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ABSTRACT

Urban areas face challenges in jointly addressing the global climate change and nature loss crises amidst socioeconomic development agendas. This trade-off prompts the need to explore sensitive intervention points that can be leveraged for positive climate and nature conservation outcomes, namely the implementation of nature-based solutions that provide synergistic benefits for climate and nature while enhancing human wellbeing. Using Hong Kong as a case study, this dissertation, presented as a submission draft to the journal *Land Use Policy*, employs geospatial approaches to model carbon storage, biodiversity, and climate risk trade-offs under five land use change scenarios for 2030. The results show that Hong Kong would suffer large reductions in nature and climate benefits if future urban expansion plans are realized. The study ultimately highlights opportunities to implement nature-based solutions to enhance existing carbon stores in natural habitats, reshape built infrastructure for nature connectivity, and adapt coastlines to mitigate climate risks.

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Abbreviations

(N)BSAP	(National) Biodiversity Strategy and Action Plan
CAP	Climate Action Plan
GBF	Global Biodiversity Framework
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs® platform
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LULC	Land use and land cover
NbS	Nature-based Solutions
NDA	New Development Area
NDC	Nationally Determined Contributions
NFF	Nature Futures Framework
PA	Protected Area
SAR	Special Administrative Region
SDG	Sustainable Development Goals
SIP	Sensitive intervention point
SSP	Shared Socioeconomic Pathway
SSSI	Site of Special Scientific Interest
WDPA	World Database on Protected Areas

Extended Literature Review

Global urban expansion & environmental change

Over half the world's populations currently reside in urban areas, concentrated within just 1–3 percent of the global land surface (Liu et al. 2014; UN DESA 2019). The rapid expansion of urban areas has led to a myriad of environmental impacts across spatial and temporal scales, such as the destruction of natural habitats supporting biodiversity, rise in global greenhouse gas emissions, transformation of freshwater quality and availability, and alteration of biogeochemical cycles (Grimm et al. 2008; Gao & O'Neill 2020). Cities have also been estimated to contribute to at least 70 percent of global CO_2 emissions, demonstrating the significance of engaging with urban areas in addressing climate change (IPCC 2022; Calvin et al. 2023). Together with biodiversity and nature loss, these issues (hereon referred to collectively as 'environmental change') are expected to worsen in future decades as urban expansion accelerates. Global urban populations are projected to increase from 4.4 billion to as much as 12.6 billion, leading to an associated 1.8–5.9 increase in urban land area (Gao & O'Neill 2020; Kii 2021). The largest urban expansions are expected to take place in Africa and Asia, particularly through the formation of 'megacities' with populations exceeding 10 million (Gao & O'Neill 2020). India, for instance, is expected to undergo the fastest and largest urban transition in history, with an estimated 8 percent annual increase in energy consumption from its buildings (Khosla & Janda 2019). Much of the environmental change associated with future urban expansion has yet to take place: an estimated three quarters of the infrastructure expected to be in place by 2050 has not yet been constructed (IPCC 2022). The energy consumption, natural resource extraction, and land use change that is required of this projected infrastructural development, coupled with the growth in consumption patterns of urban individuals, holds severe implications for global environmental systems.

Considering the immense dependence of current and future environmental change on global urbanization patterns, urban areas have been established as an important lever to shift towards sustainable development pathways. Cities act as highly dense catchment areas in which policy change can be implemented at large and long-lasting timescales, particularly given the lengthy lifespan of buildings and transport infrastructure (Seto et al. 2021). Associated policy agendas encompass many dimensions of environmental change: the mitigation of climate change, adaptation to its impacts, and net recovery of nature and biodiversity. Here, the idea of sensitive intervention points (SIPs) comes into play: a relatively small intervention in a complex system can trigger a much larger, irreversible change (Farmer et al. 2019). Within the context of addressing climate change and nature loss, urban areas can act as key implementation grounds for research or policy SIPs that deliver outsized impacts (Farmer et al. 2019). Some policy levers may be associated with shifting lifestyles and behaviours to low- or zero-impact alternatives (e.g., increasing public transport use, decreasing meat consumption). In Singapore, for instance, the institution of an Electronic Road Pricing congestion charge system led to a 17 percent drop in traffic pollution and associated air pollution within the first month of its implementation (Goh 2002). Other interventions involve the transition to net zero infrastructure and the conservation or restoration of natural landscapes: the recent implementation of the Biodiversity Net Gain approach for land development in the UK and the EU nature restoration law are two such examples of recent policy that addresses the impacts of urban expansion. The use of policy as a tool to mitigate negative environmental impacts, therefore, is an important lever for reaching global environmental goals in a future of urbanization.

Further embedded in the complexity of urban systems is the urgency to not only mitigate climate change and nature loss, but also adapt to the adverse effects of environmental change. These impacts are disproportionately felt in urban communities, and the observed human and economic losses from climate-related events have continued to rise as one-off events cause cascading impacts throughout urban areas (e.g., the damage of energy infrastructure by a flood event causing city-wide blackouts; Calvin et al. 2023). This necessitates the rapid development and deployment of adaptation strategies, which include the adaptation of both social and physical infrastructural systems to manage the interconnected risks affecting urban communities. The Intergovernmental Panel on Climate Change (IPCC) has called for the immediate implementation of urban adaptation plans that identify synergies between mitigation, adaptation, and Sustainable Development Goals (SDGs), but progress has to-date been slow and uneven (Shaw et al. 2023). Asian urban areas are considered to be particularly high-risk, presenting opportunities to implement adaptation strategies (Shaw et al. 2023). Such measures include: infrastructural adaptation (e.g., flood protection measures), institutional adaptation (e.g., sustainable land-use planning), natural ecosystem-based adaptation (e.g., coastal mangrove restoration, urban greening), and behavioural adaptation (e.g., capacity building and preparedness measures; Shaw et al. 2023). The implementation of these strategies in Asian countries, however, faces barriers relating to governance, financing, and inadequate evidence for prioritizing actions – necessitating further research and partnership across the region (Shaw et al. 2023).

