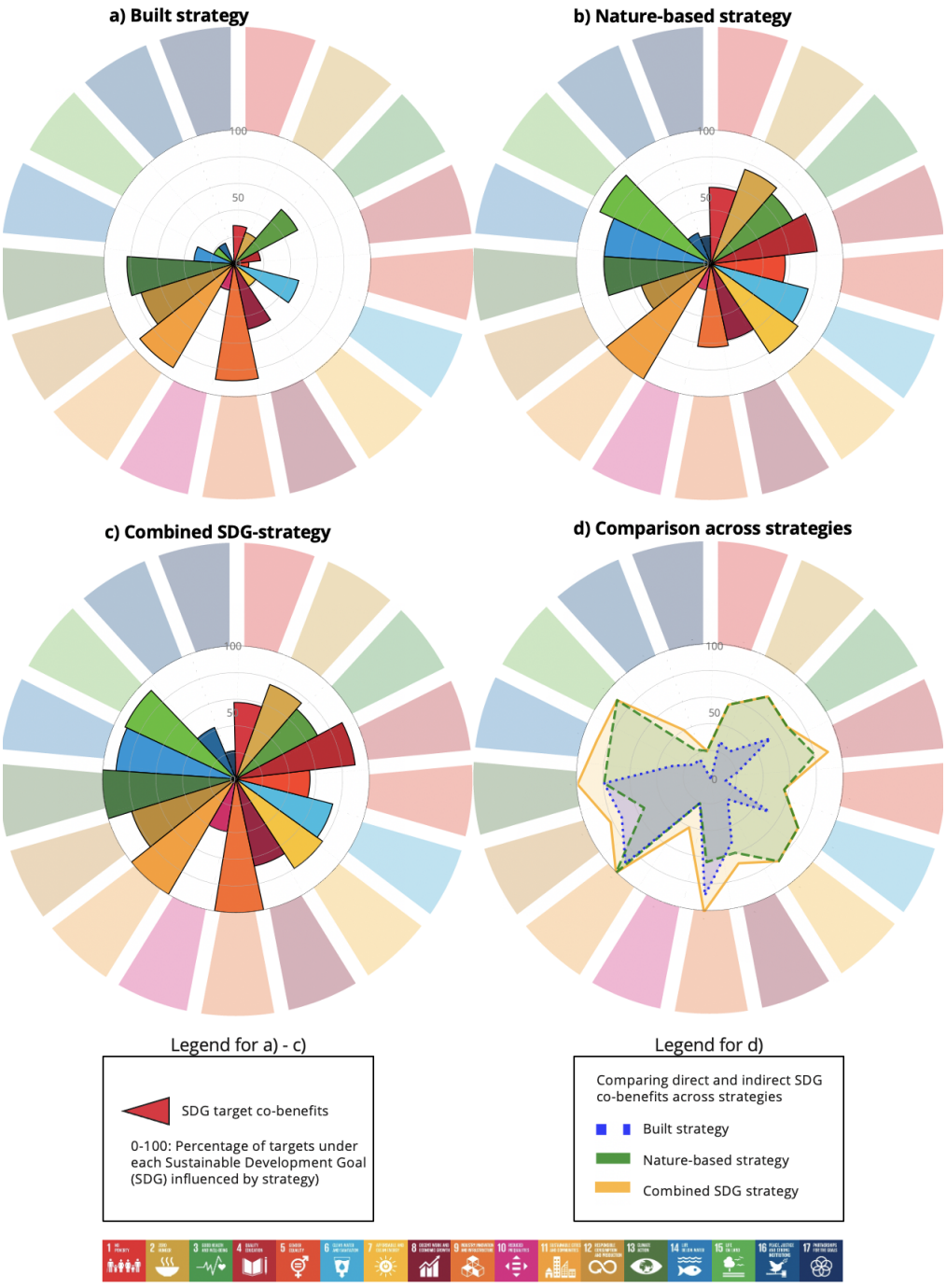


Figure 6.8: Evaluating SDG target co-benefits of adaptation strategies across the energy and transport sectors.

2019; Fuldauer, Thacker, Haggis, et al. n.d.), which has recently been spatially translated to incorporate the number of SDG targets that can be safeguarded through adapting specific assets (Fuldauer et al. 2021). Past research has also identified how adaptation options can contribute to the SDGs, focussing on nature-based adaptation options and

a broad goal level analysis (Gómez Martín et al. 2020). However, to date, no paper has demonstrated a methodology to quantitatively embed an SDG vision at the outset of adaptation needs assessments with the use of combined SDG-risk indicators, or to evaluate the full range of SDG target co-benefits of implementing alternative adaptation strategies. Such information is however critical for decision-makers to evaluate and maximise the full SDG benefits of adaptation in their national context.

6.5.1 Implications for adaptation in Ghana

While the application 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 bio-physical 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. Whilst service provision in these areas has improved over the past decades, this development progress is at risk of flooding impacts. This finding aligns with previous studies on the importance of building adaptive capacity in urban slums in Accra (Owusu et al. 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 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 sets of 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', 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, it was possible to add specificity to the broadly formulated options represented in national documents. The participatory nature of this methodological step allowed verifying resulting options as well as combining sets of feasible options under strategies, a critical factor to ensure the feasibility of adaptation implementation (Ford et al. 2017). Further, showcasing the range of potential SDG target co-benefits of these different adaptation strategies provided an important first step to illustrate the range of non-quantifiable benefits of adopting nature-based adaptation options in Ghana, 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). By identifying the broad range of all *potential* SDG influences of adaptation strategies at the outset of the adaptation planning process, it was possible to more systematically maximise these potential influences whilst minimising the potential maladaptive consequences of adaptation prominent in Ghana (Antwi-Agyei et al. 2018).

More broadly, establishing an SDG vision for 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 (Figure 6.6), it would also be 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 2019b; 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 methodology

developed here could 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).

6.5.2 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, Kelly, et al. 2017; 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 to meet increasing calls to link adaptation and sustainable development. 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, Thacker, Haggis, et al. n.d.).

More broadly, by integrating quantitative performance indicators linked to the SDG targets within 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). Thereby, it can maximise the potential of SDG-adaptation synergies.

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 for evaluating adaptation options (Tompkins et al. 2018; Owen 2020; Nalau et al. 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 should be seen as an additional metric that is evaluated alongside other metrics such as economic cost-benefit ratio (Thacker, Kelly, et al. 2017), feasibility criteria (Singh et al. 2020; Williams et al. 2021), implementation time, and others.

6.5.3 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 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 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. Future work should consider additional indicators and performance values for the 2030 timeline 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.

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 based on the arithmetic mean, following the approach adopted by the global SDG Index (Lafortune et al. 2018). One critical limitation of a linear aggregation approach 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 et al. (2019) for a discussion and implication of different weightings and to Booysen (2002) and the OECD and European Union Joint Research Centre (2008) for 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 approach for its simplicity of interpretation (see Lafortune et al. (2018) for details).

Third, the application of the proposed methodology 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, Rozenberg, et al. (2019)). Moreover, given that the scope of hazards considered 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 focused 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, Metternicht, Wiedmann, and Pedercini (2019), and Allen, Metternicht, Wiedmann, and Pedercini (2021)) as well as future hazard scenarios will be critical to complement the proposed methodological contributions towards identifying synergistic adaptation-development strategies that reduce future climate risk *and* advance the SDGs.

6.6 Conclusion

This paper proposed a methodology 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. An application 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 adaptation and development in Ghana. Iterative application of the proposed methodology 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. This paper demonstrates how integrating SDG targets at the outset of national adaptation assessments can help better evaluate adaptation strategies that contribute to both a climate-resilient and sustainable future.

Code availability

All Python source code can be requested from the corresponding author.

Supplementary Appendix and Supplementary Tables

Supplementary Appendix A: SDG target co-benefit method

First, each built adaptation option is assigned manufacturing, construction, wastewater management, or other built environment services based on the description of the option and stakeholder engagement (e.g. a seawall requires manufacturing and construction services). In contrast, each nature-based adaptation option is initially assigned to a certain type of natural environment which provides a multitude of ecosystem services simultaneously (see Fuldauer, Thacker, Haggis, et al. (n.d.)). This assignment can be derived from the wording of the adaptation option (e.g. the adaptation option 'afforestation' is assigned the type 'forest') or geospatial land-use maps surrounding the prioritised asset (e.g. for a generic adaptation option such as 'restoring nature', a land-use map might identify a degraded wetland surrounding a prioritised road, thereby assigning the option to the type 'wetland & peatland'). Using published literature and stakeholder knowledge, the multiple ecosystem services provided by that natural environment type are linked to the considered nature-based adaptation option (see Bateman et al. (2020)).

Second, each adaptation option - irrespective of its type - is assigned generic adaptation SDG influences, adopting prior influence definitions: an influence is identified whereby the SDG target is described in terms of the words 'adaptation' or 'resilience' (see Supplementary Information Tab 1 for all specific word strings).

Third, each built or nature-based adaptation option is assigned a spatial location, based on the asset it protects. A poverty or vulnerability map is used to identify if this spatial location refers to an area of high poverty/vulnerability according to national classifications. If the asset protected by the adaptation option lies in an area of high poverty/vulnerability, additional poverty-based SDG influences are identified for SDG targets described in terms of adaptation or resilience *and* poverty (see Supplementary Information Tab 1 for word strings).

Supplementary Tables

Supplementary Table 6.2: Overview of SDG target and indicator datasets collected for Phase I and related spatial infrastructure data used. Source: Ghana Infrastructure Plan (NDPC 2019c). D= dimension for indicator where SP = Service Provision and EN = Environmental dimension, following Adshead et al. (2019). * Consistent with the Ghana Infrastructure Plan, the spatial powerplant dataset was adjusted to define hydropower plants below 100MW as renewable, whilst those above 100MW are considered non-renewable (NDPC 2019a).

Sector	**National performance indicator (I_s)**	**D**	**Desired optimal performance value (2047) ($O_{t,s}$)**	**Related spatial infrastructure data**	**Directly aligned to SDG targets (t)**
Energy: Distribution	Electricity access (% of population)	SP	100	Substations, demand Voronoi	7.1, 9.1, 11.1
Energy: Generation	Renewables (% of energy generation)	EN	18	Renewables*, all powerplants	7.2, 7.b, 9.1, 9.4, 9.a,11.6
Road transport	Length of road network (km)	SP	253,000	OSM roads	9.1, 11.1, 11.2, 11.a

Supplementary Table 6.3: Geospatial asset and socio-economic data linked to baseline performance used in the Ghana adaptation assessment. Sources: [a)]The World Bank (2020), [b)]ECOWREX (2020), [c)]OSM (2020), [d)]NITA (2020), [e)]Geo-referenced from the EPA (2020, p.194), [f)]Geo-referenced from the District Energy Plan (Energy Commission 2019), [g)] Energy Commission (2020).

Geospatial data	**Number of assets**	**Unit**	**Related socio-economic data**	**Unit**
Energy: sub-stations	76[a)]	assets	Population with access to electricity[f)]	%
Renewable power plants	6[b)]	assets	Installed capacity[g)]	MW
Non-renewable power plants	23[b)]	assets	Installed capacity[b)]	MW
Roads	152,000[c)]	km	n/a	n/a
Districts	216[d)]	districts	Population number[d)]	People
Adaptive capacity	216[e)]	districts		
Administrative regions	16[d)]	regions	Population number[d)]	People

Supplementary Table 6.4: Overview of built and natural adaptation options assessed in Ghana, based on data obtained from the literature and participatory workshop. B= built; N=nature-based. See Supplementary Information Tab 3 for details.

Sector	**Hazard**	**Strategy type**	**Option name**
Cross-sectoral (Built)	Flood	B	Elevation of asset
Cross-sectoral (Built)	Flood	B	Construct temporary barrier
Cross-sectoral (Built)	Landslide	B	Built slope stabilisation (anchors/bolts)
Cross-sectoral (Natural)	Landslide	N	Natural slope stabilisation (natural terracing)
Cross-sectoral (Riverine)	Flood	N	Catchment-level water management
Cross-sectoral (Riverine)	Flood	N	Protection of riparian vegetation
Cross-sectoral (Riverine)	Flood	N	Urban green areas and trees
Cross-sectoral (Urban)	Flood	N/B	Sponge city measures
Cross-sectoral (Urban)	Flood	N/B	Urban drainage Greater Accra
Road transport	Flood	B	Re-enforcing road structure

7 Discussion and conclusions

Having presented three substantive chapters that concern the three components of conceptualising, assessing, and evaluating climate adaptation for sustainable development, the concluding chapter of this thesis is comprised of the following: a summary of the findings in light of the research questions posed; the main conceptual, methodological, and practical contributions of this thesis to the field of sustainable development and climate change research; a reflection of key limitations and suggestions for future research; and a call to action.

7.1 Thesis summary and main findings

The aim of this thesis was to investigate the complex links between sustainable development targets and climate change impacts to better inform climate adaptation planning in the context of the SDGs and the Paris Agreement. To address this aim, three research questions were identified: (1) How can the links between global sustainable development targets and climate change impacts be *conceptualised* at a scale useful to inform adaptation?; (2) How can the impacts of climate-change hazards on sustainable development targets be spatially *assessed* to inform national adaptation?; and (3) How can adaptation needs and options be *evaluated* based on sustainable development targets? These research questions were addressed through three substantive chapters, which have been accepted in, or submitted to, peer-reviewed journals in the form of first-author papers.

Research Question 1. With respect to Research Question 1, the first substantive chapter of this thesis (Chapter 4) proposed a *conceptual framework* to better understand how the relationship between the SDG targets and climate change impacts is mediated by socio-economic sectors and ecosystems and the services these provide. Populating the conceptual framework with the best available evidence demonstrated that all 169 SDG targets are potentially affected by the impacts of climate change. The finding on the magnitude of climate change impacts on SDGs targets inversely provided insight into the SDG benefit of adaptation. In this context, this chapter demonstrated the importance of ecosystems, which not only provide essential climate adaptation services, but also regulating, supporting, cultural, and provisioning services that complement and substitute socio-economic sectors in influencing 21% of SDG targets. An initial global application of the conceptual framework revealed that cross-sectoral adaptation of wetlands, rivers, cropland, construction, water, electricity, and housing in the most vulnerable countries is urgently required to safeguard the achievement of 68% of SDG targets from near-term sectoral risk by 2030. Chapter 4 concluded with five considerations for further applying and extending the conceptual framework: (1) Is the sector-SDG and sector-climate influence positive or negative?; (2) Is the current magnitude of the influence direction strong or weak?; (3) How robust is the influence?; (4) Where are gaps in our understanding of influences, including interdependent influences?; (5) Is the influence bi-directional? These five considerations are related to how the conceptual framework is operationalised to align climate adaptation planning under the Paris Agreement with the SDG targets, including using a climate-first or a development-first approach.

Research Question 2. With respect to Research Question 2, the second substantive chapter (Chapter 5) of this thesis operationalised the conceptual framework using a climate-first approach. The chapter *developed and applied a national-scale methodology* to spatially assess the impacts of climate-change hazards across all a nation's sectors and physical assets, and to understand how these impacts propagate and interact to influence SDG targets. In relation to the five considerations proposed in Chapter 4, the methodology included an estimation of the quantified magnitude of negative climate-sector as well as qualitative sector-SDG influences. Thereby, it focused on influences for which robust

evidence could be identified. Interdependent influences between sectors were accounted for qualitatively, and a uni-directional influence framing was adopted: from impacts of climate change via sectors to SDG targets. The developed methodology was applied to the small island Saint Lucia using real-world data from three climate-change hazards (storm surges, flash floods, and landslides), one multi-hazard, 24 national sectors and all of these sectors' physical assets, and the holistic set of 169 SDG targets. Due to its use of participatory methods, this application helped Saint Lucia's national decision-makers make the case for adaptation to safeguard sustainable development outcomes, and provided evidence on where and how to add spatial granularity and specificity to the country's existing National Adaptation Plan (NAP).

Research Question 3. With respect to Research Question 3, the third substantive chapter (Chapter 6) of this thesis operationalised the conceptual framework using a development-first approach, thereby grounding adaptation planning in an SDG vision. The chapter *developed and applied a national-scale methodology* to quantify the adaptation that is needed to safeguard SDG target progress, and to evaluate adaptation options to meet those needs whilst advancing SDG target co-benefits. In relation to the five considerations proposed in Chapter 4, the methodology included an estimation of a quantified magnitude of negative climate-sector influences as well as a quantified magnitude of existing positive sector-SDG influences. It focused on those influences for which robust evidence could be identified, integrating all three components of climate risks on sectors: hazards, exposure, and vulnerability. Further, the chapter presented new methods for identifying bi-directional influences, including how working backwards from SDG targets can provide insights for adaptation to both reduce risk *and* maximise SDG target co-benefits. Due to the use of participatory methods and national development plans to define desired sustainable development outcomes, the methodology is transferable to a range of contexts. In this case, the application to Ghana's energy and transport sector enabled national stakeholders to discuss and evaluate a broad set of built and nature-based adaptation options to reduce climate risk from flooding and landslides and safeguard existing SDG progress. The methodology application showed how adopting a combined adaptation strategy of both built and nature-based options can advance 116 SDG target co-benefits,

knowledge of which can help reduce maladaptive outcomes. By highlighting evidence of the potential SDG benefits of adaptation, the application provided a useful starting point to discuss how much and what type of adaptation could be implemented to align Ghana's adaptation commitments under the Paris Agreement with sustainable development.