Nature-based solutions & ecosystem services

Nature-based solutions (NbS) jointly offer climate change mitigation and adaptation opportunities while providing benefits to human wellbeing and biodiversity (Cohen-Shacham et al. 2016). NbS can maintain and enhance ecosystem services in urban contexts, including those that bolster resilience to environmental change (e.g., mitigation of urban heat island effect, protection from floods, regulation of air quality; Babí Almenar et al. 2021). NbS have been categorized in literature based on the type of modification or management strategy they implement: solutions in existing natural areas with minimal intervention (e.g., the protection of a woodland), solutions that restore or manage traditional ecosystems (e.g., agroforestry, restoration of a coastal wetland), or solutions that engineer new ecosystems in modified environment (e.g., green walls, urban gardens; Pereira et al. 2023). All of these NbS types are relevant and useful for increasing the resilience of urban areas to environmental change and have increasingly been recommended in literature as an effective adaptation strategy (Pereira et al. 2023; Prodanovic et al. 2024). The IPCC has cited the "failure to address complex interconnected risks" as one of the "greatest gaps between policy and action" for urban adaptation (Shaw et al. 2023, pg. 6). NbS provide a pathway to bridge this gap in a manner that considers both social and environmental challenges, offering a promising and important area for research.

In urban environments, green infrastructure has emerged as an important component of NbS, facilitating the development of natural adaptive capacities alongside urban development (Pauleit et al. 2017). Actions include the addition or enlargement of urban green spaces (e.g., peri-urban parks, gardens, green walkways), construction of green roofs, walls, or road barriers, and replacement of impermeable pavements with permeable alternatives (Cortinovis & Geneletti 2018). While more traditional NbS, such as the large-scale protection or restoration of natural landscapes, also have their role to play in mitigating climate change and biodiversity loss, they are often infeasible to implement in highly fragmented, urbanized environments (Goddard et al. 2010; Kowarik 2011). Green infrastructure NbS offer a useful way to avert these competing trade-offs, as they can be directly integrated into existing urban infrastructure or new development plans (Khodadad et al. 2023; Prodanovic et al. 2024). These solutions have commonly been recommended as 'low-regret' measures for disaster risk reduction and adaptation and are increasingly being adopted in urban planning processes (Dodman et al. 2023).

Environmental policy in Hong Kong

The vulnerabilities of urban areas to environmental change, and the potential they hold to identify impactful SIPs, are notably salient for the Hong Kong Special Administrative Region (SAR; hereon referred to as 'Hong Kong'). As the case study site selected for this dissertation, Hong Kong demonstrates a unique combination of intensely modified urban areas and well-preserved natural landscapes. Historic environmental policy took shape during its time as a British colony from 1841 to 1997, which saw the establishment of the Environmental Protection Department and implementation of environmental legislation such as the Country Parks Ordinance (1976), Air Pollution Control Ordinance (1983), and Environmental Impact Assessment Ordinance (1997; Jim 1986; Liebman 1998; Hills 2002). The city's approach to environmental policy has undergone a transition from tackling major pollution issues to proactively pursuing sustainable development at the local and regional level (Hills 2002; Li 2021). In particular, Hong Kong and the neighbouring Macao SAR and Guangdong Province announced a joint plan in 2012 for long-term cooperation in transforming the region into a 'low-carbon, high technology' city cluster (Mah & Hills 2016).

Hong Kong's modern environmental policy revolves around four pillars: waste management, clean air, climate change, and biodiversity & conservation. The first Climate Action Plan (CAP) was released in 2017 in response to the Paris Agreement, setting a target to reduce its carbon intensity by 65–70 percent by 2030 relative to a 2005 baseline (HK Government 2017b). The CAP was also accompanied by the launch of a Climate Change Working Group on Infrastructure to focus on bolstering infrastructural adaptive capacities, with some references to the implementation of green infrastructure (HK Government 2017a). Separately, the first Biodiversity Strategy and Action Plan (BSAP) was released in 2016 with mention of various urban NbS opportunities that would be explored (e.g., urban parks, sustainable slope greening, green infrastructure). In 2021, the Hong Kong Government updated its CAP to report on progress and set a net zero target for 2050 (HK Government 2021), in addition to also releasing its Clean Air Plan and Waste Blueprint for 2035. To date, however, there is little exploration of the opportunities for joint environmental interventions across the various administrative pillars. Each of the policy plans are developed separately across different timelines, despite all outlining goals that converge in 2035 and 2050. With the imminent update of the BSAP and CAP approaching, research to elucidate the areas of potential synergy between Hong Kong's various environmental policy agendas will be particularly important.

Justification of Research Approach

Choice of target journal

The target journal that has been selected for submission is *Land Use Policy*, an interdisciplinary journal focusing on the intersection of urban and rural land use for the formulation of effective land use policies (see Appendix I for journal submission guidelines). This journal was selected for several reasons: firstly, the interdisciplinary nature of the journal is aligned with the range of methods and disciplines drawn from in this dissertation, including human and physical geography, conservation biology, and urban development. Secondly, the aim of this dissertation is to inform policy development in Hong Kong for climate change action and nature conservation. This objective is similarly reflected in the aim of the journal: 'to provide policy guidance to governments and planners and it is also a valuable teaching resource'. To facilitate the dissemination of research to broader, non-technical audience, the journal also includes a plain language 'highlights' section and graphical abstract submission. Both of these components will be practical for sharing this research with Hong Kong policymakers and non-academic stakeholders and were additional factors that informed the journal selection process. The outcomes of this dissertation are also highly applicable and informative to global geographies beyond the case study site, and thus the international scope of *Land Use Policy* also lends well to disseminating learnings more broadly. Finally, the journal was selected because it supports open access, an important criterion in ensuring that outcomes are accessible to a wide range of audiences and socioeconomic backgrounds.

Justification of methods

This subsection proves additional discussion and justification for the methodological approach developed for this study, supplementing the Materials and Methods section of the journal submission draft (pg. 19). In light of the gaps and existing literature discussed, this dissertation seeks to address the following research questions:

- How can geospatial methods be used to map linkages between climate and biodiversity policy action?
- To what extent can the risks and opportunities stemming from climate change and nature loss be quantified to mobilize joint policy action on these issues?
- What are the priority areas and opportunities for Hong Kong to implement nature-based solutions that leverage joint climate and nature benefits?

The research approach developed aims to apply existing methodological tools and frameworks to a novel context – both with regards to the climate-nature interface and the geographic context. It was designed with several factors in mind: practicality, feasibility, and academic novelty. Given that the primary aim of this study is to inform policy action, specifically in Hong Kong, it was important to derive research outcomes and outputs that would be practically oriented towards decision-making stakeholders. Secondly, the study needed to be feasibly conducted within the available timespan (approximately 6 months) and therefore leveraged existing datasets as opposed to primary data collection methods. Finally, the study also aimed to contribute novel and interdisciplinary insights to academic disciplines intersecting with geography, conservation biology, and environmental policy. With these criteria in mind, the initial direction of the research approach was shaped through consultation with a broad range of stakeholders from academia, local NGOs, policymakers, think tanks, and business (see Exhibit A), held via 1-on-1 meetings (virtually and in-person), to assess:

a) Current gaps and barriers pertaining to NbS, climate change policy, and conservation action in Hong Kong;
b) Existing and ongoing work on this topic in Hong Kong and the broader region;
c) Datasets that are available for use;
d) Gaps in academic theory;
e) Appropriate methodologies and approaches to address key gaps given the available data.

The consultation process helped determine that an empirical approach would be most effective for engaging with decision-making stakeholders and contributing to the existing body of scientific literature. From there, the methodology was shaped by considering data availability in relation to analytical frameworks that would address the research aims. Two primary methodological components were selected: geospatial analysis and land use scenario modelling. A geospatial analytical approach was chosen due to its effectiveness in informing land use management strategies and policy decisions at various geographic scales. Their outputs are also easy to interpret and visually engaging, lending itself to communicating research insights with non-academics (Miller & Small 2003; Scott & Rajabifard 2017). Specifically, land use scenario modelling was chosen as a framework under which future decisions and pathways could be visualized, compared, and evaluated. The use of scenarios is widely applied across disciplines to develop effective strategies for uncertain futures (Ramírez & Wilkinson 2016), including strategies to mitigate climate change and address nature loss (Chen et al. 2020; Wikramanayake et al. 2020; Kim et al. 2023).

The geospatial tools, analyses, and platforms used were also selected based on data availability and resolution. Local datasets were sourced wherever possible to achieve granularity and accuracy, such as a high-resolution land use map of Hong Kong from the Chinese University of Hong Kong (Kwong et al. 2021). However, given that this study addresses a topic that is relatively nascent and understudied in Hong Kong, local data were not always available – nor were they feasible to collect within the constraints of this study. As a result, secondary data were retrieved from regional substitutes (e.g., studies conducted in the adjacent Guangdong Province) to use as model inputs. Global datasets were leveraged for large-scale, complex modelling outputs when downscaling or resource-intensive data processing fell outside the scope of this study (e.g., models of sea level rise under future climate change pathways). However, the study could only utilize datasets with a spatial resolution that was granular enough for Hong Kong's small geographic scale, leading to the omission of some relevant nature-related global datasets with coarse spatial resolution. This was another factor that led to adjustments to the methodology from existing frameworks and approaches taken in other studies, requiring a level of creativity and flexibility when devising the methodology for this dissertation. Ultimately, this research approach formed an empirical methodology that aimed to balance scientific rigor with applicability for policy stakeholders. The exact models, analyses, and platforms used are further described in the Materials and Methods section (pg. 19).

Exhibit A. List of individuals consulted for the initial scoping phase of the research approach development process, ordered alphabetically by first name (Sept. 2023 to Jan. 2024).

Name	Company	Role	Location
David Baker	School of Biological Sciences, University of Hong Kong	Associate Professor	Hong Kong, HK
Felix Leung	The Nature Conservancy	Climate Change Fellow	Hong Kong, HK
Hollie Booth	The Biodiversity Consultancy	Technical Director, Nature Strategies	Jakarta, Indonesia
Jason Wong	Hong Kong Environment and Ecology Bureau	Conservation Officer	Hong Kong, HK
Joseph Bull	Dept of Biology, University of Oxford	Associate Professor in Climate Change Biology	Oxford, UK
Karen Ho	World Wildlife Fund	Head of Corporate and Community Sustainability	Hong Kong, HK
Katie Chan	Business Environment Council	Senior Officer, Policy and Research	Hong Kong, HK
Katrina Kendall	Nature-based Solutions Initiative, University of Oxford	DPhil Student	Manila, Philippines
Kitty Tam	Civic Exchange	Climate Transition Programme Lead	Hong Kong, HK
Lawrence Iu	Civic Exchange	Executive Director	Hong Kong, HK
Lionel Mok	Civic Exchange	Sustainable Finance Programme Lead	Hong Kong, HK
Malcolm Starkey	The Biodiversity Consultancy	Chief Innovation Officer	Cambridge, UK
Marine Thomas	The Nature Conservancy	Senior Conservation Programme Manager	Hong Kong, HK
Sophus zu Ermgassen	Leverhulme Centre for Nature Recovery, University of Oxford	Postdoctoral Researcher	Oxford, UK
Steve Smith	Oxford Net Zero / CO2RE	Executive Director	Oxford, UK

Submission Draft

The following chapter provides drafts of the cover letter and full manuscript prepared for submission to *Land Use Policy* (see Appendix I for journal submission guidelines). To maintain anonymity, any identifying information in the submission documents has been redacted.