7.2 Conceptual and methodological contributions

Beyond addressing the research questions, this thesis makes a number of conceptual and methodological contributions to the field of sustainable development and climate adaptation.

7.2.1 The role of sectors in adaptation for sustainable development

The importance of adopting a sector-scale. Conceptualising the role of sectors in mediating between achievement of sustainable development targets and impacts of climate change has been a major theme throughout this thesis. Chapter 1 and 2 demonstrated that socio-economic sectors and ecosystems can have a profound influence on achievement of sustainable development outcomes through the provision of essential services. At the same time, these chapters highlighted the increasing evidence that climate-change hazards can expose sectors and threaten service provision, thereby stalling progress on development. The understanding of *how* sectors, and the services these provide, interact and propagate to influence both development outcomes and responses to climate change impacts however required further analysis. Based on content analyses and evidence mapping of influences, the conceptual framework developed in this thesis provided a comprehensive evidence base to identify potential links between sectors and the SDG targets, as well as how these sectors are potentially affected by the impacts of climate change. Results highlighted the value of considering the scale of socio-economic sectors and ecosystems: adopting a sector scale allowed for a more nuanced understanding of the potential impacts of climate change on the SDGs as compared with previous literature in the field. When accounting for direct and indirect influences, this thesis demonstrated that the impacts of climate change can affect all 169 SDG targets, compared

to the previous finding that 72 SDG targets might be undermined by the impacts of climate change (Fuso Nerini et al. 2019).

Spatially translating the role of sectors. Whilst knowledge on potential influences between sectors, sustainable development targets, and impacts of climate change is useful, it requires further methodological developments and analysis if it is to be utilised to align national adaptation planning with the global goals in practice. The two national-scale methodologies proposed in this thesis advanced this knowledge by demonstrating how it is possible to spatially translate SDG targets and indicators to the scale of sectors' assets. This asset-scale enabled a new granularity and specificity for informing climate adaptation planning in the context of each SDG target. Using real-world asset data collected and verified in multi-stakeholder partnerships, the application of these national-scale methodologies demonstrably showed the usefulness of creating spatial maps to visualise climate impacts on the SDGs. Notably, these spatial maps visualised 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 in Chapter 5.

7.2.2 Towards more holistic climate adaptation assessments

Integrating sustainability and climate assessments. Bringing together assessments from the sustainable development and climate change literature has been a major component of this thesis. As described in Chapter 2, despite various similarities in assessing needs and options in both the sustainable development as well as the climate change literature, few studies have developed integrated conceptualisations or methodologies. Each of the three substantive chapters in this thesis has highlighted the value of bringing together the field of sustainable development with that of climate adaptation, which can make an important contribution towards more synergistic research and action.

Addressing sectoral interdependencies. As detailed in Chapter 2, traditional approaches that characterise most sustainable development and climate change adaptation assessments do not typically consider the range of interdependencies between sectors in achieving sustainable and climate-resilient outcomes. Each substantive chapter in this

thesis has considered the interdependencies between sectors in delivering services that are integral to achieving sustainable development targets, but that are also affected by, and can support in adapting to, climate change impacts. Building on both SDG influences as well as spatial climate risk assessments, the holistic approach taken in this thesis helped identify where attention to interdependent influences is required. The importance of ecosystems, nature-based adaptation options, and strong governance arrangements were highlighted as essential cross-sectoral components of safeguarding sustainable development in the face of climate change impacts.

7.2.3 Adopting flexible and iterative plans

Flexible planning. Planning for a sustainable and climate-resilient world inherently requires acknowledging the uncertain future states of the world. Rather than being constrained by data-intensive processes contained in adopting methods to deal with deeply uncertain futures, various studies reviewed in Chapter 2 propose focusing on adaptation options that are sensible now and likely beneficial in the future. Thereby, adaptation planning can move forward irrespective of the climate and development outlook, incorporating flexibility, iteration and monitoring throughout the adaptation planning process. Whilst the national-scale methodologies developed in this thesis allow integration with future climate and development outlooks, their application to Saint Lucia and Ghana emphasised the usefulness of adopting a flexible, iterative approach to adaptation planning in the case of data scarcity and uncertain futures. Adopting such a flexible and iterative approach to adaptation planning was considered particularly important in cases where future projections of climate change often cannot be resolved at a scale amenable to inform decisions. Therefore, the primary value of methodology applications in this thesis was to showcase the use of an adaptation planning process and accompanying decision-support tool that can be updated as data and conditions evolve. The methodology applications thereby provide a first estimate of national-scale adaptation prioritisation that can guide further detailed assessments at local scale. The formalised steps inherent in the methodologies can help increase depoliticise decisions and increase transparency, a key determinant of good decision-making as identified in Chapter 2.

7.3 Practical applications of the research

Along with its conceptual and methodological contributions, this thesis was conducted with an action research component and therefore included the objective of demonstrating an application of improving adaptation planning and decision-making in practice. By putting stakeholder engagement at the heart of the two test cases used in this thesis, it was possible to co-develop decision-support tools that can be used to underpin adaptation decision-making in practice. This action research component resulted in a number of real-world applications of the research, both in Saint Lucia and in Ghana.

Saint Lucia. In the small island of Saint Lucia, the newly-created National Integrated Planning and Programme Unit (NIPP) in the Department of Finance was established and assigned the responsibility to, amongst other tasks, conduct climate adaptation planning and continuously update the decision-support tool developed in this thesis (Government of Saint Lucia 2019a). Together with the NIPP team, the process of conducting the research brought together stakeholders across siloed ministries, thereby exchanging and centralising knowledge as well as collecting and standardising data across sectors. The data collection effort included manually creating a storm surge map based on existing digital elevation data, adding spatial information to 126 assets in Saint Lucia, and assigning quantitative socio-economic information to 33 assets. Data was standardised across a total of 725 socio-economic and ecosystem assets, which was combined in the decision-support tool. This decision-support tool, including its user guide and video tutorial, enabled decision-makers and analysts to view and update asset and hazard data as well as perform a hazard exposure assessment. A workshop on the tool demonstrably allowed national stakeholders across the public and private sector to engage with the data and results of the adaptation assessments to help guide future adaptation planning (Saint Lucia Times 2020). An accompanying report, backed by the Prime Minister, detailed how the results of the adaptation assessment can help add spatial granularity and specificity to Saint Lucia's comprehensive NAP, in a manner aligned with the SDGs (Government of Saint Lucia 2020; Adshead, Roman, et al. 2020).

Ghana. In Ghana, the methodology application to the nation's energy and transport sector formed part of a broader adaptation needs and options assessment that demonstrates the country's regional leadership in climate-resilient and sustainable adaptation planning (Adshead et al. n.d.). Led by the Ministry of Environment, Science, Technology and Innovation, the assessment brought together stakeholders from separate ministries, NGOs, the private sector and academia through multi-stakeholder partnerships and remote workshops. These partnerships and workshops provide the foundation for iterative updating of adaptation assessments into the future. The participatory nature of the methodology application has enabled stakeholders in Ghana to discuss a broad set of 58 built and nature-based adaptation options, of which 12 were considered particularly feasible in the context of Ghana's energy and transport sectors. Some of these options aligned with existing proposed options, whilst others built on best practices documented throughout the world. The development of a decision-support tool, with its accompanying user guide, enabled participants that were not able to join in-country meetings to engage with the standardised and centralised geospatial data and results of this research. A national adaptation assessment report, endorsed by Ghana's environment minister, entails key analyses that can be used as a basis to align adaptation with the global agendas.

National adaptation planning and transferability. As more countries revise their adaptation commitments under the Paris Agreement, a large opportunity exists to ensure climate adaptation safeguards and advances sustainable development. By applying methodologies to both assess and evaluate adaptation in the context of the SDG targets, the research presented in this thesis helped deliver depoliticised evidence to shape and prioritise adaptation decisions in practice. Whilst the small size of Saint Lucia provided a contained environment in which it was possible to engage with all national decision-makers and assess climate impacts on all sectors, transferring such a holistic adaptation assessment to larger developing countries might be restrained by data availability and logistical problems with regard to stakeholder engagement (see Chapter 5). The Ghana application showed how such problems might be overcome in larger nations, by integrating fewer sectors and building on existing initiatives such as Ghana's cross-sectoral geospatial unit.

7.4 Limitations and future research

Several opportunities exist to improve upon the conceptual, methodological, and practical research presented in this thesis, which are described below.

Conceptualisation and definitions used. The conceptualisations of climate change impacts, sustainable development, and sectors used in this thesis reflect practical and globally accepted definitions by international bodies, which however are amenable to different national interpretations. Notably, this thesis conceptualised sustainable development in normative terms through the global SDGs and their targets, acknowledging that these were politically determined and might imperfectly represent all dimensions of sustainable development (see McGowan et al. (2019) for discussion). Further, the services provided by sectors were based on international classifications where possible, yet, ecosystems are interrelated and the relationship between natural assets and services is non-linear, highly complex, and not well understood (Maseyk et al. 2017). Future research might update the framework with additional impacts of climate change, post-SDG targets, and updated conceptualisations of sectors and the services these provide.

More dynamic and extensive evidence mapping. The conceptual framework developed in this thesis was largely populated with the available evidence base on influences. Future research might use machine learning algorithms to help dynamically identify and georeference evidence of influences to enable regional or country comparisons. A dynamic global evidence platform, as is available for nature-based solutions (University of Oxford 2020), could bring together existing evidence of influences across both the global South and North. This requires field work and qualitative research to collect additional positive and negative evidence of influences, including from less represented areas and voices. Further research is also needed to understand how sectors are affected by chronic climatic impact-drivers, for which less evidence was available. Thereby, the importance of climate stressors as opposed to non-climatic stressors in affecting sectors should be highlighted. A holistic evidence mapping exercise of the role of sectors in SDG achievement, climate mitigation *and* climate adaptation could play an essential role towards achieving low-carbon and climate-resilient development pathways.

Methodology development. The methodologies developed as part of this thesis helped operationalise the proposed conceptual framework via a spatial lens, focusing on the bio-physical dimension of adaptation needs and options in the context of the SDG targets. Assessing social and financial adaptation alongside bio-physical ones are considered useful extensions of the work presented in this thesis. Additional methodology is needed to capture all five considerations in applying the conceptual framework as proposed in Chapter 4. Notable, this includes examining potential gaps in our understanding of the links between the SDG targets and impacts from climate change: the influence of chronic climatic impact-drivers, potential self-reinforcing loops, negative sector-SDG influences, and cascading impacts.

Data. The application of the proposed conceptual framework and national-scale methodologies inevitably lacked perfect data. Opportunities to expand upon the research presented in this thesis include integrating additional hazard scenarios, future asset data, or additional SDG indicators. High-resolution data allows for more dynamic modelling of the impacts of current and future hazard scenarios on the SDGs, nationally and eventually globally.

Informing adaptation in the context of the global agendas. This thesis made a conceptual, methodological, and practical contribution to informing climate adaptation in the context of the SDGs and the Paris Agreement. The contributions in this thesis could be expanded to account for targets and indicators related to other global agendas. These include, amongst others: the Sendai Framework for Disaster Risk Reduction, which is comprised of seven global targets on preventing new and reducing existing disaster risk (UNISDR 2015); the Aichi Biodiversity Targets that aim to safeguard ecosystem services (CBD 2011); or targets of the New Urban Agenda, which are focused on improved human settlement planning for sustainable development in the face of uncertain climate futures (United Nations 2017).

Transferability. The conceptual framework and methodologies in this thesis are global in nature and can, in principle, be applied to any nation. Provided sufficient quality and quantity of data is available, the mathematical formulations and python codes developed as part of the national-scale methodologies in this thesis are transferable to

other contexts. The participatory processes that are part of these methodologies can also be transferred to other nations. Yet, given that these participatory processes place national decision-makers and stakeholders at the heart of the data collection, verification, and the adaptation planning process, they may be less applicable in some countries. This is likely to be the case in those countries hampered by weak governance structures, corruption, or little interest in transparent decision-making. No single answer to these issues exists. Additional research and further national-scale applications can provide one useful means by which to identify and overcome potential barriers with respect to transferability, further expanding upon the methodologies presented in this thesis.

Participation. The participatory methods that lie at the heart of the methodology applications are prone to participant sample, author positionality, and the potential influence of outside organisations. The adaptation options considered feasible as part of the methodology application in this thesis are largely based on participants able to attend the workshops, their background and interest, as well as who is heard in stakeholder engagements. Whilst care was taken to engage stakeholder representing the interest of the private sector, the public sector, and communities, further research is needed that invites a larger range of stakeholders reflective of the population in adaptation options evaluations.

Community-driven, iterative adaptation planning. Unless the voices of marginalised and indigenous peoples are explicitly considered, applications of the proposed conceptual and methodological contributions in this thesis are unlikely to results in sustainable adaptation implementation. Community-driven research, alongside site-specific adaptation option evaluations, is needed to ensure that the identified potential positive outcomes of adaptation for sustainable development can be realised in practice and 'leave no one behind'. Iterative cycles of adaptation planning and adaptation implementation are important to identify what has been achieved, and where additional work is required. This necessitates better monitoring and evaluation, which qualitatively and quantitatively describes the realised impacts of adaptation on all components of climate risk *and* sustainable development targets. Mechanisms must be put in place to ensure that negative impacts, especially on the most vulnerable, can be addressed.

7.5 Towards climate-resilient and sustainable action

The year 2015 marked a turning point in the world's efforts towards achieving a more sustainable and climate-resilient future. Two key global agendas were adopted by the majority of national governments: the SDGs and the Paris Agreement on Climate Change. Whilst adopted independently, success in delivering on the shared vision of the two agendas requires synergistic action that addresses both development and climate goals in a coordinated and integrated manner. To date, nations are not on track to meeting either of these two key global agendas.

Some progress has been made in certain areas of sustainable development. Yet, this progress is at risk. This is partly due to climate change, but also the degradation of ecosystems and the essential services these provide. Without explicit efforts to reverse these trends, efforts to achieve sustainable development will stall, leaving behind the most vulnerable and least developed countries. Although current efforts to achieve the SDGs and address the impacts of climate change are insufficient, there is still time for action. To ensure that this action synergistically addresses development and climate goals, planning and implementation must be better aligned and better resourced.

Alignment between the SDG targets and *climate mitigation* is emerging, at global and national levels. Yet, alignment between the SDG targets and *climate adaptation* is under-researched and under-explored to date. With the frequency and severity of climate-change hazards increasing and the impacts becoming ever more interdependent and disproportionately affecting the most vulnerable, there is a clear need for methodologies and real-world applications to shape climate adaptation for sustainable development. This thesis makes a contribution to integrating desired sustainability outcomes into adaptation planning, placing the global development agendas at the core of more holistic and formalised adaptation assessments. Adopting a holistic assessment helps to bring to light the essential, yet often ignored, role that ecosystems play in complementing and substituting all other socio-economic sectors to deliver on the SDGs *and* to adapt to climate change. Embracing a more formalised adaptation assessment at the scale

of sectors and assets helps decision-makers to identify specific adaptation options that advance, rather than detract from, progress on sustainable development.

The decade of the 2020s offers an opportunity to put in place holistic and formalised adaptation assessments towards achieving the shared vision of the global agendas. As more nations around the world update their adaptation commitments under the Paris Agreement, integrating more holistic and formalised assessments at the core of adaptation decision-making can help safeguard and advance the SDGs. This requires a transition towards overcoming siloed practices within governments and within sectors. It also requires building capacity through collaborations in broader partnerships including local communities, academia, governments, and businesses. Yet, unless the world scales up the ambition to build the much-needed climate resilience for sustainable development, it risks reversing hard-earned development gains. This thesis underscores the need for synergistic action towards both sustainable development *and* adaptation goals to ensure a healthy planet and a good life for all, now and into the future.

Bibliography

Abubakari, M., P. K. B. Asamoah, and F. O. Agyemang (2018). "Ghana and Sustainable Development: The 40-Year National Development Plan in Retrospective". In: *Journal of Human Resource and Sustainability Studies* 06.01, pp. 24–36. DOI: 10.4236/jhrss.2018.61024.

Acemoglu, D. and J. A. Robinson (2013). *Why Nations Fail: The Origins of Power, Prosperity, and Poverty*. London: Profile Books.

Acheampong, E. N., N. Ozor, and E. S. Owusu (2014). "Vulnerability assessment of Northern Ghana to climate variability". In: *Climatic Change* 126.1-2. DOI: 10.1007/s10584-014-1195-z.