16th August 2024

Dr JA Zevenbergen & Dr Xiaoling Zhang
Co Editors-in-Chief
Land Use Policy

Dear Dr Zevenbergen and Dr Zhang,

We are writing regarding the manuscript entitled: *Opportunities to balance urbanization, climate change, and nature conservation policy agendas via nature-based solutions: A case study of Hong Kong*, which we have submitted for consideration for your journal.

Amidst a pressing need to reach global climate and biodiversity goals, urban areas face challenges in balancing socioeconomic development and environmental trade-offs. In this manuscript, we model these trade-offs for Hong Kong under a range of plausible land use change scenarios, producing policy-relevant recommendations that are relevant to both local stakeholders and the global scientific community.

We believe this research is highly relevant for *Land Use Policy* as it explores present and future urban land use regimes for the formulation of effective land use policies. It aligns with the journal's interdisciplinary coverage of topics and practical aims, applying geospatial methods to bridge the gap between urban development and environmental policy agendas.

We hope you agree that the manuscript is well suited for the journal and addresses a topic of practical relevance to decision-making stakeholders across urban settings. We believe that joint policy action to address climate change and biodiversity loss in urban areas will be a key component of solving global environmental challenges – but it is crucial that this action is effectively informed by multidisciplinary and science-based evidence.

We look forward to hearing back from the journal.

Sincerely,

Ashley HY Bang
On behalf of all co-authors

Title Page

Article title

Opportunities to balance urbanization, climate change, and nature conservation policy agendas via nature-based solutions: A case study of Hong Kong

Author name(s) and affiliation(s)

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CRediT author contribution statement

AB: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – reviewing & editing, Visualization, Project Administration.
AF: Conceptualization, Methodology, Writing – review and editing, Supervision.
EM: Conceptualization, Methodology, Writing – review and editing, Supervision.

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Declaration of Interest statement

I have nothing to declare.

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Abstract

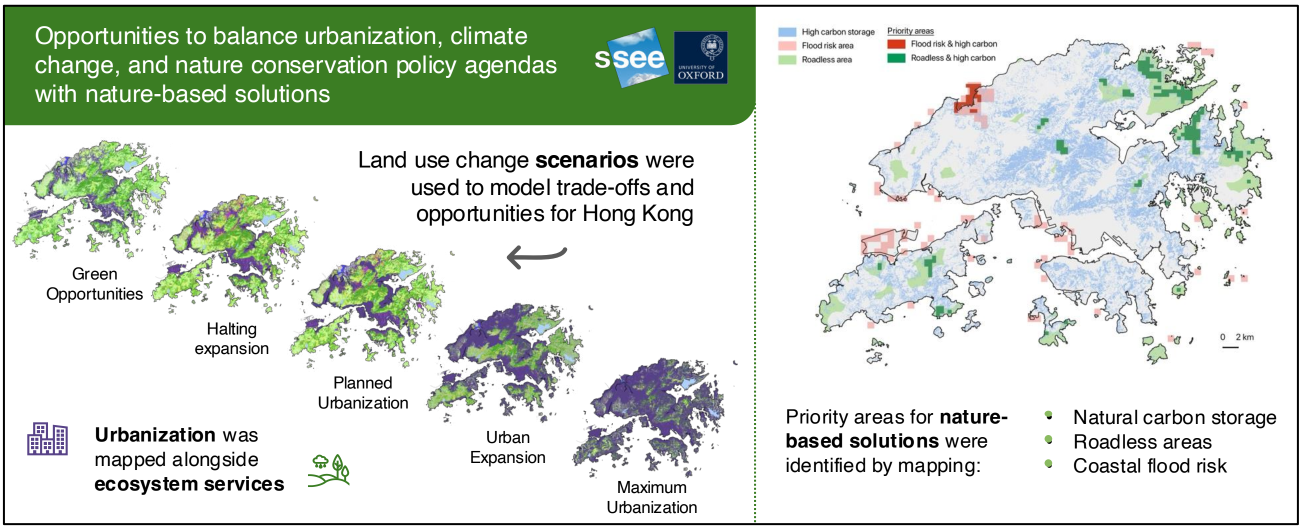
Urban areas face challenges in jointly addressing the global climate change and nature loss crises amidst the pursuit of socioeconomic development agendas. This trade-off prompts the need to explore sensitive intervention points that can be leveraged for positive climate and nature conservation outcomes, namely the implementation of nature-based solutions that provide synergistic benefits for climate and nature. Using Hong Kong as a case study, this study employs geospatial approaches to model the carbon storage, natural habitat, and climate risk trade-offs under five land use change scenarios for 2030. The results show that Hong Kong would suffer large reductions in climate mitigation benefits if new real estate developments and expansion plans are implemented, compromising natural habitats and the ecosystem services they provide. Several key areas are identified where urban development should be avoided to maximize these future benefits and minimize risk exposure, namely Mai Po, Chek Lap Kok, and Sai Kung. Furthermore, the results highlight opportunities to implement nature-based solutions to enhance existing carbon stores in natural habitats, reshape built infrastructure for nature connectivity, and adapt coastlines to mitigate climate risks. This study provides an evidence foundation for the implementation of nature-based solutions to bridge climate and nature policy agendas in Hong Kong and other urban environments.