Adaptation Committee (2016). *Tenth meeting of the Adaptation Committee Bonn, Germany, 13-16 September 2016 Methodologies for assessing adaptation needs with a view to assisting developing country Parties, without placing an undue burden on them*. Tech. rep. Bonn, Germany: AdaptationCommittee2016.

Adger, W. N. et al. (2011). "Resilience implications of policy responses to climate change". In: *WIREs Climate Change* 2, pp. 757–766. DOI: 10.1002/wcc.133.

Adger, W. N. (2006). "Vulnerability". In: *Global Environmental Change* 16.3, pp. 268–281. DOI: 10.1016/J.GLOENVCHA.2006.02.006.

Adger, W. N., I. Brown, and S. Surminski (2018). "Advances in risk assessment for climate change adaptation policy". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2121, pp. 1–13. DOI: 10.1098/rsta.2018.0106.

Adger, W. N., S. Huq, K. Brown, D. Conway, and M. Hulme (2003). "Adaptation to climate change in the developing world". In: *Progress in Development Studies* 3, pp. 179–195. DOI: 10.1191/1464993403ps060oa.

Adger, W. N. and P. M. Nelly (1999). "Social vulnerability to climate change and the architecture of entitlements". In: *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1023/A:1009601904210.

Adger, W. et al. (2007). "Assessment of adaptation practices, options, constraints and capacity". In: *Climate change 2007: Impacts, adaptation and vulnerability.* Vol. 2. Intergovernmental Panel on Climate Change, pp. 719–743.

Adshead, D., L. Fuldauer, et al. (2020). *Saint Lucia: National Infrastructure Assessment*. Tech. rep. Copenhagen, Denmark: United Nations Office for Project Services.

Adshead, D., O. R. García, S. Thacker, and J. W. Hall (2021). "Infrastructure strategies for achieving the global development agendas in small islands". In: *Earth's Future* 9.2. DOI: 10.1029/2020EF001699. URL: https://onlinelibrary.wiley.com/doi/10.1029/2020EF001699.

Adshead, D., O. Roman, S. Thacker, F. Felix, and L. Fuldauer (2020). *Long-term strategic infrastructure planning model for Saint Lucia*. Tech. rep. Oxford, UK: University of Oxford and United Nations Office for Project Services.

Adshead, D., S. Thacker, L. Fuldauer, and J. W. Hall (2019). "Delivering on the Sustainable Development Goals through long-term infrastructure planning". In: *Global Environmental Change* 59, p. 101975. DOI: 10.1016/j.gloenvcha.2019.101975.

Adshead et al. (n.d.). *Ghana Resilient Infrastructure Roadmap. In Preparation.* Tech. rep. Accra, Ghana: University of Oxford, Global Centre on Adaptation, the Ministry of Environment, Science, Technology, and Innovation.

Aerts, J. C., W. J. Botzen, K. Emanuel, N. Lin, H. De Moel, and E. O. Michel-Kerjan (2014). *Climate adaptation: Evaluating flood resilience strategies for coastal megacities*. DOI: 10.1126/science.1248222.

Alawadi, K. and S. Dooling (2016). "Challenges and opportunities for participatory planning approaches within Dubai's urban context". In: *Journal of Urbanism: International Research on Placemaking and Urban Sustainability* 9.3, pp. 276–301. DOI: 10.1080/17549175.2015.1045924.

Allen, C., G. Metternicht, and T. Wiedmann (2018). "Initial progress in implementing the Sustainable Development Goals (SDGs) – A review of evidence from countries". In: *Sustainability Science* 14.5, pp. 1453–1467. DOI: 10.1007/s11625-018-0572-3.

Allen, C., G. Metternicht, T. Wiedmann, and M. Pedercini (2019). "Greater gains for Australia by tackling all SDGs but the final steps will be the most challenging". In: *Nature Sustainability* 2.11, pp. 1041–1050. DOI: 10.1038/s41893-019-0409-9.

Allen, C., G. Metternicht, and T. Wiedmann (2017). "An Iterative Framework for National Scenario Modelling for the Sustainable Development Goals (SDGs)". In: *Sustainable Development* 25.5, pp. 372–385. DOI: 10.1002/sd.1662.

— (2019). "Prioritising SDG targets: assessing baselines, gaps and interlinkages". In: *Sustainability Science* 14.2, pp. 421–438. DOI: 10.1007/s11625-018-0596-8.

— (2021). "Priorities for science to support national implementation of the sustainable development goals: A review of progress and gaps". In: *Sustainable Development* 29.4, pp. 635–652. DOI: 10.1002/SD.2164.

Allen, C., G. Metternicht, T. Wiedmann, and M. Pedercini (2021). "Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states". In: *Global Sustainability* 4.e15, pp. 1–13. DOI: 10.1017/SUS.2021.13.

Allison, E. H. et al. (2009). "Vulnerability of national economies to the impacts of climate change on fisheries". In: *Fish and Fisheries* 10.2, pp. 173–196. DOI: 10.1111/j.1467-2979.2008.00310.x.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer (1976). *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*. Tech. rep. URL: https://pubs.usgs.gov/pp/0964/report.pdf.

Andrijevic, M., J. Crespo Cuaresma, R. Muttarak, and C. F. Schleussner (2020). "Governance in socioeconomic pathways and its role for future adaptive capacity". In: *Nat. Sustain.* 3.1, pp. 35–41. DOI: 10.1038/s41893-019-0405-0.

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

Antwi-Agyei, P., A. J. Dougill, and L. C. Stringer (2017). "Assessing Coherence between Sector Policies and Climate Compatible Development: Opportunities for Triple Wins". In: *Sustainability* 9, p. 2130. DOI: 10.3390/su9112130.

Antwi-Agyei, P., A. J. Dougill, L. C. Stringer, and S. N. A. Codjoe (2018). "Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana". In: *Climate Risk Management* 19, pp. 83–93. DOI: 10.1016/j.crm.2017.11.003.

Antwi-Agyei, P., E. D. Fraser, A. J. Dougill, L. C. Stringer, and E. Simelton (2012). "Mapping the vulnerability of crop production to drought in Ghana using rainfall, yield and socioeconomic data". In: *Applied Geography* 32.2, pp. 324–334. DOI: 10.1016/J.APGEOG.2011.06.010.

Apuri, I., K. Peprah, and G. T. W. Achana (2018). "Climate change adaptation through agroforestry: The case of Kassena Nankana West District, Ghana". In: *Environmental Development* 28, pp. 32–41. DOI: 10.1016/J.ENVDEV.2018.09.002.

Asante, F. A. and F. Amuakwa-Mensah (2015). "Climate Change and Variability in Ghana: Stocktaking". In: *Climate* 3.1, pp. 78–99. DOI: 10.3390/CLI3010078.

Bailey, R. W., M. Gorlach, and A. Arbor (1986). "English as a World Language". In: *RELC J.* 17, pp. 91–96.

Ballard, D. (2005). "Using learning processes to promote change for sustainable development". In: *Action Research* 3.2, pp. 135–156. DOI: 10.1177/1476750305052138.

Barnett, J. and S. O'Neill (2010). "Maladaptation". In: *Global Environmental Change* 20.2, pp. 211–213.
Barnett, J., J. Campbell, C. Change, S. Island, and S. Power (2010). *Climate Change and Small Island States*. London: Routledge. DOI: 10.4324/9781849774895.
Bateman, I. J. and G. M. Mace (2020). "The natural capital framework for sustainably efficient and equitable decision making". In: *Nature Sustainability* 3.10, pp. 776–783. DOI: 10.1038/s41893-020-0552-3.
Beck, M. W., I. J. Losada, P. Menéndez, B. G. Reguero, P. Díaz-Simal, and F. Fernández (2018). "The global flood protection savings provided by coral reefs". In: *Nature Communications* 9.1, pp. 1–9. DOI: 10.1038/s41467-018-04568-z.
Beg, N. et al. (2002). "Linkages between climate change and sustainable development". In: *Climate Policy* 2.2, pp. 129–144. DOI: 10.3763/cpol.2002.0216.
Bennich, T., N. Weitz, and H. Carlsen (2020). "Deciphering the scientific literature on SDG interactions: A review and reading guide". In: *Science of The Total Environment* 728, p. 138405. DOI: 10.1016/J.SCITOTENV.2020.138405.
Benzies, K. M., S. Premji, K. A. Hayden, and K. Serrett (2006). "State-of-the-Evidence Reviews: Advantages and Challenges of Including Grey Literature". In: *Worldviews on Evidence-Based Nursing* 3.2, pp. 55–61. DOI: 10.1111/j.1741-6787.2006.00051.x.
Berrang-Ford, L., J. D. Ford, and J. Paterson (2011). "Are we adapting to climate change?" In: *Global Environmental Change* 21.1, pp. 25–33. DOI: 10.1016/j.gloenvcha.2010.09.012.
Berrang-Ford, L., T. Pearce, and J. D. Ford (2015). "Systematic review approaches for climate change adaptation research". In: *Reg Environ Change*. DOI: 10.1007/s10113-014-0708-7.
Biagini, B., R. Bierbaum, M. Stults, S. Dobardzic, and S. M. McNeeley (2014). "A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility". In: *Global Environmental Change* 25.1, pp. 97–108. DOI: 10.1016/j.gloenvcha.2014.01.003.
Bizikova, L., J. Robinson, and S. Cohen (2007). "Climate Policy Linking climate change and sustainable development at the local level". In: *Climate Policy* 7.4, pp. 271–277. DOI: 10.1080/14693062.2007.9685655.
Bjurström, A. and M. Polk (2011). "Physical and economic bias in climate change research: a scientometric study of IPCC Third Assessment Report". In: *Climatic Change 2011 108:1* 108.1, pp. 1–22. DOI: 10.1007/S10584-011-0018-8.
Blicharska, M., R. J. Smithers, G. Mikusiński, P. Rönnbäck, P. A. Harrison, M. Nilsson, and W. J. Sutherland (2019). "Biodiversity's contributions to sustainable development". In: *Nat. Sustain.* 2.12, pp. 1083–1093. DOI: 10.1038/s41893-019-0417-9.
Bogaart, P. et al. (2019). *Discussion paper 1.1: An ecosystem type classification for the System of Environmental Economic Accounting - Ecosystem Accounting Areas*. Tech. rep. URL: https://seea.un.org/sites/seea.un.org/files/documents/EEA/seea_eea_revision_wg1_discussion_paper_1.1_classification_ecosystemtypes.pdf.
Böhringer, C. and A. Löschel (2006). "Computable general equilibrium models for sustainability impact assessment: Status quo and prospects". In: *Ecological Economics* 60.1, pp. 49–64. DOI: 10.1016/J.ECOLECON.2006.03.006.
Booysen, F. (2002). "An Overview and Evaluation of Composite Indices of Development". In: *Social Indicators Research* 59.2, pp. 115–151. DOI: 10.1023/A:1016275505152. URL: https://link.springer.com/article/10.1023/A:1016275505152.
Bradfield, R., G. Wright, G. Burt, G. Cairns, and K. Van Der Heijden (2005). "The origins and evolution of scenario techniques in long range business planning". In: *Futures* 37.8, pp. 795–812. DOI: 10.1016/j.futures.2005.01.003.
Breuer, A., H. Janetschek, and D. Malerba (2019). "Translating Sustainable Development Goal (SDG) Interdependencies into Policy Advice". In: *Sustainability* 11.7, p. 2092. DOI: 10.3390/SU11072092.
Briner, S., C. Elkin, R. Huber, and A. Grêt-Regamey (2012). "Assessing the impacts of economic and climate changes on land-use in mountain regions: A spatial dynamic

modeling approach". In: *Agriculture, Ecosystems and Environment* 149, pp. 50–63. DOI: 10.1016/j.agee.2011.12.011.
Brooks, N., W. N. Adger, and P. M. Kelly (2005). "The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation". In: *Global Environmental Change*. DOI: 10.1016/j.gloenvcha.2004.12.006.
Brown, C. (2011). *Decision-Scaling for Robust Planning and Policy under Climate Uncertainty*. Tech. rep. Washington D.C.: International Research Institute for Climate and Society of Columbia University. URL: http://www.worldresourcesreport.org/files/wrr/papers/wrr_brown_uncertainty.pdf.
Burke, M., S. M. Hsiang, and E. Miguel (2015). "Global non-linear effect of temperature on economic production". In: *Nature* 527.7577, pp. 235–239. DOI: 10.1038/nature15725.
Burton, I. (1993). *The environment as hazard*. New York: Guilford Press.
Burton, I., S. Huq, B. Lim, O. Pilifosova, and E. L. F. Schipper (2002). "From impacts assessment to adaptation priorities: the shaping of adaptation policy". In: *Climate Policy* 2.2-3, pp. 145–159.
Butler, J. R. A. et al. (2016). "Climate Risk Management Scenario planning to leap-frog the Sustainable Development Goals: An adaptation pathways approach". In: *Climate Risk Management* 12, pp. 83–99. DOI: 10.1016/j.crm.2015.11.003.
Byrd, D. M. and R. C. Cothern (2000). *Introduction to risk analysis: a systematic approach to science-based decision making*. Government Institutes.
Cai, W., C. Clapp, I. Das, S. Perkins-Kirkpatrick, A. Thomas, and J. E. Tierney (2021). "Reflections on weather and climate research". In: *Nature Reviews Earth & Environment* 2.1, pp. 9–14. DOI: 10.1038/s43017-020-00123-x.
Cairns, G., I. Ahmed, J. Mullett, and G. Wright (2013). "Scenario method and stakeholder engagement: Critical reflections on a climate change scenarios case study". In: *Technological Forecasting and Social Change* 80.1, pp. 1–10. DOI: 10.1016/j.techfore.2012.08.005.
Caniglia, G. et al. (2020). *A pluralistic and integrated approach to action-oriented knowledge for sustainability*. DOI: 10.1038/s41893-020-00616-z.
Carleton, T. A. and S. M. Hsiang (2016). "Social and economic impacts of climate". In: *Science* 9.353, p. 6304. DOI: 10.1126/science.aad9837.
Carmin, J., I. Anguelovski, and D. Roberts (2012). "Urban Climate Adaptation in the Global South". In: *Journal of Planning Education and Research* 32, pp. 18–32. DOI: 10.1177/0739456x11430951.
Carter, T., M. Parry, H. Harasawa, and S. Nishioka (1994). *Intergovernmental Panel on Climate Change Technical Guidelines for Assessing Climate Change Impacts and Adaptation*. Tech. rep. London: University College London and Center for Global Envrionmental Research.
CBD (2011). *Aichi Biodiversity Targets*. Tech. rep. Convention on Biological Diversity.
Central Statistical Office of Saint Lucia (2018). *Economy: Trade statistics*. URL: https://www.stats.gov.lc/subjects/economy/.
Challinor, A. J., W. N. Adger, T. G. Benton, D. Conway, M. Joshi, and D. Frame (2018). "Transmission of climate risks across sectors and borders". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2121. DOI: 10.1098/rsta.2017.0301.
Charim (2016). *Caribbean Handbook on Risk Information Management*. URL: http://www.charim.net/Zero-a.
Chatterton, P., D. Fuller, and P. Routledge (2008). "Relating Action to Activism: Theoretical and Methodological Reflections". In: *Participatory Action Research Approaches and Methods: Connecting People, Participation and Place*. London: Routledge, pp. 216–22.
Chausson, A. et al. (2020). "Mapping the effectiveness of nature-based solutions for climate change adaptation". In: *Global Change Biology* 26.11, pp. 6134–6155. DOI: 10.1111/gcb.15310.

Chester, M. V., B. S. Underwood, and C. Samaras (2020). "Keeping infrastructure reliable under climate uncertainty". In: *Nature Climate Change* 10.6, pp. 488–490. DOI: 10.1038/s41558-020-0741-0.

Cohen, F., C. J. Hepburn, and A. Teytelboym (2019). "Is Natural Capital Really Substitutable?" In: *Annual Review of Environment and Resources* 44.1, pp. 425–448. DOI: 10.1146/annurev-environ-101718-033055. URL: https://www.annualreviews.org/doi/10.1146/annurev-environ-101718-033055.

Cohen-Shacham, E., C. Janzen, S. Maginnis, and G. Walters (2016). *Nature-based solutions to address global societal challenges*. Tech. rep. Gland: International Union for Conservation of Nature. DOI: 10.2305/IUCN.CH.2016.13.EN.

Collste, D., M. Pedercini, and S. E. Cornell (2017). "Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies". In: *Sustainability Science* 12.6, pp. 921–931. DOI: 10.1007/S11625-017-0457-X.

Commission for Africa (2005). *Our Common Interest: An Argument*. London: Penguin UK.

Conway, D. and J. Mustelin (2014). "Strategies for improving adaptation practice in developing countries". In: *Nature Climate Change* 4.5, pp. 339–342. DOI: 10.1038/nclimate2199.

Conway, D. et al. (2019). "The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions". In: *Nature Climate Change* 9, pp. 503–511. DOI: 10.1038/s41558-019-0502-0.

Cutter, S. (1993). *Living with risk: the geography of technological hazards*. London: Edward Arnold.

Cutter, S., B. J. Boruff, and W. L. Shirley (2003). "Social vulnerability to environmental hazards". In: *Social Science Quarterly* 84.1, pp. 242–261. DOI: 10.1111/1540-6237.8402002.

Cutter, S., C. T. Emrich, D. P. Morath, and C. M. Dunning (2013). "Integrating social vulnerability into federal flood risk management planning". In: *Journal of Flood Risk Management* 6.4, pp. 332–344. DOI: 10.1111/JFR3.12018.

Cutter, S., J. Mitchell, and M. Scott (2000). "Revealing the vulnerability of people and places: A case study of georgetown county, South Carolina". In: *Annals of the Association of American Geographers* 90.4, pp. 713–737. DOI: 10.1111/0004-5608.00219.

D'Agostino, G. and A. Scala (2014). *Networks of Networks: The Last Frontier of Complexity Science*. Berlin: Springer.

Daly, H. and J. Cobb (1989). *For the Common Good: Redirecting the Economy Towards Community, the Environment and a Sustainable Future*. London: Green Print, pp. 267–27.

Dasgupta, P. (2020). *The Dasgupta Review-Independent Review on the Economics of Biodiversity Interim Report*. Tech. rep. London: HM Treasury.

Dawson, R. et al. (2018). "A systems framework for national assessment of climate risks to infrastructure". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2121. DOI: 10.1098/rsta.2017.0298.

Dell, M., B. F. Jones, and B. A. Olken (2012). "Temperature Shocks and Economic Growth: Evidence from the Last Half Century". In: *American Economic Journal: Macroeconomics* 4.3, pp. 66–95. DOI: 10.1257/mac.4.3.66.

Denton, F. et al. (2015). "Climate-resilient pathways: Adaptation, mitigation, and sustainable development". In: *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*. Ed. by C. Field et al. United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1101–1131. DOI: 10.1017/CBO9781107415379.025.

De Sherbinin, A. (2014). "Climate change hotspots mapping: What have we learned?" In: *Climatic Change* 123.1, pp. 23–37. DOI: 10.1007/s10584-013-0900-7.

Dessai, S., M. Hulme, R. Lempert, R. Pielke, S. Dessai, and M. Hulme (2009). "Climate prediction: a limit to adaptation. Adapting to climate change: thresholds, values, governance". In: *Adapting to climate change: thresholds, values, governance.* Pp. 64–78. DOI: http://dx.doi.org/10.1017/CBO9780511596667.006.

Dessai, S. and M. Hulme (2004). "Does climate adaptation policy need probabilities?" In: *Climate Policy* 4.2, pp. 107–128. DOI: 10.1080/14693062.2004.9685515.
Dewar, J., C. Builder, W. Hix, and M. Levin (1993). *Assumption-based planning: a planning tool for very uncertain times*. Tech. rep. Rand Corporation Santa Monica CA.
Díaz, S. et al. (2018). "Assessing nature's contributions to people". In: *Science* 359.6373, pp. 270–272. DOI: 10.1126/science.aap8826.
Díaz, S. et al. (2019). "Pervasive human-driven decline of life on Earth points to the need for transformative change". In: *Science* 366.6471. DOI: 10.1126/SCIENCE.AAX3100.
Diaz-Sarachaga, J. M., D. Jato-Espino, and D. Castro-Fresno (2018). "Is the Sustainable Development Goals (SDG) index an adequate framework to measure the progress of the 2030 Agenda?" In: *Sustainable Development* 26.6, pp. 663–671. DOI: 10.1002/SD.1735.
Dilling, L. and M. C. Lemos (2011). "Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy". In: *Global Environmental Change* 21.2, pp. 680–689. DOI: 10.1016/J.GLOENVCHA.2010.11.006.
Dovie, B. (2015). *Ghana's intended Nationally Determined Contributions (iNDCs) 2020-2030: Options Paper on Adaptation*. Tech. rep. Accra, Ghana: MESTI.
Eakin, H. and M. C. Lemos (2006). "Adaptation and the state: Latin America and the challenge of capacity-building under globalization". In: *Global Environmental Change* 16, pp. 7–18. DOI: 10.1016/j.gloenvcha.2005.10.004.
ECOWREX (2020). *Spatial Data Infrastructure*. URL: http://www.ecowrex.org/page/maps.
Edwards, P. E., A. E. Sutton-Grier, and G. E. Coyle (2013). "Investing in nature: Restoring coastal habitat blue infrastructure and green job creation". In: *Marine Policy* 38, pp. 65–71. DOI: 10.1016/j.marpol.2012.05.020.
EEA (2018). *Common International Classification of Ecosystem Services (CICES)*. URL: https://cices.eu/.
Eisenack, K., R. Stecker, D. Reckien, and E. Hoffmann (2012). "Adaptation to climate change in the transport sector: A review of actions and actors". In: *Mitigation and Adaptation Strategies for Global Change* 17.5, pp. 451–469. DOI: 10.1007/s11027-011-9336-4.
Eisenack, K. et al. (2014). *Explaining and overcoming barriers to climate change adaptation*. DOI: 10.1038/nclimate2350.
Emerson, K., T. Nabatchi, and S. Balogh (2012). "An Integrative Framework for Collaborative Governance". In: *Journal of Public Administration Research and Theory* 22.1, pp. 1–29. DOI: 10.1093/JOPART/MUR011.
Energy Commission (2019). *Energy Profile of Districts in Ghana*. Tech. rep. Accra, Ghana: Energy Commission Ghana.
— (2020). *2020 Energy (Supply and Demand) Outlook for Ghana*. Tech. rep. Accra, Ghana: Energy Commission Ghana. URL: http://cleancookstoves.org/binary-data/RESOURCE/file/000/000/83-1.pdf.
EPA (2015). *Ghana's Third National Communication Report to the UNFCCC*. Tech. rep. Accra, Ghana: Environmental Protection Agency, p. 240. URL: https://unfccc.int/resource/docs/natc/ghanc3.pdf.
— (2020). *Ghana's Fourth National Communication to the United Nations Framework Convention on Climate Change*. Tech. rep. Accra, Ghana: Environmental Protection Agency.
Eriksen, S. et al. (2021). "Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance?" In: *World Development* 141, p. 105383. DOI: 10.1016/j.worlddev.2020.105383.
Eriksen, S. et al. (2011). "When not every response to climate change is a good one: Identifying principles for sustainable adaptation". In: *Climate and Development* 3, pp. 7–20. DOI: 10.3763/cdev.2010.0060.

European Environment Agency (2021). *Climate-Adapt*. Brussels, Belgium. URL: https://climate-adapt.eea.europa.eu/.

Fairclough, N. (2010). *Critical Discourse Analysis: The Critical Study of Language*. Oxford, UK: Routledge.

Fankhauser, S. and T. K. McDermott (2014). "Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries?" In: *Global Environmental Change* 27.1, pp. 9–18. DOI: 10.1016/j.gloenvcha.2014.04.014.

Fekete, A., K. Tzavella, and •. Roland Baumhauer (2017). "Spatial exposure aspects contributing to vulnerability and resilience assessments of urban critical infrastructure in a flood and blackout context". In: *Natural Hazards* 86, pp. 151–176. DOI: 10.1007/s11069-016-2720-3.

Feyen, L., R. Dankers, K. Bódis, P. Salamon, and J. I. Barredo (2012). "Fluvial flood risk in Europe in present and future climates". In: *Climatic Change* 112.1, pp. 47–62. DOI: 10.1007/S10584-011-0339-7. URL: https://link.springer.com/article/10.1007/s10584-011-0339-7.

Fidelman, P. I., A. M. Leitch, and D. R. Nelson (2013). "Unpacking multilevel adaptation to climate change in the Great Barrier Reef, Australia". In: *Global Environmental Change* 23.4, pp. 800–812. DOI: 10.1016/J.GLOENVCHA.2013.02.016.

Field, C. et al. (2014). "Technical summary". In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: IPCC.

Fitter, A. H. (2013). "Are Ecosystem Services Replaceable by Technology?" In: *Environmental and Resource Economics 2013 55:4* 55.4, pp. 513–524. DOI: 10.1007/S10640-013-9676-5.

Ford, J. D., L. Cameron, J. Rubis, M. Maillet, D. Nakashima, A. C. Willox, and T. Pearce (2016). "Including indigenous knowledge and experience in IPCC assessment reports". In: *Nature Climate Change* 6.4, pp. 349–353. DOI: 10.1038/nclimate2954.

Ford, J. D., J. Labbé, M. Flynn, and M. Araos (2017). "Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada". In: *Climatic Change* 145.1, pp. 85–100. DOI: 10.1007/S10584-017-2071-4.

Ford, J. D., T. Pearce, F. Duerden, C. Furgal, and B. Smit (2010). "Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation". In: *Global Environmental Change* 20.1, pp. 177–191. DOI: 10.1016/j.gloenvcha.2009.10.008.

Forestry Department Saint Lucia (2009). *Land-use map*. Castries, Saint Lucia.

Forsyth, T. (2007). "Promoting the "Development Dividend" of Climate Technology Transfer: Can Cross-sector Partnerships Help?" In: *World Development* 35.10, pp. 1684–1698. DOI: 10.1016/J.WORLDDEV.2007.06.001.

Frieler, K. et al. (2017). "Assessing the impacts of 1.5°C global warming-simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b)". In: *Geosci. Model Dev* 10, pp. 4321–4345. DOI: 10.5194/gmd-10-4321-2017.

Fritz, S. et al. (2019). "Citizen science and the United Nations Sustainable Development Goals". In: *Nature Sustainability* 2.10, pp. 922–930. DOI: 10.1038/s41893-019-0390-3. URL: https://doi.org/10.1038/s41893-019-0390-3.

Fukuda-Parr, S. (2014). "Global Goals as a Policy Tool: Intended and Unintended Consequences". In: *Journal of Human Development and Capabilities* 15.2-3, pp. 118–131. DOI: 10.1080/19452829.2014.910180.

Fuldauer, L., D. Adshead, S. Thacker, S. Gall, N. Chow, and J. Hall (n.d.). "Evaluating the benefits of national adaptation to climate risks in the context of the Sustainable Development Goals". In: *Under Review at Global Environmental Change* ().

Fuldauer, L., M. C. Ives, D. Adshead, S. Thacker, and J. W. Hall (2019). "Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals". In: *Journal of Cleaner Production* 223, pp. 147–162. DOI: 10.1016/j.jclepro.2019.02.269.

Fuldauer, L., S. Thacker, R. Haggis, F. Fuso Nerini, R. Nicholls, and J. Hall (n.d.). "Targeting climate adaptation to safeguard and advance the Sustainable Development Goals". In: *Under Review at Nature Communications. Preprint for Version 1 available.* (). DOI: 10.21203/rs.3.rs-235355/v1.

Fuldauer, L., S. Thacker, and J. Hall (2021). "Informing national adaptation for sustainable development through spatial systems modelling". In: *Global Environmental Change* 71.11.

Fünfgeld, H. and D. Mcevoy (2011). *Framing Climate Change Adaptation in Policy and Practice*. Tech. rep. Melbourne: Victorian Centre for Climate Change Adaptation Research, pp. 1–65.

Funtowicz, S. O. and J. R. Ravetz (1993). "Science for the post-normal age". In: *Futures* 25.7, pp. 739–755.

Funtowicz, S. and J. Ravetz (1990). *Uncertainty and quality in science for policy*. Dordrecht, The Netherlands: Springer.

Fuso Nerini, F. et al. (2018). "Mapping synergies and trade-offs between energy and the Sustainable Development Goals". In: *Nature Energy* 3.10-15, p. 2018. DOI: 10.1038/s41560-017-0036-5.

Fuso Nerini, F. et al. (2019). "Connecting climate action with other Sustainable Development Goals". In: *Nature Sustainability* 2.8, pp. 674–680. DOI: 10.1038/s41893-019-0334-y. URL: http://dx.doi.org/10.1038/s41893-019-0334-y.

Füssel, H. M. (2007). "Vulnerability: A generally applicable conceptual framework for climate change research". In: *Global Environmental Change* 17, pp. 155–167. DOI: 10.1016/j.gloenvcha.2006.05.002.

Gao, J. and B. C. O'Neill (2020). "Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways". In: *Nature Communications* 11.1, pp. 1–12. DOI: 10.1038/s41467-020-15788-7. URL: https://doi.org/10.1038/s41467-020-15788-7.

Garg, A., R. C. Dhiman, S. Bhattacharya, and P. R. Shukla (2009). "Development, malaria and adaptation to climate change: A case study from India". In: *Environmental Management* 43.5, pp. 779–789. DOI: 10.1007/S00267-008-9242-Z.

GCA (2021). *State and Trends in Adaptation Report 2021: Africa*. Tech. rep. Rotterdam, NL: Global Centre on Adaptation. URL: https://gca.org/reports/state-and-trends-in-adaptation-report-2021/.

Glade, T. and K. Elverfeldt (2005). "MultiRISK: an innovative concept to model natural risks". In: *Landslide risk management*. CRC Press, pp. 561–566.

Glass, L.-M. and J. Newig (2019). "Governance for achieving the Sustainable Development Goals: How important are participation, policy coherence, reflexivity, adaptation and democratic institutions?" In: *Earth System Governance* 2, p. 100031. DOI: 10.1016/J.ESG.2019.100031.

Gómez Martín, E., R. Giordano, A. Pagano, P. van der Keur, and M. Máñez Costa (2020). "Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals". In: *Science of The Total Environment* 738, p. 139693. DOI: 10.1016/J.SCITOTENV.2020.139693.

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)". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2119. DOI: 10.1098/rsta.2016.0444.

Government of Saint Lucia (2017a). *Economic and social review*. Tech. rep. Castries, Saint Lucia. URL: https://www.stats.gov.lc/wp-content/uploads/2018/06/2017-ESR.pdf.

— (2017b). *Third National Communication on Climate Change for Saint Lucia*. Tech. rep. Castries, Saint Lucia.

— (2018). *National Adaptation Plan Saint Lucia*. Tech. rep. Castries, Saint Lucia.

— (2019a). *NIPP Unit Launched*. URL: http://www.govt.lc/news/nippunit-%0Alaunched.%0A.

Government of Saint Lucia (2019b). *Saint Lucia Voluntary Review Report of the implementation of the 2030 Agenda for Sustainable Development*. Tech. rep. Castries, Saint Lucia: Sustainable Development United Nations. URL: https://sustainabledevelopment.un.org/content/documents/23570SAINT_LUCIA_VNR_REPORT_JUNE_2019.pdf.

— (2020). *National Infrastructure Assessment completed.* Tech. rep. Castries, Saint Lucia. URL: http://www.govt.lc/news/national-infrastructure-assessment-completed.

Greco, S., A. Ishizaka, M. Tasiou, and G. Torrisi (2018). "On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness". In: *Social Indicators Research* 141.1, pp. 61–94. DOI: 10.1007/S11205-017-1832-9. URL: https://link.springer.com/article/10.1007/s11205-017-1832-9.

Griggs, D. et al. (2014). "An integrated framework for sustainable development goals". In: *Ecology and Society*. DOI: 10.5751/ES-07082-190449.

Groves, D. and R. Lempert (2007). "A new analytic method for finding policy-relevant scenarios". In: *Global Environmental Change* 17.1, pp. 73–85. DOI: 10.1016/j.gloenvcha.2006.11.006.

Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. ter Maat (2013). "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world". In: *Global Environmental Change*. DOI: 10.1016/j.gloenvcha.2012.12.006.

Haasnoot, M., H. Middelkoop, A. Offermans, E. V. Beek, and W. P. A. V. Deursen (2012). "Exploring pathways for sustainable water management in river deltas in a changing environment". In: *Climatic Change* 115, pp. 795–819. DOI: 10.1007/s10584-012-0444-2.

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

Hall, J. et al. (2019). *Adaptation of Infrastructure Systems: Background Paper for the Global Commission on Adaptation*. Tech. rep. Oxford: Environmental Change Institute.

Hall, J. and D. Solomatine (2008). "A framework for uncertainty analysis in flood risk management decisions". In: *International Journal of River Basin Management* 6.2, pp. 85–98.

Hall, N. and Å. Persson (2017). "Global climate adaptation governance: Why is it not legally binding?" In: *European Journal of International Relations* 24.3, pp. 540–566. DOI: 10.1177/1354066117725157.

Hallegatte, S. (2009). "Strategies to adapt to an uncertain climate change". In: *Global Environmental Change* 19.2, pp. 240–247. DOI: 10.1016/j.gloenvcha.2008.12.003.

Hallegatte, S., A. Shah, R. Lempert, C. Brown, and S. Gill (2012). *Investment decision making under deep uncertainty: Application to climate change*. Tech. rep. 6193. Washington, D.C.: The World Bank, p. 41. DOI: doi:10.1596/1813-9450-6193. URL: https://elibrary.worldbank.org/doi/pdf/10.1596/1813-9450-6193.