Keywords: Climate change, nature, urbanization, ecosystem services, nature-based solutions, land use, Hong Kong

Highlights

- Urban areas face challenges in jointly addressing climate and biodiversity issues
- Scenarios of future land use change were modelled for Hong Kong
- Future urban expansion would lead to large losses in climate and nature benefits
- Nature-based solutions offer a way to balance both urban and environmental agendas

Graphical Abstract



1. Introduction

1.1. The joint climate and nature crisis

Climate change and nature loss are two of the most pressing environmental and societal challenges of the 21st century. The impacts of climate change, ranging from sea level rise to extreme weather events, have continued to intensify as global greenhouse gas emissions rise at faster rates each year (Calvin et al. 2023). Simultaneously, the relative abundance of vertebrate species, as measured by the Living Planet Index, has declined by 69 percent since 1970 (WWF 2022). It is well-established that climate change is a key driver of nature and biodiversity loss, alongside other drivers such as pollution, land use change, and invasive alien species (Balvanera et al. 2019). The impacts of climate change, including shifts in rainfall patterns, rising temperatures, and increasing intensities of extreme weather events, have significantly contributed to losses and changes in biodiversity at genetic, species, and ecosystem levels (Rinawati et al. 2013). On the other hand, the conservation of nature serves as a key climate change mitigation strategy, while also maintaining the diverse benefits for human health, environmental integrity, cultural value, and resilience to climate change that well-functioning ecosystems provide (Costanza et al. 1997 p. 199; Sandifer et al. 2015; Smith et al. 2021). These multifaceted benefits, often referred to as ecosystem services, crucially demonstrate the interlinkage between climate change and biodiversity – both in their causes and solutions (Smith et al. 2022).

At the global level, international frameworks have outlined commitments to tackle climate change and nature loss, but these issues are often addressed in parallel rather than in tandem (Pettorelli et al. 2021). The 2015 Paris Agreement established an international target to limit global temperature rise to 2 degrees Celsius above pre-industrial levels, prompting the widespread establishment of targets to reach net zero greenhouse gas emissions. In parallel, the 2022 Kunming-Montreal Global Biodiversity Framework (GBF) outlines a global goal to halt and reverse biodiversity loss by 2030 and reach full recovery by 2050, which are framed under nature positive commitments (UNFCCC 2015; CBD 2023). The separate governance of climate and nature agendas at the global level subsequently shapes regional and subnational policy. Each signatory nation of the Paris Agreement and GBF is expected to action and implement targets through mechanisms such as Nationally Determined Contributions (NDCs) for climate action and National Biodiversity Strategies and Action Plans (NBSAPs) for nature conservation (CBD 2011; UNFCCC 2015). Outside of these national frameworks, self-convening networks and coalitions have outlined nature positive and net zero ambitions across cities, sectors, and regions (e.g., C40 Cities Climate Leadership Group, Nature Positive Universities, the Fashion Pact). Individual companies and businesses are also being held accountable amidst the ongoing development of climate- and nature-related reporting standards, such as the EU Corporate Sustainability Reporting Directive and the International Sustainability Standards Board. The current segregation of climate and nature policy action in both government and private sector agendas demonstrates a missed opportunity to effectively deliver on international commitments within the ambitious timelines set forth.

1.2. Challenges associated with urbanization

Progress towards environmental goals on the whole has varied across the globe as societies balance challenges that stem from economic growth and social development agendas (Scherer et al. 2018; Raiser et al. 2020; Hughes et al. 2022). Historically, urbanization levels have been tightly linked with traditional measures of economic growth (i.e., GDP per capita), whereby economic growth promotes the expansion of modern infrastructure and urban populations, and vice versa (Henderson 2003; Chen et al. 2014). Urban expansion is projected to continue accelerating in the coming decades: 68 percent of the world's population is estimated to be urban by 2050, with close to 90 percent of this growth taking place in Africa and Asia (UN DESA 2019). However, these trends place large constraints on reaching global climate and nature goals, given that early to mid-stages of economic growth and urbanization have been established as drivers of CO_2 emissions, energy consumption, and land conversion (Kasman & Duman 2015; Wang et al. 2018; Liu & Bae 2018; Chen et al. 2020). Urban areas therefore serve as important sites of study on sensitive intervention points that can be leveraged for positive climate and nature outcomes for both the environment and society.

An international finance centre within the Asia Pacific (APAC) region, Hong Kong is a particularly compelling study site that encapsulates these intersectional challenges. The city's densely populated and compact urban area has experienced decades of urban development and globalization (Cui & Chui 2021). While built-up areas currently cover a quarter of the land surface, development plans laid out for the next five to ten years emphasize the need for expansion in housing supply, mixed-use commercial developments, and transportation infrastructure (HK Development Bureau 2021). At the same time, Hong Kong preserves a large proportion of its land area for conservation and recreational use, which provides important habitats for migratory bird species and local wildlife (Jim 1987; Wikramanayake et al. 2020). Hong Kong's climate change and nature conservation policy agendas are developed by separate governance bodies – the Environmental Protection Department directing the former and the Agriculture, Fisheries & Conservation Department (AFCD) managing the latter – with little mention of nature, biodiversity, or ecosystem services in its Climate Action Plan (CAP) for 2050 (HK Government 2021a). In 2025, the government will simultaneously evaluate the short-term targets set forth in the 2050 CAP and update the city's Biodiversity Strategy and Action Plan (BSAP) for the first time since its release in 2016 (HK Government 2021a; ADM Capital Foundation 2024). Furthermore, there is a growing private sector interest in supporting activities that mitigate climate- and nature-related risks, with market-led desires to become a regional leader in this regard (Yiu 2023; Hong Kong Monetary Authority 2024). Given these contextual aspects, a study that provides an evidence base for the alignment of nature and climate policy agendas with infrastructural development plans is of high interest for Hong Kong. At a broader level, lessons from this research would provide insights into the trade-offs associated with balancing ambitious plans for urbanization alongside action for climate change and nature conservation.