Hallegatte, S., M. Bangalore, L. Bonzanigo, et al. (2016). *SHOCK WAVES Climate Change and Development Series Managing the Impacts of Climate Change on Poverty*. Tech. rep. World Bank.

Hallegatte, S., M. Bangalore, and A. Vogt-Schilb (2016). "Socioeconomic Resilience: Multi-Hazard Estimates in 117 Countries". Washington D.C.

Halonen, M. et al. (2017). *Mobilizing climate finance flows*. TemaNord. Copenhagen: Nordic Council of Ministers. DOI: 10.6027/TN2017-519.

Hansman, R. J., C. Magee, R. De Neufville, R. Robins, and D. Roos (2006). "Research agenda for an integrated approach to infrastructure planning, design and management". In: *International Journal of Critical Infrastructures* 2.2-3, pp. 146–159.

Hanson, H. I., B. Wickenberg, and J. Alkan Olsson (2020). "Working on the boundaries—How do science use and interpret the nature-based solution concept?" In: *Land Use Policy* 90, p. 104302. DOI: 10.1016/J.LANDUSEPOL.2019.104302.

Hardee, K. and C. Mutunga (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)". In: *Mitigation and Adaptation Strategies for Global Change* 15.2, pp. 113–126. DOI: 10.1007/s11027-009-9208-3.

Harrison, P. A., R. W. Dunford, I. P. Holman, and M. D. Rounsevell (2016). "Climate change impact modelling needs to include cross-sectoral interactions". In: *Nature Climate Change* 6.9, pp. 885–890. DOI: 10.1038/nclimate3039.

Harrison, P. A., I. P. Holman, and P. M. Berry (2015). "Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project". In: *Climatic Change* 128.3-4, pp. 153–167. DOI: 10.1007/s10584-015-1324-3.

Haughton, G. and C. Hunter (1994). *Sustainable Cities*. London: Kingsley.

Haughton, G. (1999). "Environmental Justice and the Sustainable City:" in: *Journal of Planning Education and Research* 18.3, pp. 233–243. DOI: 10.1177/0739456X9901800305. URL: https://journals.sagepub.com/doi/10.1177/0739456X9901800305.

Hay, I. (2016). *Qualitative Research Methods in Human Geography*. 4th ed. Ontario, Canada: Oxford University Press.

Helgeson, J. and J. Ellis (2015). *The Role of the 2015 Agreement in Enhancing Adaptation to Climate Change*. Tech. rep. URL: www.oecd.org/environment/cc/ccxg.htm.

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

Hickford, A., R. Nicholls, A. Otto, J. Hall, S. P. Blainey, M. Tran, and P. Baruah (2015). "Creating an ensemble of future strategies for national infrastructure provision". In: *Futures* 66, pp. 13–24. DOI: 10.1016/j.futures.2014.11.009.

Hinkel, J., S. Brown, L. Exner, R. J. Nicholls, A. T. Vafeidis, and A. S. Kebede (2011). "Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA". In: *Regional Environmental Change* 12.1, pp. 207–224. DOI: 10.1007/S10113-011-0249-2. URL: https://link.springer.com/article/10.1007/s10113-011-0249-2.

Hinkel, J., C. Jaeger, R. J. Nicholls, J. Lowe, O. Renn, and S. Peijun (2015). "Sea-level rise scenarios and coastal risk management". In: *Nature Climate Change* 5.3, pp. 188–190. DOI: 10.1038/nclimate2505.

Holling, C. (1995). "Engineering resilience versus ecological resilience". In: *Engineering Within Ecological Constraints*. Ed. by P. Schulze. Washington D.C: National Academy of Engineering.

Howarth, C., D. Viner, S. Dessai, C. Rapley, and A. Jones (2017). "Enhancing the contribution and role of practitioner knowledge in the Intergovernmental Panel on Climate Change (IPCC) Working Group (WG) II process: Insights from UK workshops". In: *Climate Services* 5, pp. 3–10. DOI: 10.1016/J.CLISER.2017.04.003.

Howells, M. et al. (2013). "Integrated analysis of climate change, land-use, energy and water strategies". In: *Nature Climate Change 2013 3:7* 3.7, pp. 621–626. DOI: 10.1038/nclimate1789. URL: https://www.nature.com/articles/nclimate1789.

Huizinga, J., H. d. Moel, and W. Szewczyk (2017). *Global flood depth-damage functions: Methodology and the database with guidelines*. Tech. rep. Luxembourg: European Union, EUR 28552. DOI: 10.2760/16510.

Huq, S. (2001). "Climate change and Bangladesh". In: *Science* 294.5547, p. 1617. DOI: 10.1126/SCIENCE.294.5547.1617. URL: https://www.science.org/doi/10.1126/science.294.5547.1617.

Huq, S. and H. Reid (2009). "Mainstreaming adaptation in development". In: *IDS Bulletin* 35.3, pp. 15–21. URL: https://www.deepdyve.com/lp/wiley/mainstreaming-adaptation-in-development-dVPT3MHkAg.

IADB (2018). *What is Sustainable Infrastructure? A Framework to Guide Sustainability Across the Project Cycle*. Tech. rep. Inter-American Development Bank, IDB-TN–1388. URL: http://dx.doi.org/10.18235/0001043.
IAPS (2007). *IAP2 Public Participation Spectrum*. URL: http://www.iap2.org/associations/4748/files/IAP2%20Spectrum_vertical.pdf.
ICSU (2015). *Report: Review of Targets for the Sustainable Development Goals: The Science Perspective*. Tech. rep. Paris, France.: International Council for Science (ICSU). DOI: 10.1177/0973408215600602h.
IDEA (2008). *Saint Lucia National Vision Plan*. Tech. rep. Castries, Saint Lucia.
IEAG (2016). *Third meeting of the inter-agency and expert group on sustainable development goal indicators: introduction to provisional tiers of global SDG indicators*. URL: http://unstats.un.org/sdgs/files/meetings/iaeg-sdgs-meeting-03/3rd-IAEG-SDGs-presentation-UNSD%E2%80%93%20Introduction-to-indicator-tiers.pdf..
Independent Group of Scientists (2019). *Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development*. Tech. rep. New York, US: United Nations.
IPBES (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Tech. rep. Bonn, Germany: IPBES secretariat.
IPCC (2012). "Summary for Policymakers". In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Ed. by C. Field et al. Cambridge, UK, and New York, NY, USA: Cambridge University Press, 582 pp.
— (2014a). *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Tech. rep. October 2013. Geneva: Intergovernmental Panel on Climate Change, pp. 1–76. DOI: 10.1017/CBO9781107415379.
— (2014b). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]* Tech. rep. Geneva, Switzerland: IPCC, p. 151.
— (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*. Tech. rep.
— (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*. Tech. rep. IPCC.
— (2021). *Assessment Report 6 Climate Change 2021: The Physical Science Basis*. Tech. rep. Intergovernmental Panel on Climate Change.
Islam, S. M., M. Munasinghe, and M. Clarke (2003). "Making long-term economic growth more sustainable: evaluating the costs and benefits". In: *Ecological Economics* 47.2-3, pp. 149–166. DOI: 10.1016/S0921-8009(03)00162-9.
IUCN (1980). *World Conservation Strategy: Living Resource Conservation for Sustainable Development*. Tech. rep. Gland, Switzerland: International Union for the Conservation of Nature and Natural Resources.
Izaguirre, C., I. J. Losada, P. Camus, J. L. Vigh, and V. Stenek (2021). "Climate change risk to global port operations". In: *Nature Climate Change* 11.1, pp. 14–20. DOI: 10.1038/s41558-020-00937-z.
Jafino, B. A., S. Hallegatte, and J. Rozenberg (2021). "Focusing on differences across scenarios could lead to bad adaptation policy advice". In: *Nature Climate Change* 11.4, pp. 394–396. DOI: 10.1038/s41558-021-01030-9.
Jerneck, A. et al. (2011). "Structuring sustainability science". In: *Sustainability Science*. DOI: 10.1007/s11625-010-0117-x.
Jetten, V. (2016). *CHARIM Project Saint Lucia National Flood Hazard Map Methodology and Validation Report*. Twente, The Netherlands. URL: http://charim.net/sites/default/files/handbook/maps/SAINT_LUCIA/SLUFloodReport.pdf.

Jones, H. P., D. G. Hole, and E. S. Zavaleta (2012). "Harnessing nature to help people adapt to climate change". In: *Nature Climate Change* 2.7, pp. 504–509. DOI: 10.1038/nclimate1463.

Jones, L. et al. (2015). "Ensuring climate information guides long-term development". In: *Nature Climate Change* 5.9, pp. 812–814. DOI: 10.1038/nclimate2701. URL: https://www.nature.com/articles/nclimate2701.

Jones, R. et al. (2014). "Foundations for Decision Making". In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 195–228. DOI: 10.1017/CBO9781107415379.007.

Jongman, B. (2018). "Effective adaptation to rising flood risk". In: *Nature Communications* 9.1, pp. 1–3. DOI: 10.1038/s41467-018-04396-1.

Juhola, S., E. Glaas, B. O. Linnér, and T. S. Neset (2016). "Redefining maladaptation". In: *Environmental Science and Policy* 55, pp. 135–140. DOI: 10.1016/j.envsci.2015.09.014.

Jurgilevich, A., A. Räsänen, F. Groundstroem, and S. Juhola (2017). "A systematic review of dynamics in climate risk and vulnerability assessments". In: *Environmental Research Letters* 12.1, p. 013002. DOI: 10.1088/1748-9326/aa5508.

Kalra, N., D. Groves, L. Bonzanigo, E. M. Perez, C. L. Ramos Taipe, I. R. Cabanillas, and C. J. Brandon (2015). *Robust decision-making in the water sector: a strategy for implementing Lima's long-term water resources master plan*. Tech. rep.

Kalra, N., S. Hallegatte, R. Lempert, C. Brown, A. Fozzard, S. Gill, and A. Shah (2015). "Agreeing on Robust Decisions New Processes for Decision Making Under Deep Uncertainty". In: *World Bank Policy Research Working Paper* 6906. DOI: doi:10.1596/1813-9450-6906.

Kanie, N. et al. (2019). "Rules to goals: emergence of new governance strategies for sustainable development: Governance for global sustainability is undergoing a major transformation from rule-based to goal-based. But with no compliance measures, success will require an unprecede". In: *Sustainability Science* 14.6, pp. 1745–1749. DOI: 10.1007/s11625-019-00729-1.

Kappes, M. S., M. Keiler, K. von Elverfeldt, and T. Glade (2012). "Challenges of analyzing multi-hazard risk: A review". In: *Natural Hazards* 64.2, pp. 1925–1958. DOI: 10.1007/s11069-012-0294-2.

Kates, R. W. (2011). "What kind of a science is sustainability science?" In: *Proceedings of the National Academy of Sciences* 108.6, pp. 19449–50. DOI: 10.1073/pnas.1116097108.

Kates, R. W. et al. (2001). "Environment and development: Sustainability science". In: *Science* 292.5517, pp. 641–642. DOI: 10.1126/SCIENCE.1059386.

Kates, R. W. (1987). "The Human Environment: The Road Not Taken, The Road Still Beckoning". In: *Annals of the Association of American Geographers* 77.4, pp. 525–534. DOI: 10.1111/J.1467-8306.1987.TB00178.X.

Kates, R. W., T. M. Parris, and A. A. Leiserowitz (2005). "What is sustainable development? Goals, indicators, values, and practice". In: *Environment: Science and Policy for Sustainable Development* 47.3, pp. 8–21. DOI: 10.1080/00139157.2005.10524444.

Keitsch, M. (2018). "Structuring ethical interpretations of the sustainable development goals—Concepts, implications and progress". In: *Sustainability* 10.3, p. 829.

Kelman, I. and J. West (2009). "Climate Change and Small Island Developing States: A Critical Review". In: *Ecological and Environmental Anthropology* 5.1, pp. 1–16.

Khan, M. and G. Schmidt-Traub (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)*. Tech. rep. Paris, France: SDSN.

Khan, M. R. (2013). *Toward a binding climate change adaptation regime: A proposed framework*. 1st Editio. London and New York: Routledge. DOI: 10.4324/9780203073384.

Kheradmand, S., O. Seidou, D. Konte, and M. B. Barmou Batoure (2018). "Evaluation of adaptation options to flood risk in a probabilistic framework". In: *Journal of Hydrology: Regional Studies* 19, pp. 1–16. DOI: 10.1016/j.ejrh.2018.07.001.

King, D., D. Schrag, D. Zhou, Q. Ye, and A. Ghosh (2015). *Climate Change: A Risk Assessment*. Tech. rep. Cambridge, England, p. 154.

Kirchner, M. et al. (2015). "Ecosystem services and economic development in Austrian agricultural landscapes - The impact of policy and climate change scenarios on trade-offs and synergies". In: *Ecological Economics* 109, pp. 161–174. DOI: 10.1016/j.ecolecon.2014.11.005.

Klein, R. J., K. M. Adams, A. Dzebo, M. Davis, and C. K. Siebert (2017). "Advancing climate adaptation practices and solutions: Emerging research priorities". Stockholm, Sweden. URL: https://link.springer.com/content/pdf/10.1007%2Fs10784-017-9357-x.pdf.

Klein, R. J. et al. (2014). "Adaptation opportunities, constraints, and limits". In: *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*. Cambridge, United Kingdom and New York: Cambridge University Press, pp. 899–943. DOI: 10.1017/CBO9781107415379.021.

Klijn, F., M. Marchand, K. Meijer, H. van der Most, and D. Stuparu (2021). "Tailored flood risk management: Accounting for socio-economic and cultural differences when designing strategies". In: *Water Security* 12, p. 100084. DOI: 10.1016/J.WASEC.2021.100084.

Kok, K., R. Biggs, and M. Zurek (2007). "Methods for developing multiscale participatory scenarios: Insights from Southern Africa and Europe". In: *Ecology and Society* 12.1. DOI: 10.5751/ES-01971-120108.

Koks, E., M. Thissen, L. Alfieri, H. D. Moel, L. Feyen, B. Jongman, and J. C. J. H. Aerts (2019). "The macroeconomic impacts of future river flooding in Europe". In: *Environmental Research Letters* 14.8, p. 084042. DOI: 10.1088/1748-9326/AB3306.

Koks, E. E., B. Jongman, T. G. Husby, and W. J. Botzen (2015). "Combining hazard, exposure and social vulnerability to provide lessons for flood risk management". In: *Environmental Science and Policy* 47, pp. 42–52. DOI: 10.1016/j.envsci.2014.10.013.

Koks, E. E., J. Rozenberg, et al. (2019). "A global multi-hazard risk analysis of road and railway infrastructure assets". In: *Nature Communications* 10.1, pp. 1–11. DOI: 10.1038/s41467-019-10442-3.

Koks, E. (2018). "Moving flood risk modelling forwards". In: *Nature Climate Change* 8, pp. 561–562. DOI: 10.1038/s41558-018-0185-y.

Kremen, C. and A. M. Merenlender (2018). "Landscapes that work for biodiversity and people". In: *Science* 362. DOI: 10.1126/science.aau6020.

Kroll, C., A. Warchold, and P. Pradhan (2019). "Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies?" In: *Palgrave Communications* 5.1, pp. 1–11. DOI: 10.1057/s41599-019-0335-5.

Lafortune, G., G. Fuller, J. Moreno, G. Schmidt-Traub, and C. Kroll (2018). *SDG Index and Dashboards: Detailed Methodological Paper*. Tech. rep. September. New York (NY, US): Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), pp. 1–476.

Lang, D. J. et al. (2012). "Transdisciplinary research in sustainability science: Practice, principles, and challenges". In: *Sustainability Science* 7.1, pp. 25–43. DOI: 10.1007/s11625-011-0149-x.

Langford, M., A. Sumner, and A. Yamin (2013). *The Millennium Development Goals and Human Rights*. New York, US: Cambridge University Press, Cambridge, pp. 539–558.

Lawson, E. T., R. S. Alare, A. R. Z. Salifu, and M. Thompson-Hall (2019). "Dealing with climate change in semi-arid Ghana: understanding intersectional perceptions and adaptation strategies of women farmers". In: *GeoJournal* 85.2, pp. 439–452. DOI: 10.1007/S10708-019-09974-4.

Le Blanc, D. (2015). "Towards Integration at Last? The Sustainable Development Goals as a Network of Targets". In: *Sustainable Development* 23.176-187. DOI: 10.1002/sd.1582.