The linkage between climate change and nature loss has been explored indirectly in Hong Kong through studies on land use, carbon sequestration, and ecosystem services (e.g., Delang & Hang 2010; Kong et al. 2014; Liu & Lai 2019; Liang et al. 2022), but few have directly focused on synergistic linkages and benefits. Elsewhere in the greater China region, geospatial approaches have been employed to model changes in carbon storage under various land use scenarios and map critical habitats for land management strategies (Jiang et al. 2017; Liu et al. 2019; Wu et al. 2021). A broad range of studies that investigate the joint benefits of climate and biodiversity actions exist under a high-level framing at the global level (e.g., Smith et al. 2019, 2022; Soto-Navarro et al. 2019) or largely explore case studies in the Global North (e.g., (Bryan et al. 2016; Dybala et al. 2019; Gorman et al. 2023). Such studies highlight the usefulness of geospatial approaches for advising decision-making for joint climate, nature, and human development benefits that have not yet been applied to the Hong Kong or broader regional context. With many other cities in the greater China and Asia Pacific regions positioned to undergo rapid urbanization in the coming decades, the lessons learned from a locally rooted case study will be particularly salient.

1.3. Bridging with nature-based solutions

Nature-based solutions (NbS), defined as actions to protect, sustainably manage, or restore natural ecosystems in ways that benefit both people and nature, are one such integrated approach that jointly addresses environmental and social challenges (Cohen-Shacham et al. 2016; Seddon et al. 2020). For example, the protection or restoration of coastal mangrove habitats provide a highly effective means for carbon sequestration whilst protecting human and natural systems from flood inundation (Pontee et al. 2016). Provided that appropriate monitoring systems can demonstrate the long-term sequestration of carbon and uplift of biodiversity associated with these interventions, the investment in a single NbS project would effectively contribute to both net zero and nature positive goals. NbS are therefore a crucial tool for jointly addressing the climate and biodiversity crises in a manner that is resource-efficient, equitable, and rapidly deployable (Seddon et al. 2020; Key et al. 2022). While not every NbS project would be able to deliver joint benefits of equal magnitude for climate change and nature, they nevertheless demonstrate the importance in investigating the climate mitigation and adaptation benefits that conservation projects provide, and conversely the ways in which positive biodiversity outcomes can be derived from climate change mitigation measures.

Using Hong Kong as an urban case study, this paper aims to demonstrate key leverage points and areas of synergy between climate and nature policy agendas. Geospatial methods and land use scenario modelling is used to: a) model the present-day carbon storage capacity of natural ecosystems; b) quantify the carbon storage, natural habitat, and climate risk trade-offs under five plausible land use change scenarios for 2030; c) provide an evidence foundation for spatial prioritization of areas to implement nature-based solutions alongside urbanization agendas.

2. Materials and methods

The study is divided into three methodological components, outlined in Figure 1. Firstly, the ecosystem services offered by Hong Kong's landscapes are scoped through the mapping of carbon storage, roadless areas, and coastal flood risk. Secondly, the changes in these risks and benefits are modelled under various urbanization and land use change scenarios. Lastly, the identified risks and benefits are spatially overlaid to prioritize areas for joint climate and biodiversity action with NbS. All spatial data processing and analysis was carried out in the Geographic Information Systems platform QGIS (*v3.34*; QGIS Association 2024).

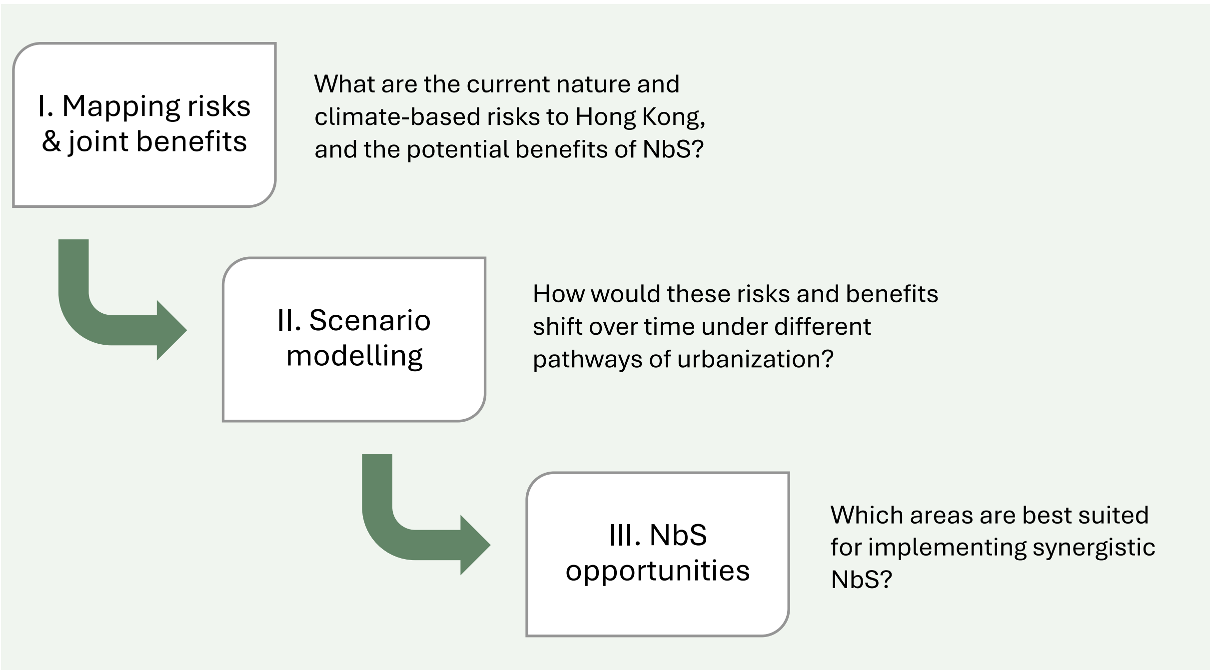


Figure 1. Overview of methodological approach, comprised of three components: mapping risks & joint benefits, scenario modelling, and identifying nature-based solution (NbS) opportunities.

2.1. Study Area

Hong Kong, a Special Administrative Region of the People's Republic of China, is among the world's most densely populated regions (Xie et al. 2024). A total population of 7.54 million is concentrated in a land area of 1,114 km^2, approximately 7 percent of which is reclaimed and 7 percent is used for residential purposes (HK Government 2017, 2023, 2024b). By comparison, the average residential land supply ratio for coastal cities in mainland China is approximately 22 percent (Han et al. 2020). Geographically, Hong Kong lies in a subtropical climatic zone with mountainous terrain and rocky coastlines. It is divided into eighteen districts distributed across three regions: Hong Kong Island, Kowloon, and the New Territories (inclusive of outlying islands such as Lantau Island; Figure 2). The majority of urban areas and commercial business districts border the Victoria Harbour along Kowloon and the north side of Hong Kong Island. By contrast, the New Territories largely consists of small-scale agricultural land, residential communities, and nature reserves.

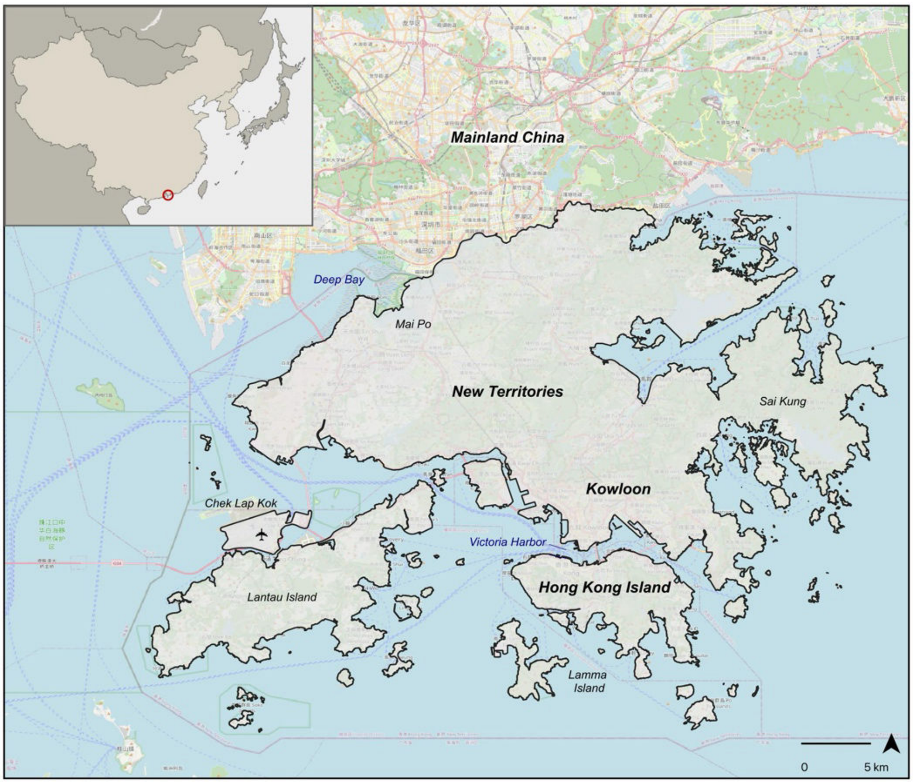


Figure 2. Map of the study area. Hong Kong is located on the southern coast of mainland China and is comprise of three geographic regions: Hong Kong Island, Kowloon, and New Territories. Major outlying islands include Lantau Island, Lamma Island, and Chek Lap Kok (site of the Hong Kong International Airport). Note: map lines delineate study areas and do not necessarily depict accepted national boundaries.

Much of Hong Kong's protected area (PA) network was established under the 1976 Country Parks Ordinance during its time as a British colony from 1871 to 1997 (Jim 1986). Managed and monitored by the AFCD, the PA network consists of 25 country parks, which include recreational facilities and hiking trails, and 22 special areas, which are primarily focused on nature conservation. In total, they cover 38 percent of Hong Kong's land area (HK Government 2024b).

2.2. Mapping ecosystem services

A selection of ecosystem services provided by Hong Kong's natural habitats were mapped to explore potential overlaps and synergies between areas supporting Hong Kong's climate and nature conservation agendas, namely carbon storage and the provision of habitats for wildlife. The risk of coastlines to flood inundation were also mapped to identify where the maintenance or enhancement of ecosystems providing coastline protection would be most needed in Hong Kong.