Leach, M., A. C. Stirling, and I. Scoones (2010). *Dynamic sustainabilities: technology, environment, social justice*. London: Routledge.
Leitch, A. M. et al. (2019). "Co-development of a climate change decision support framework through engagement with stakeholders". In: *Climatic Change* 153, pp. 587–605. DOI: 10.1007/s10584-019-02401-0.
Lemos, M. C., A. Agrawal, H. Eakin, D. R. Nelson, N. L. Engle, and O. Johns (2013). "Building Adaptive Capacity to Climate Change in Less Developed Countries". In: *Climate Science for Serving Society*. Dordrecht: Springer, Dordrecht, pp. 437–457. DOI: 10.1007/978-94-007-6692-1{_}16.
Lemos, M. C., Y. J. Lo, D. R. Nelson, H. Eakin, and A. M. Bedran-Martins (2016). "Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil". In: *Global Environmental Change* 39, pp. 170–179. DOI: 10.1016/J.GLOENVCHA.2016.05.001.
Lempert, R. and M. T. Collins (2007). "Managing the risk of uncertain threshold responses: Comparison of robust, optimum, and precautionary approaches". In: *Risk Analysis* 27.4, pp. 1009–1026. DOI: 10.1111/j.1539-6924.2007.00940.x.
Lempert, R., S. W. Popper, and S. C. Bankes (2010). "Robust decision making: Coping with uncertainty". In: *Futurist* 44.1, pp. 47–48.
Lempert, R. et al. (2013). *Making Good Decisions Without Predictions: Robust Decision Making for Planning Under Deep Uncertainty*. Tech. rep. Los Angeles: RAND.
Lesnikowski, A., J. D. Ford, L. Berrang-Ford, M. Barrera, P. Berry, J. Henderson, and S. J. Heymann (2013). "National-level factors affecting planned, public adaptation to health impacts of climate change". In: *Global Environmental Change* 23.5, pp. 1153–1163. DOI: 10.1016/j.gloenvcha.2013.04.008.
Lesnikowski, A., J. D. Ford, L. Berrang-Ford, J. A. Paterson, M. Barrera, and S. J. Heymann (2011). "Adapting to health impacts of climate change: A study of UNFCCC Annex i parties". In: *Environmental Research Letters* 6.4, p. 044009. DOI: 10.1088/1748-9326/6/4/044009.
Lesnikowski, A., J. D. Ford, R. Biesbroek, L. Berrang-Ford, M. Maillet, M. Araos, and S. E. Austin (2017). "What does the Paris Agreement mean for adaptation?" In: *Climate Policy* 17.7, pp. 825–831. DOI: 10.1080/14693062.2016.1248889.
Lewis, T. G. (2006). *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*. New Jersey: Wiley. DOI: 10.1002/0471789542.
Liu, J. et al. (2015). "Systems integration for global sustainability". In: *Science* 347.6225, p. 1258832. DOI: 10.1126/science.1258832.
Liu, J. et al. (2018). "Nexus approaches to global sustainable development". In: *Nature Sustainability* 1.9, pp. 466–476. DOI: 10.1038/s41893-018-0135-8.
Liverman, D. M. (1990a). "Drought impacts in Mexico: climate, agriculture, technology, and land tenure in Sonora and Puebla". In: *Annals of the Association of American Geographers* 80.1, pp. 49–72.
— (1990b). *Vulnerability to global environmental change*. Ed. by S. Cutter. Vol. 26. Saddle River: Worcester, MA, Clark University, pp. 27–44.
Lu, Y., N. Nakicenovic, M. Visbeck, and A.-S. Stevance (2015). "Policy: Five priorities for the UN Sustainable Development Goals". In: *Nature* 520.7548, pp. 432–433. DOI: 10.1038/520432a. URL: https://www.nature.com/articles/520432a.
Lusseau, D. and F. Mancini (2019). "Income-based variation in Sustainable Development Goal interaction networks". In: *Nature Sustainability* 2.3, pp. 242–247. DOI: 10.1038/s41893-019-0231-4.
Lynch, A. J. et al. (2020). "Inland fish and fisheries integral to achieving the Sustainable Development Goals". In: *Nature Sustainability*, pp. 1–9. DOI: 10.1038/s41893-020-0517-6.
Magnan, A. K. and T. Ribera (2016). "Global adaptation after Paris". In: *Science* 352.6291, pp. 1280–1282. DOI: 10.1126/science.aaf5002.
Mair, S., A. Jones, J. Ward, I. Christie, A. Druckman, and F. Lyon (2018). "A Critical Review of the Role of Indicators in Implementing the Sustainable Development Goals". In: *World Sustainability Series*. Springer, pp. 41–56. DOI:

10.1007/978-3-319-63007-6{_}3. URL: https://link.springer.com/chapter/10.1007/978-3-319-63007-6_3.

Malhi, Y., J. Franklin, N. Seddon, M. Solan, M. G. Turner, C. B. Field, and N. Knowlton (2020). "Climate change and ecosystems: Threats, opportunities and solutions". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 375.1794. DOI: 10.1098/rstb.2019.0104.

Malone, E. L. and N. L. Engle (2011). "Evaluating regional vulnerability to climate change: purposes and methods". In: *Wiley Interdisciplinary Reviews: Climate Change* 2.3, pp. 462–474. DOI: 10.1002/WCC.116. URL: https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wcc.116.

Marcelo, D., C. Mandri-perrott, and S. House (2015). *Prioritization of Infrastructure Projects : A Decision Support Framework*. Tech. rep., pp. 1–30.

Marzocchi, W., A. Garcia-Aristizabal, P. Gasparini, M. L. Mastellone, and A. Di Ruocco (2012). "Basic principles of multi-risk assessment: a case study in Italy". In: *Natural Hazards 2012 62:2* 62.2, pp. 551–573. DOI: 10.1007/S11069-012-0092-X.

Maseyk, F. J., A. D. Mackay, H. P. Possingham, E. J. Dominati, and Y. M. Buckley (2017). "Managing Natural Capital Stocks for the Provision of Ecosystem Services". In: *Conservation Letters* 10.2, pp. 211–220. DOI: 10.1111/conl.12242.

Masson-Delmotte, V. et al. (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*. Tech. rep.

McCollum, D. L. et al. (2018). "Connecting the sustainable development goals by their energy inter-linkages". In: *Environmental Research Letters* 13.3, p. 033006. DOI: 10.1088/1748-9326/aaafe3.

McGowan, P. J., G. B. Stewart, G. Long, and M. J. Grainger (2019). "An imperfect vision of indivisibility in the Sustainable Development Goals". In: *Nat. Sustain.* 2.1, pp. 43–45. DOI: 10.1038/s41893-018-0190-1.

McNamara, K. E. et al. (2020). "An assessment of community-based adaptation initiatives in the Pacific Islands". In: *Nature Climate Change* 10.7, pp. 628–639. DOI: 10.1038/s41558-020-0813-1.

Mcsweeney, C., M. New, and G. Lizcano (2010). *UNDP Climate Change Country Profiles: Ghana*. Tech. rep. URL: http://www.geog.ox.ac.uk/research/climate/projects/undp-cp/..

Mechler, R., L. M. Bouwer, J. Linnerooth-Bayer, S. Hochrainer-Stigler, J. C. J. H. Aerts, S. Surminski, and K. Williges (2014). "Managing unnatural disaster risk from climate extremes". In: *Nature Climate Change* 4.4, pp. 235–237. DOI: 10.1038/nclimate2137. URL: https://www.nature.com/articles/nclimate2137.

Menéndez, P., I. J. Losada, S. Torres-Ortega, S. Narayan, and M. W. Beck (2020). "The Global Flood Protection Benefits of Mangroves". In: *Scientific Reports* 10.1, pp. 1–11. DOI: 10.1038/s41598-020-61136-6. URL: https://doi.org/10.1038/s41598-020-61136-6.

Mensah, J. (2019). "Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review". In: *Cogent Social Sciences* 5.1. Ed. by S. Ricart Casadevall, p. 1653531. DOI: 10.1080/23311886.2019.1653531. URL: https://doi.org/10.1080/23311886.2019.1653531.

Messerli, P. et al. (2019). *Global sustainable development report 2019: the future is now–science for achieving sustainable development*. Tech. rep. New York: United Nations.

Meuleman, L. and I. Niestroy (2015). "Common But Differentiated Governance: A Metagovernance Approach to Make the SDGs Work". In: *Sustainability* 7.9, pp. 12295–12321. DOI: 10.3390/SU70912295.

Meurs, P. and B. Abelshausen (2018). "Quid Sustainability—The SDG's from a Critical Perspective". In: *Network of Universities from the Capitals of Europe (UNICA): Brussels, Belgium*.

Meyer, V. et al. (2013). "Review article: Assessing the costs of natural hazards-state of the art and knowledge gaps". In: *Natural Hazards and Earth System Science* 13, pp. 1351–1373. DOI: 10.5194/nhess-13-1351-2013.
Middleton, N., P. O'Keefe, and S. Moyo (1993). *Tears of the Crocodile: from Rio to Reality in the Developing World*. London: Pluto.
Midgley, G. and A. E. Ochoa-Arias (2004). "An introduction to community operational research". In: *Community Operational Research*. Springer, pp. 1–36.
Midgley, G. (2000). *Systemic Intervention: Philosophy, Methodology and Practice*. Boston: Springer. DOI: 10.1007/978-1-84996-125-7.
Millenium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Synthesis*. Tech. rep. Washington D.C.: World Resources Institute.
Mimura, N. et al. (2014). "Adaptation planning and implementation". In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Ed. by C. B. Field et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 869–898.
Ministry of Agriculture Forestry and Fisheries Saint Lucia (2002). *Coastal Zone Management in Saint Lucia*. Tech. rep. Castries, Saint Lucia: Ministry of Agriculture, Forestry and Fisheries.
Miola, A. and F. Schiltz (2019). "Measuring sustainable development goals performance: How to monitor policy action in the 2030 Agenda implementation?" In: *Ecological Economics* 164, p. 106373. DOI: 10.1016/J.ECOLECON.2019.106373.
Mitchell, R. (2006). *Global Environmental Assessments*. Cambridge, Ma, USA: MIT Press, p. 344.
Moore, F. C. (2012). "Costing Adaptation: Revealing Tensions in the Normative Basis of Adaptation Policy in Adaptation Cost Estimates". In: *Science, Technology, and Human Values* 37.2, pp. 171–198. DOI: 10.1177/0162243911402364.
Morgan, E. A., J. Nalau, and B. Mackey (2019). "Assessing the alignment of national-level adaptation plans to the Paris Agreement". In: *Environmental Science and Policy* 93, pp. 208–220. DOI: 10.1016/j.envsci.2018.10.012.
Morgan, M. G., M. Henrion, and M. Small (1990). *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge, England: Cambridge University Press, p. 332. DOI: 10.1016/0169-2070(92)90021-Z.
Moyer, J. D. and D. K. Bohl (2019). "Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals". In: *Futures* 105, pp. 199–210. DOI: 10.1016/J.FUTURES.2018.10.007.
Mulugetta, Y., E. B. Hagan, and D. Kammen (2019). "Energy access for sustainable development". In: *Environmental Research Letters* 14.2, p. 020201. DOI: 10.1088/1748-9326/AAF449.
Munasinghe, M. (2009). *Sustainable development in practice: sustainomics methodology and applications*. Cambridge: Cambridge University Press, p. 633.
NADMO (2015). *National level Flood and Drought Risk Assessment and Mapping - Technical Report*. Tech. rep. Accra, Ghana: NADMO, Government of Ghana.
Naess, L. O., P. Newell, A. Newsham, J. Phillips, J. Quan, and T. Tanner (2015). "Climate policy meets national development contexts: Insights from Kenya and Mozambique". In: *Global Environmental Change* 35, pp. 534–544. DOI: 10.1016/j.gloenvcha.2015.08.015. URL: http://dx.doi.org/10.1016/j.gloenvcha.2015.08.015.
Nalau, J. and B. Verrall (2021). "Mapping the evolution and current trends in climate change adaptation science". In: *Climate Risk Management* 32, p. 100290. DOI: 10.1016/j.crm.2021.100290.
National Research Council (1999). *Our Common Journey: A Transition toward Sustainability*. Washington D.C.
— (2009a). *Informing Decisions in a Changing Climate*. Tech. rep. Washington, D.C., p. 201.

National Research Council (2009b). *Science and Decisions: Advancing Risk Assessment*. Tech. rep. Washington, D.C.: National Academies Press, p. 424.
Nay, J. J., M. Abkowitz, E. Chu, D. Gallagher, and H. Wright (2014). "A review of decision-support models for adaptation to climate change in the context of development". In: *Climate and Development* 6.4, pp. 357–367. DOI: 10.1080/17565529.2014.912196. URL: https://www.tandfonline.com/doi/abs/10.1080/17565529.2014.912196.
NDPC (2019a). *Energy Infrastructure Framework of the Ghana Infrastructure Plan (2018-2047): A companion document of the long-term national development plan (2018-2057)*. Tech. rep. Accra, Ghana: NDPC.
— (2019b). *Ghana Infrastructure Plan (2018 – 2047) Volume One*. Tech. rep. Accra, Ghana: National Development Planning Commission.
— (2019c). *Results Framework of the Ghana Infrastructure Plan (2018-2047): A companion document of the long-term national development plan (2018-2057)*. Tech. rep. Accra, Ghana: NDPC.
Newig, J. and T. M. Koontz (2014). "Multi-level governance, policy implementation and participation: the EU's mandated participatory planning approach to implementing environmental policy". In: *Journal of European Public Policy* 21.2, pp. 248–267. DOI: 10.1080/13501763.2013.834070. URL: https://www.tandfonline.com/doi/abs/10.1080/13501763.2013.834070.
Niestroy, I. (2016). *The 2030 Agenda for Sustainable Development in the EU and Its Member States: Analysis and Action So Far*. URL: https://www.die-gdi.de/%20uploads/media/DP_9.2016.pdf.
Nilsson, M., D. Griggs, and M. Visbeck (2016). "Policy: Map the interactions between Sustainable Development Goals". In: *Nature* 534.6, pp. 320–322. DOI: 10.1038/534320a.
Nilsson, M., P. Lucas, and T. Yoshida (2013). "Towards an Integrated Framework for SDGs: Ultimate and Enabling Goals for the Case of Energy". In: *Sustainability* 5.10, pp. 4124–4151. DOI: 10.3390/su5104124. URL: www.mdpi.com/journal/sustainabilityArticle.
Nilsson, M. et al. (2018). "Mapping interactions between the sustainable development goals: lessons learned and ways forward". In: *Sustainability Science* 13.6, pp. 1489–1503. DOI: 10.1007/s11625-018-0604-z.
NITA (2020). *Ghana Open Data Initiative*. URL: https://data.gov.gh/.
Noble, I. R. et al. (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.
Norström, A. V. et al. (2020). "Principles for knowledge co-production in sustainability research". In: *Nature Sustainability* 3.3, pp. 182–190. DOI: 10.1038/s41893-019-0448-2. URL: https://www.nature.com/articles/s41893-019-0448-2.
Nurse, L. et al. (2014). "Small Islands". In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC, pp. 1613–1654. DOI: 10.2134/jeq2008.0015br.
O'Brien, K. (2017). "Climate Change Adaptation and Social Transformation". In: *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, pp. 1–8. DOI: 10.1002/9781118786352.WBIEG0987. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/9781118786352.wbieg0987%20https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118786352.wbieg0987%20https://onlinelibrary.wiley.com/doi/10.1002/9781118786352.wbieg0987.
O'Brien, K., S. Eriksen, L. P. Nygaard, and A. Schjolden (2007). "Why different interpretations of vulnerability matter in climate change discourses". In: *Climate Policy* 7.1, pp. 73–88. DOI: 10.1080/14693062.2007.9685639.

O'Brien, K., S. Eriksen, A. Schjolden, and L. Nygaard (2004). "Conflicting interpretations of vulnerability in climate change research". Norway. URL: http://www.cicero.uio.no.

O'Brien, K. L. (2016). "Climate change and social transformations: is it time for a quantum leap?" In: *Wiley Interdisciplinary Reviews: Climate Change* 7.5, pp. 618–626. DOI: 10.1002/WCC.413.

O'Brien, K. L. and R. M. Leichenko (2000). "Double exposure: assessing the impacts of climate change within the context of economic globalization". In: *Global Environmental Change* 10.3, pp. 221–232. DOI: 10.1016/S0959-3780(00)00021-2.

O'Neill, B. C. et al. (2014). "A new scenario framework for climate change research: the concept of shared socioeconomic pathways". In: *Climatic Change* 122.3, pp. 387–400. DOI: 10.1007/S10584-013-0905-2. URL: https://link.springer.com/article/10.1007/s10584-013-0905-2.

O'Riordan, T. (1989). "The challenge for environmentalism". In: *New Models in Geography*. Peet R, Th. London: Unwin Hyman, pp. 77–102.

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

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

Ojha, H. et al. (2020). "Improving science-policy interface: Lessons from the policy lab methodology in Nepal's community forest governance". In: *Forest Policy and Economics* 114, p. 101997. DOI: 10.1016/J.FORPOL.2019.101997.

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. C. O'Neill, and K. Takahashi (2014). "Emergent risks and key vulnerabilities". In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Ed. by C. B. Field et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1039–1099.

OSM (2020). *Open Street Map*. URL: https://www.openstreetmap.org/.

Ostrom, E. (2007). "A diagnostic approach for going beyond panaceas". In: *Proceedings of the National Academy of Sciences* 104.39, pp. 15181–15187. DOI: 10.1073/PNAS.0702288104. URL: https://www.pnas.org/content/104/39/15181%20https://www.pnas.org/content/104/39/15181.abstract.

Otto, A., J. Hall, A. Hickford, R. Nicholls, D. Alderson, and S. Barr (2016). "A quantified system of systems modeling framework for robust national infrastructure planning". In: *IEEE Systems Journal* 10.2, p. 11. DOI: 10.1109/JSYST.2014.2361157.

Otto, F. (2017). "Annual Review of Environment and Resources Attribution of Weather and Climate Events". In: *Annual Review of Environment and Resources* 42.627-646. DOI: 10.1146/annurev-environ. URL: https://doi.org/10.1146/annurev-environ-.

Owen, G. (2020). "What makes climate change adaptation effective? A systematic review of the literature". In: *Global Environmental Change* 62.5, p. 102071. DOI: 10.1016/j.gloenvcha.2020.102071. URL: https://doi.org/10.1016/j.gloenvcha.2020.102071.

Owusu, M. and M. Nursey-Bray (2019). "Socio-economic and institutional drivers of vulnerability to climate change in urban slums: the case of Accra, Ghana". In: *Climate and Development* 11.8, pp. 687–698. DOI: 10.1080/17565529.2018.1532870. URL: https://doi.org/10.1080/17565529.2018.1532870.

Palmer, B. J. et al. (2011). "Preliminary coastal vulnerability assessment for KwaZulu-Natal, South Africa". In: *Journal of Coastal Research* 64, pp. 1390–1395.

Pant, R., S. Thacker, and J. Hall (2017). "System of systems framework for global infrastructure vulnerability assessments". In: *GGKP Annual Conference*.

Pant, R., S. Thacker, J. Hall, D. Alderson, and S. Barr (2016). "Critical infrastructure impact assessment due to flood exposure". In: *Journal of Flood Risk Management* 11.2, pp. 1–12. DOI: 10.1111/jfr3.12288.

Pant, R. et al. (n.d.). *From local to global scales – Quantifying climate risks and adaptation opportunities for networked infrastructure systems.* Tech. rep. Under production. Geneva, Switzerland: Global Assessment Report on Disaster Risk Reduction.

Pant, R., E. E. Koks, H. Paltan, T. Russell, and J. W. Hall (2019). *Argentina – Transport risk analysis*. Tech. rep. August. Oxford, UK: Oxford Infrastructure Analytics, pp. 1–154.

Pant, R., S. Thacker, J. Hall, S. Barr, and D. Alderson (2013). "Analyzing Interdependent National Infrastructure Provisions Under Extreme Climate Risk". In: *International Symposium for Next Generation Infrastructure*. DOI: 10.14453/isngi2013.proc.35. URL: http://ro.uow.edu.au/isngi2013/proceedings/1/35.

Pant, R., S. Thacker, J. W. Hall, S. Barr, and D. Alderson (2014). "Analyzing Interdependent National Infrastructure Provisions Under Extreme Climate Analyzing Interdependent National Infrastructure Provisions Under Extreme Climate Risk". In: January. DOI: 10.14453/isngi2013.proc.35.

Patterson, J. et al. (2017). "Exploring the governance and politics of transformations towards sustainability". In: *Environmental Innovation and Societal Transitions* 24, pp. 1–16. DOI: 10.1016/J.EIST.2016.09.001.

Patton, M. Q. (2002). *Qualitative Research & evaluation methodos*. 3rd. Thousand Oaks, California: Sage Publications. DOI: 10.1037/a0033788.

Peterson, G. D., G. S. Cumming, and S. R. Carpenter (2003). "Scenario planning: A tool for conservation in an uncertain world". In: *Conservation Biology* 17, pp. 358–366. DOI: 10.1046/j.1523-1739.2003.01491.x.

Pidgeon, N. and C. Butler (2009). "Risk analysis and climate change". In: *Environmental Politics* 18.5, pp. 670–688. DOI: 10.1080/09644010903156976.

Pimm, S. L. (1984). "The complexity and stability of ecosystems". In: *Nature* 307.5949, pp. 321–326. DOI: 10.1038/307321A0.

Pradhan, P. (2019). "Antagonists to meeting the 2030 Agenda". In: *Nat. Sustain.* 2.3, pp. 171–172. DOI: 10.1038/s41893-019-0248-8. URL: https://www.nature.com/articles/s41893-019-0248-8.

Pradhan, P., L. Costa, D. Rybski, W. Lucht, and J. P. Kropp (2017). "A Systematic Study of Sustainable Development Goal (SDG) Interactions". In: *Earth's Future* 5.11, pp. 1169–1179. DOI: 10.1002/2017EF000632.

Prakash, M., K. Teksoz, J. Espey, and J. D. Sachs (2017). *Achieving a Sustainable America. The U.S. Cities Sustainable Development Goals Index 2017*. Tech. rep. New York, USA: Sustainable Development Solutions Network. DOI: 10.13140/RG.2.2.25012.09601.

Preston, B. L., R. M. Westaway, and E. J. Yuen (2011). "Climate adaptation planning in practice: An evaluation of adaptation plans from three developed nations". In: *Mitigation and Adaptation Strategies for Global Change* 16.4, pp. 407–438. DOI: 10.1007/s11027-010-9270-x. URL: https://link.springer.com/article/10.1007/s11027-010-9270-x.

Purvis, B., Y. Mao, and D. Robinson (2018). "Three pillars of sustainability: in search of conceptual origins". In: *Sustainability Science* 14.3, pp. 681–695. DOI: 10.1007/S11625-018-0627-5. URL: https://link.springer.com/article/10.1007/s11625-018-0627-5.

Ranger, N. and S.-L. Garbett-Shiels (2012). "Accounting for a changing and uncertain climate in planning and policymaking today: lessons for developing countries". In: *Climate and Development* 4.4, pp. 288–300. DOI: 10.1080/17565529.2012.732919. URL: https://www.tandfonline.com/doi/abs/10.1080/17565529.2012.732919.

Rao, P. (2000). *Sustainable Development: Economics and Policy*. Oxford, UK: Blackwell Publishers.

Raskin, P. D., C. Electris, and R. A. Rosen (2010). "The Century Ahead: Searching for Sustainability". In: *Sustainability* 2.8, pp. 2626–2651. DOI: 10.3390/SU2082626.

URL: https://www.mdpi.com/2071-1050/2/8/2626/htm%20https://www.mdpi.com/2071-1050/2/8/2626.

Raworth, K. (2017). *Doughnut economics: seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

Raymond, C. et al. (2020). "Understanding and managing connected extreme events". In: *Nature Climate Change* 10.7, pp. 611–621. DOI: 10.1038/s41558-020-0790-4. URL: https://doi.org/10.1038/s41558-020-0790-4.

Reason, P. and H. Bradbury (2001). *Handbook of Action Research: Participative Inquiry and Practice*. London, UK: Sage Publications. DOI: 0432.

Rees, W. (1998). "Understanding sustainable development". In: *Sustainable Development and the Future of Cities*. Ed. by M. Hamm B and P. (eds). London: Intermediate Technology, pp. 19–42.

Reichstein, M., F. Riede, and D. Frank (2021). "More floods, fires and cyclones — plan for domino effects on sustainability goals". In: *Nature* 592.7854, pp. 347–349. DOI: 10.1038/d41586-021-00927-x. URL: https://www.nature.com/articles/d41586-021-00927-x.

Reid, H., L. Faulkner, and A. Weiser (2013). "The role of community-based natural resource management in climate change adaptation in Ethiopia".

Renn, O., K. Lucas, A. Haas, and C. Jaeger (2019). "Things are different today: the challenge of global systemic risks". In: *Journal of Risk Research* 22.4, pp. 401–415. DOI: 10.1080/13669877.2017.1409252. URL: https://www.tandfonline.com/action/journalInformation?journalCode=rjrr20.

Riahi, K. et al. (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview". In: *Global Environmental Change* 42, pp. 153–168. DOI: 10.1016/J.GLOENVCHA.2016.05.009.

Ribot, J. (2014). "Cause and response: vulnerability and climate in the Anthropocene". In: *The Journal of Peasant Studies* 41.5, pp. 667–705. DOI: 10.1080/03066150.2014.894911. URL: https://www.tandfonline.com/doi/abs/10.1080/03066150.2014.894911.

Rittel, H. and M. Webber (1973). "Dilemmas in a general theory of planning". In: *Policy sciences* 4.2, pp. 155–169.

Robinson, J., S. Burch, S. Talwar, M. O'Shea, and M. Walsh (2011). "Envisioning sustainability: Recent progress in the use of participatory backcasting approaches for sustainability research". In: *Technological Forecasting and Social Change* 78.5, pp. 756–768. DOI: 10.1016/j.techfore.2010.12.006.

Rockström, J. et al. (2009). "Planetary boundaries: Exploring the safe operating space for humanity". In: *Ecology and Society* 14.2. DOI: 10.5751/ES-03180-140232.

Roseland, M. (1998). *Towards Sustainable Communities: Resources for Citizens and their Governments*. Gabriola Island, Canada: New Society.

Roy, M. and H. D. Venema (2002). "Reducing risk and vulnerability to climate change in India: The capabilities approach". In: *Gender and Development* 10.2, pp. 78–83. DOI: 10.1080/13552070215904.

Sachs, J., J. McArthur, G. Schmidt-Traub, M. Kruk, C. Bahadur, M. Faye, and G. McCord (2004). "Ending Africa's Poverty Trap". New York.

Sachs, J. D., G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, and J. Rockström (2019). "Six Transformations to achieve the Sustainable Development Goals". In: *Nat. Sustain.* 2.9, pp. 805–814. DOI: 10.1038/s41893-019-0352-9. URL: http://dx.doi.org/10.1038/s41893-019-0352-9.

Sachs, W. (1999). *Planet Dialectics*. London: Zed.

Saint Lucia Times (2020). *New Tools To Help Saint Lucia Build Resilient Infrastructure*. URL: https://stluciatimes.com/new-tools-to-help-saint-lucia-build-resilient-infrastructure/.

Santini, M., G. Caccamo, A. Laurenti, S. Noce, and R. Valentini (2010). "A multi-component GIS framework for desertification risk assessment by an integrated index". In: *Applied Geography* 30.3, pp. 394–415. DOI: 10.1016/J.APGEOG.2009.11.003.

Schipper, E. L. F. (2006). "Conceptual History of Adaptation in the UNFCCC Process". In: *Review of European Community & International Environmental Law* 15.1, pp. 82–92. DOI: 10.1111/J.1467-9388.2006.00501.X.

Schipper, E. L. F., J. Ayers, H. Reid, S. Huq, and A. Rahman (2014). *Community-Based Adaptation to Climate Change*. 1st editio. Routledge.

Schipper, E. L. F., T. Tanner, O. P. Dube, K. M. Adams, and S. Huq (2020). "The debate: Is global development adapting to climate change?" In: *World Development Perspectives* 18, p. 100205. DOI: 10.1016/j.wdp.2020.100205.

Schipper, E. L. F., F. Thomalla, G. Vulturius, and K. Johnson (2016). "Linking disaster risk reduction, climate change and development". In: *International Journal of Disaster Resilience in the Built Environment* 7.2, pp. 216–228. DOI: 10.1108/IJDRBE-03-2015-0014.

Schipper, E. L. F. (2020). "Maladaptation: When Adaptation to Climate Change Goes Very Wrong". In: *One Earth* 3.4, pp. 409–414. DOI: 10.1016/J.ONEEAR.2020.09.014.

Schmidt-Traub, G., C. Kroll, K. Teksoz, D. Durand-Delacre, and J. D. Sachs (2017). "National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards". In: *Nature Geoscience* 10.8, pp. 547–555. DOI: 10.1038/NGEO2985. URL: https://www.nature.com/articles/ngeo2985.

Schneiderbauer, S. et al. (2020). "Spatial-Explicit Climate Change Vulnerability Assessments Based on Impact Chains. Findings from a Case Study in Burundi". In: *Sustainability* 12.16, p. 6354. DOI: 10.3390/su12166354. URL: https://www.mdpi.com/2071-1050/12/16/6354.

SDSN (2015). *Indicators and a Monitoring Framework for Sustainable Development Goals: Launching a data revolution for the SDGs*. Tech. rep. Paris and New York: Sustainable Development Solutions Network.

Seballos, F. and S. Kreft (2011). "Towards an Understanding of the Political Economy of the PPCR". In: *IDS Bulletin* 42.3, pp. 33–41. DOI: 10.1111/J.1759-5436.2011.00220.X.

Seddon, N., A. Chausson, P. Berry, C. A. Girardin, A. Smith, and B. Turner (2020). "Understanding the value and limits of nature-based solutions to climate change and other global challenges". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 375.1794. DOI: 10.1098/rstb.2019.0120.

Seddon, N. et al. (2021). "Getting the message right on nature-based solutions to climate change". In: *Global Change Biology* 27.8, pp. 1518–1546. DOI: https://doi.org/10.1111/gcb.15513.

Sen, A. (1999). *Development as Freedom*. New York, NY, USA: Alfred A. Knopf, Inc., p. 333366.

Sietsma, A. J., J. D. Ford, M. W. Callaghan, and J. C. Minx (2021). "Progress in climate change adaptation research". In: *Environmental Research Letters* 16.5, p. 054038. DOI: 10.1088/1748-9326/ABF7F3. URL: https://iopscience.iop.org/article/10.1088/1748-9326/abf7f3%20https://iopscience.iop.org/article/10.1088/1748-9326/abf7f3/meta.

Simpson, M. et al. (2016). "Decision analysis for management of natural hazards". In: *Annual Review of Environment and Resources* 41.1, pp. 489–516. DOI: 10.1146/annurev-environ-110615-090011.

Simpson, M. C., D. Scott, M. Harrison, and N. Silver (2010). *Quantification and magnitude of losses and damages resulting from the impacts of climate change: Modelling the transformational impacts and costs of sea level rise in the Caribbean*. Tech. rep. Barbados, West Indies: United Nations Development Programme.

Simpson, N. P. et al. (2021). "A framework for complex climate change risk assessment". In: *One Earth* 4.4, pp. 489–501. DOI: 10.1016/j.oneear.2021.03.005. URL: https://linkinghub.elsevier.com/retrieve/pii/S2590332221001792.

Singh, C., J. D. Ford, D. Ley, A. Bazaz, and A. Revi (2020). "Assessing the feasibility of adaptation options: methodological advancements and directions for climate

adaptation research and practice". In: *Climatic Change* 162.2, pp. 255–277. DOI: 10.1007/s10584-020-02762-x.
Singh, G. G. et al. (2018). "A rapid assessment of co-benefits and trade-offs among Sustainable Development Goals". In: *Marine Policy* 92.7, pp. 223–231. DOI: 10.1016/j.marpol.2017.05.030.
Singh, P. K. and H. Chudasama (2021). "Pathways for climate resilient development: Human well-being within a safe and just space in the 21st century". In: *Global Environmental Change* 68, p. 102277. DOI: 10.1016/J.GLOENVCHA.2021.102277.
Skourtos, M., C. Tourkolias, D. Damigos, A. Kontogianni, P. A. Harrison, and P. Berry (2014). "Incorporating cross-sectoral effects into analysis of the cost-effectiveness of climate change adaptation measures". In: *Climatic Change* 128.3-4, pp. 307–321. DOI: 10.1007/s10584-014-1168-2. URL: www.climsave.eu/.
SLASPA (2017). *Port statistics*. URL: https://www.slaspa.com/index.php/port-side-stats.
SLUSWMA (2015). *Saint Lucia Solid Waste Management Authority Annual Report 2014-2015*. Tech. rep. Saint Lucia Solid Waste Management Authority.
Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R. J. T. Klein, and S. J (2001). "Adaptation to climate change in the context of sustainable development and equity". In: *Climate change 2001. Impacts, adaptation, and vulnerability*. Ed. by J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White. Cambridge, England: Cambridge University Press.
Smith, A. C. et al. (2017). *How natural capital delivers ecosystem services: A typology derived from a systematic review*. DOI: 10.1016/j.ecoser.2017.06.006.
Smith, A. J. P., M. W. Jones, J. T. Abatzoglou, J. G. Canadell, and R. A. Betts (2020). "Climate Change Increases the Risk of Wildfires update". URL: https://sciencebrief.org/topics/climate-.
Smith, J. B., R. J. T. Klein, and S. Huq (2003). *Climate change, adaptive capacity and development*. London: Imperial College Press, p. 347.
Soergel, B. et al. (2021). "A sustainable development pathway for climate action within the UN 2030 Agenda". In: *Nature Climate Change 2021* 11.8, pp. 656–664. DOI: 10.1038/s41558-021-01098-3. URL: https://www.nature.com/articles/s41558-021-01098-3.
Spahn, A. (2018). ""The first generation to end poverty and the last to save the planet?"—Western individualism, human rights and the value of nature in the ethics of global sustainable development". In: *Sustainability* 10.6, p. 1853.
Srivastava, L., L. Gomez-Echeverri, and F. Schlegel (2021). *Transformations within reach: Pathways to a sustainable and resilient world*. Tech. rep. IIASA, ISC, pp. 1–48.
Stafford-Smith, M. et al. (2016). "Integration: the key to implementing the Sustainable Development Goals". In: *Sustainability Science* 12.6, pp. 911–919. DOI: 10.1007/S11625-016-0383-3. URL: https://link.springer.com/article/10.1007/s11625-016-0383-3.
Steffen, W. et al. (2015). "Planetary boundaries: Guiding human development on a changing planet". In: *Science* 347.6223, p. 1259855. DOI: 10.1126/science.1259855.
Stern, N. (2006). "The stern review on the economic effects of climate change". In: *Population and Development Review* 32.4, pp. 793–798.
Stirling, A. (2010). "Keep it complex". In: *Nature* 468, pp. 1029–1031. DOI: 10.1038/4681029a.
Stirling, A. C. and I. Scoones (2009). "From risk assessment to knowledge mapping: science, precaution, and participation in disease ecology". In: *Ecology and Society* 14.2.
Sultana, P. and S. Abeyasekera (2008). "Effectiveness of participatory planning for community management of fisheries in Bangladesh". In: *Journal of Environmental Management* 86.1, pp. 201–213. DOI: 10.1016/J.JENVMAN.2006.12.027.
Sussman, F., C. P. Weaver, and A. Grambsch (2014). "Challenges in applying the paradigm of welfare economics to climate change". In: *Journal of Benefit-Cost Analysis* 5.3, pp. 347–376.

Swartz, M. S., J. W. Swanson, V. A. Hiday, R. Borum, R. Wagner, and B. J. Burns (1998). "Taking the wrong drugs: The role of substance abuse and medication noncompliance in violence among severely mentally ill individuals". In: *Social Psychiatry and Psychiatric Epidemiology* 33. DOI: 10.1007/s001270050213. URL: https://pubmed.ncbi.nlm.nih.gov/9857783/.

Termeer, C., R. Biesbroek, and M. Van Den Brink (2012). "Institutions for adaptation to climate change: Comparing National Adaptation strategies in Europe". In: *European Political Science*. Vol. 11. 1. Palgrave, pp. 41–53. DOI: 10.1057/eps.2011.7. URL: www.palgrave-journals.com/eps/.

Thacker, S., J. W. Hall, T. Russell, R. Pant, J. Leung, and E. Koks (2017). "System-of-systems infrastructure modelling to support national sustainable development outcomes". In: *Proceedings of the 2017 International Symposium of Next Generation Infrastructure, London, UK*. Vol. 170. 1, pp. 39–47. DOI: http://dx.doi.org/. URL: http://isngi.org/conference-outputs/.

Thacker, S., S. Barr, R. Pant, J. W. Hall, and D. Alderson (2017). "Geographic Hotspots of Critical National Infrastructure". In: *Risk Analysis* 37.12, pp. 2490–2505. DOI: 10.1111/risa.12840.

Thacker, S., S. Kelly, R. Pant, and J. W. Hall (2017). "Evaluating the Benefits of Adaptation of Critical Infrastructures to Hydrometeorological Risks". In: *Risk Analysis* 38.1, pp. 134–150. DOI: 10.1111/risa.12839.

Thacker, S., R. Pant, and J. W. J. Hall (2017). "System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures". In: *Reliability Engineering and System Safety* 167.4, pp. 30–41. DOI: 10.1016/j.ress.2017.04.023. URL: http://dx.doi.org/10.1016/j.ress.2017.04.023.

Thacker, S. et al. (2019). "Infrastructure for sustainable development". In: *Nat. Sustain.* 2, pp. 324–331. DOI: 10.1038/s41893-019-0256-8.

The World Bank (2020). *Data Catalog*. URL: https://datacatalog.worldbank.org/.

— (2021). *Revisiting Resilience in the Caribbean: a 360 degree approach. Pre-Print*. Tech. rep. Washington D.C: The World Bank.

Todini, E. (2004). "Role and treatment of uncertainty in real-time flood forecasting". In: *Hydrological Processes* 18.14, pp. 2743–2746. DOI: 10.1002/HYP.5687. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.5687%20https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.5687%20https://onlinelibrary.wiley.com/doi/10.1002/hyp.5687.

Tompkins, E. L., K. Vincent, R. J. Nicholls, and N. Suckall (2018). "Documenting the state of adaptation for the global stocktake of the Paris Agreement". In: *Wiley Interdisciplinary Reviews: Climate Change* 9.5. DOI: 10.1002/wcc.545. URL: http://doi.wiley.com/10.1002/wcc.545.

Townley, B. (1992). "In the eye of the gaze: The constitutive role of performance appraisal". In: *Managing organisations in 1992: Strategic responses*. London: Routledge, pp. 185–202.

Tran, L. T., R. V. O'Neill, and E. R. Smith (2010). "Spatial pattern of environmental vulnerability in the Mid-Atlantic region, USA". In: *Applied Geography* 30.2, pp. 191–202. DOI: 10.1016/j.apgeog.2009.05.003.

Tschakert, P., P. J. Das, N. Shrestha Pradhan, M. Machado, A. Lamadrid, M. Buragohain, and M. A. Hazarika (2016). "Micropolitics in collective learning spaces for adaptive decision making". In: *Global Environmental Change* 40, pp. 182–194. DOI: 10.1016/J.GLOENVCHA.2016.07.004.

TWI2050 (2018). *Transformations to Achieve the Sustainable Development Goals*. Tech. rep. Laxenburg, Austria: IIASA.

Ulrich, W. (1996). *Critical Systems Thinking for Citizens*. DOI: 10.1007/b102400.

UN (2002). *The Johannesburg Declaration on Sustainable Development*. URL: https://digitallibrary.un.org/record/499757.

— (2008). "International Standard Industrial Classification of All Economic Activities (ISIC), Revision 4". New York. URL: https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC_Rev_4_publication_English.pdf.

UN (2015). *Sustainable development knowledge platform*. URL: https://sustainabledevelopment.un.org/topics.
— (2019). *Climate action and the SDGs: Interlinked and indivisible*. URL: https://www.un.org/development/desa/en/news/sustainable/climateaction-sdgs-conference.html.
UN General Assembly (2014). "SIDS Accelerated Modalities of Action (SAMOA) Pathway". New York.
UNDP (2004). *Human Development Report 2004: Cultural Liberty in Today's Diverse World.* Tech. rep. New York: United Nations Development Programme. URL: http://hdr.undp.org/en/content/human-development-report-2004%22.
UNEP (2014). *Emerging Issues for Small Island Developing States: Results of the UNEP Foresight Process*. Tech. rep. Nairobi, Kenya: United Nations Environment Programme, pp. 1–55.
UNFCCC (2012). *National Adaptation Plans. Technical guidelines for the national adaptation plan process*. Tech. rep. Bonn, Germany: UNFCCC secretariat.
— (2015). *The Paris Agreement*. URL: http://unfccc.int/paris_agreement/items/9485.php.
— (2016a). *New elements and dimensions of adaptation under the Paris Agreement*. URL: https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/new-elements-and-dimensions-of-adaptation-under-the-paris-agreement-article-7.
— (2016b). *Report of the Conference of the Parties on its twenty-first session, held in Paris from November 30 to December 13, 2015. Addendum part two: Action taken by the Conference of the Parties at its twenty-first session*. Tech. rep. Bonn, Germany.
UNISDR (2015). *Sendai Framework for Disaster Risk Reduction*. Tech. rep. UNISDR/GE/2015 – ICLUX EN5000 1st edition.
United Nations (2015). *Sustainable Development Goals*. URL: https://www.un.org/sustainabledevelopment/sustainable-development-goals/.
— (2017). *New Urban Agenda*. Tech. rep. United Nations Conference on Housing and Sustainable Urban Development.
United Nations International Strategy for Disaster Reduction (2009). *Global assessment report on disaster risk reduction*. Tech. rep. Geneva, Switzerland.
University of Oxford (2020). *Nature-based solutions evidence platform*. Oxford, UK. URL: https://www.naturebasedsolutionsevidence.info/.
UNSDG (2020). *2030 Agenda: Decade of Action*. URL: https://unsdg.un.org/2030-agenda/decade-action.
Valls-Donderis, P., D. Ray, A. Peace, A. Stewart, A. Lawrence, and F. Galiana (2014). "Participatory development of decision support systems: which features of the process lead to improved uptake and better outcomes?" In: *Scandinavian Journal of Forest Research* 29, pp. 71–83. DOI: 10.1080/02827581.2013.837950. URL: https://www.tandfonline.com/doi/abs/10.1080/02827581.2013.837950.
Van Westen, C. (2016). *National Scale Landslide Susceptibility Assessment for Saint Lucia*. Tech. rep. CHARIM Caribbean Handbook on Risk Information Management.
Van Vuuren, D. P. et al. (2015). "Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model". In: *Technological Forecasting and Social Change* 98, pp. 303–323. DOI: 10.1016/j.techfore.2015.03.005.
Velis, M., K. I. Conti, and F. Biermann (2017). "Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals". In: *Sustainability Science* 12.6, pp. 1007–1017. DOI: 10.1007/s11625-017-0490-9.
Vergragt, P. J. and J. Quist (2011). "Backcasting for sustainability: Introduction to the special issue". In: *Technological forecasting and social change* 78, pp. 747–755. DOI: 10.1016/j.techfore.2011.03.010.
Verschuur, J., E. E. Koks, A. Haque, and J. W. Hall (2020). "Prioritising resilience policies to reduce welfare losses from natural disasters: A case study for coastal Bangladesh". In: *Global Environmental Change* 65, p. 102179. DOI: 10.1016/j.gloenvcha.2020.102179.
Verweij, S., E.-H. Klijn, J. Edelenbos, and A. V. Buuren (2013). "What makes governance networks work? A fuzzy set qualitative comparative analysis of 14 dutch

spatial planning projects". In: *Public Administration* 91.4, pp. 1035–1055. DOI: 10.1111/PADM.12007.
Victor, D. G. (2015). "Embed the social sciences in climate policy". In: *Nature* 520.7545, pp. 27–29. DOI: 10.1038/520027a.
Vinuesa, R. et al. (2020). "The role of artificial intelligence in achieving the Sustainable Development Goals". In: *Nature Communications* 11.1. DOI: 10.1038/s41467-019-14108-y.
Von Bernard, H. and M. Gorboran (2010). "Causes for unsustainability". In: *Ecología Austral* 20.3, pp. 303–306.
Waage, J. et al. (2015). "Governing the UN sustainable development goals: Interactions, infrastructures, and institutions". In: *The Lancet Global Health* 3.5. DOI: 10.1016/S2214-109X(15)70112-9.
Ward, P. J. et al. (2020). *Aqueduct Floods Methodology*. Tech. rep. January. World Resources Institute, pp. 1–28. URL: www.wri.org/publication/aqueduct-floods-methodology.
Ward, P. J. et al. (2017). "A global framework for future costs and benefits of river-flood protection in urban areas". In: *Nature Climate Change* 7.9, pp. 642–646. DOI: 10.1038/nclimate3350.
WCED (1987). *Our Common Future (The Brundtland Report)*. Oxford, UK: Oxford University Press. DOI: 10.1080/07488008808408783.
Weaver, C. P. et al. (2017). "Reframing climate change assessments around risk: recommendations for the US National Climate Assessment". In: *Environmental Research Letters* 12.8, p. 080201. DOI: 10.1088/1748-9326/AA7494.
Weichselgartner, J. and R. Kasperson (2010). "Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research". In: *Global Environmental Change* 20.2, pp. 266–277. DOI: 10.1016/J.GLOENVCHA.2009.11.006.
Weitz, N., H. Carlsen, M. Nilsson, and K. Skånberg (2018). "Towards systemic and contextual priority setting for implementing the 2030 agenda". In: *Sustainability Science* 13.2, pp. 531–548. DOI: 10.1007/s11625-017-0470-0.
Weitz, N., M. Nilsson, and M. Davis (2014). "A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs". In: *SAIS Review of International Affairs* 34.2, pp. 37–50.
Wilby, R. L. and S. Dessai (2010). "Robust adaptation to climate change". In: *Weather* 65.7, pp. 180–185. DOI: 10.1002/wea.543.
Williams, P. A., N. P. Simpson, E. Totin, M. A. North, and C. H. Trisos (2021). "Feasibility assessment of climate change adaptation options across Africa: An evidence-based review". In: *Environmental Research Letters* 16.7. DOI: 10.1088/1748-9326/ac092d.
Willner, S. N., C. Otto, and A. Levermann (2018). "Global economic response to river floods". In: *Nature Climate Change* 8, pp. 594–598. DOI: 10.1038/s41558-018-0173-2.
Winsemius, H. C. et al. (2016). "Global drivers of future river flood risk". In: *Nature Climate Change* 6.4, pp. 381–385. DOI: 10.1038/nclimate2893.
Wise, R. M., I. Fazey, M. Stafford Smith, S. E. Park, H. C. Eakin, E. R. Archer Van Garderen, and B. Campbell (2014). "Reconceptualising adaptation to climate change as part of pathways of change and response". In: *Global Environmental Change* 28, pp. 325–336. DOI: 10.1016/J.GLOENVCHA.2013.12.002.
Wisner, B., P. Blaikie, T. Cannon, and I. Davis (2004). *At Risk Natural Hazards, People's Vulnerability and Disaster*. 2nd Editio. London, UK: Routledge.
Wood, S. L. et al. (2018). "Distilling the role of ecosystem services in the Sustainable Development Goals". In: *Ecosystem Services* 29, pp. 70–82. DOI: 10.1016/j.ecoser.2017.10.010.
Woodruff, S. C. and P. Regan (2019). "Quality of national adaptation plans and opportunities for improvement". In: *Mitigation and Adaptation Strategies for Global Change*. DOI: 10.1007/s11027-018-9794-z.

World Bank (2010). *Development and Climate Change*. Washington D.C.: The World Bank, p. 417. DOI: 10.3334/CDIAC/cli.002.
Xu, Z. et al. (2020). "Assessing progress towards sustainable development over space and time". In: *Nature* 577.7788, pp. 74–78. DOI: 10.1038/s41586-019-1846-3.
Yohe, G. and R. S. Tol (2002). "Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity". In: *Global Environmental Change* 12.1, pp. 25–40. DOI: 10.1016/S0959-3780(01)00026-7.
Yokohata, T. et al. (2019). "Visualizing the Interconnections Among Climate Risks". In: *Earth's Future* 7.2, pp. 85–100. DOI: 10.1029/2018EF000945.
Young, P. C., R. J. Romanowicz, and K. J. Beven (2014). "A data-based mechanistic modelling approach to real-time flood forecasting". In: *Applied Uncertainty Analysis for Flood Risk Management, edited by: Beven, KJ and Hall, JW, Imperial College Press: London*, pp. 407–461.
Zhenmin, L. and P. Espinosa (2019). "Tackling climate change to accelerate sustainable development". In: *Nature Climate Change* 9.7, pp. 494–496. DOI: 10.1038/s41558-019-0519-4.
Zommers, Z. and K. D. Alverson (2018). *Resilience: the science of adaptation to climate change*. 1st Editio. Amsterdam, Netherlands: Elsevier.
Zscheischler, J. et al. (2018). "Future climate risk from compound events". In: *Nature Climate Change* 8.6, pp. 469–477. DOI: 10.1038/s41558-018-0156-3.

Appendices

A

Appendix A: Authorship statements

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I, Prof. Jim W. Hall, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

'Climate-change impacts on Sustainable Development Goals, and national adaptation responses'

'Informing national adaptation for sustainable development through spatial systems modelling'

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

Signature:



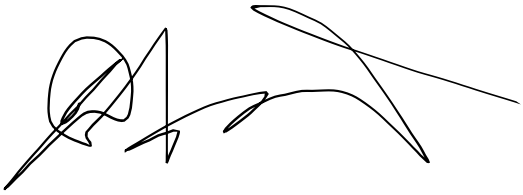
Date: 29 September 2021

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I, Dr. Daniel Adshead, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

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

Signature: 

Date: 1 October 2021

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I, Dr. Scott Thacker, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

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'Informing national adaptation for sustainable development through spatial systems modelling'

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

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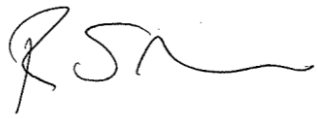


Date:
28-09-2021

I, Prof. Robert Nicholls, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

'Climate-change impacts on Sustainable Development Goals, and national adaptation responses'

Signature:



Prof. Robert J. Nicholls. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, NR4 7TJ

Date: 27 September 2021

Stockholm, 06/10/2021

To whom it may concern,

I, Dr. Francesco Fuso Nerini, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

'Climate-change impacts on Sustainable Development Goals, and national adaptation responses'

Yours sincerely,



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I, Sarah Gall, certify that Lena I. Fuldauer completed the majority of the work in the journal article below, which forms part of her DPhil thesis:

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