2.2.1. Carbon storage

To map the climate mitigation potential of the Hong Kong landscape, carbon storage was estimated using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (v3.14.1) (Natural Capital Project 2024). Developed by the Natural Capital Project, the InVEST model provides a spatially-explicit approach for assessing terrestrial carbon storage changes with relatively simple input data requirements (Deng et al. 2022). A 10-meter resolution land use and land cover (LULC) layer from Kwong et al. (2022) was used as the input for the Carbon Storage and Sequestration model on InVEST. The LULC layer provides a city-wide habitat and land use map for Hong Kong produced from high-resolution satellite imagery and ground-based field surveys in 2020 (Figure 3).

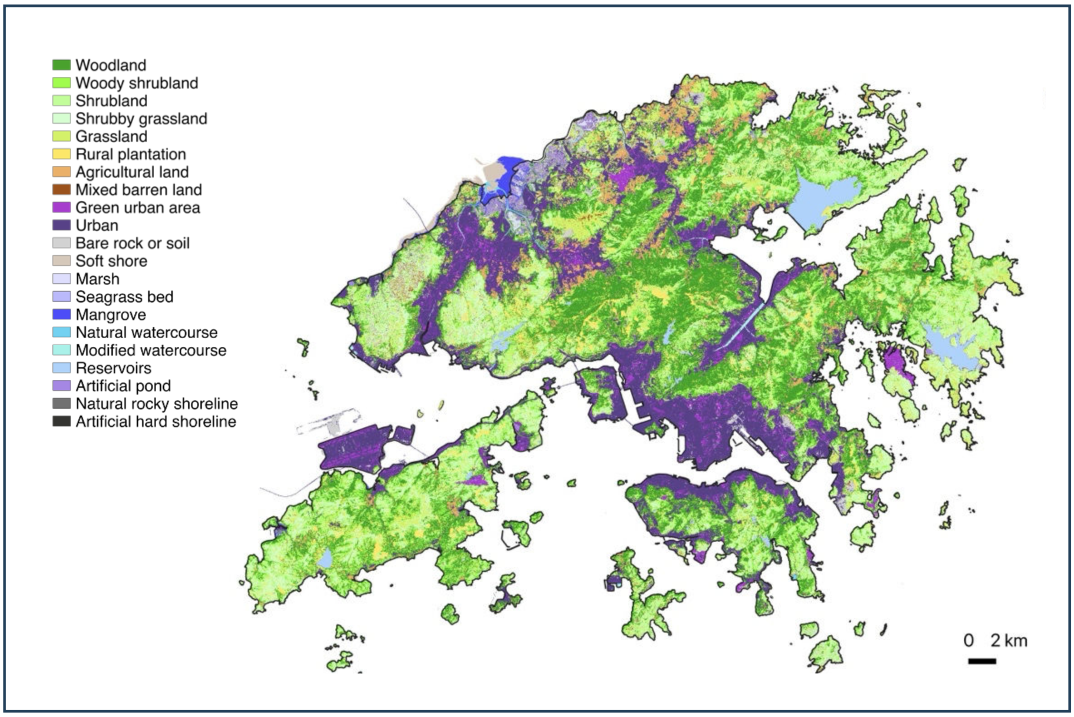


Figure 3. Land use and land cover (LULC) map of Hong Kong at 10 x 10 m resolution from 2020 (source: Kwong et al. 2021). The map delineates urban areas, vegetation, bodies of water, and other land cover types, representing a baseline reference point for modelling future land use change scenarios.

The InVEST model estimates carbon storage by summing the carbon density (C) of each land use type (*i*), comprising of: aboveground biomass (C_a), belowground biomass (C_b), soil biomass (C_s), and dead organic matter carbon storage (C_d). The carbon density values for each LULC type were acquired from existing studies within the Hong Kong-Guangdong region derived from field studies and regionally-zoned classifications (Liu et al. 2019; see Supplementary Material Table 1 for carbon density values and sources). Carbon density values for each land use type were then summed across the Hong Kong landscape to produce a total carbon storage estimate (C_{total}), as defined in Equation 1 (Zhao et al. 2023).

Equation 1.

$$C_i = C_{i,a} + C_{i,b} + C_{i,s} + C_{i,d}$$

$$C_{total} = \sum_{i=1}^{n} C_i \times A_i$$

Where:

n = the number of land use classes

A = the area of each land use class

The InVEST model makes several assumptions of note. Firstly, each pixel of a given land cover class is considered to be identical in its carbon storage capacity, which does not account for the complex heterogeneity that exists within each land cover type. For instance, the carbon storage capacity of woodlands in different locations may differ despite being classified under the same land cover type, and this is not captured by InVEST. Carbon storage estimates would therefore be conservative for circumstances where vegetation carbon storage increases with time, and vice versa in future conditions that cause carbon storage to decline. The model also takes a static, non-temporally explicit approach to carbon storage, assuming that there is no change to the carbon density of a parcel of land with time (i.e., the storage capacity of a hectare of grassland will be the same in 2030 as it is in 2020). In reality, the carbon storage capacity of natural landscapes fluctuates positively or negatively with time as a result of various climatic, environmental, and anthropogenic influences (Xu et al. 2018; Wani et al. 2023). In modified and managed landscapes, the management methods employed, such as the application of fertilizers, affect whether soils produce net emission or sequestration of carbon (Hundertmark et al. 2021), and this also impacts broader ecosystem dynamics in ways that are not captured by the model. Lastly, the carbon density data upon which this model was run was obtained from secondary sources from the broader region given the paucity of relevant data in Hong Kong. Despite these assumptions, the InVEST model provides a useful starting point to simulate changes in carbon storage under different land use change scenarios, particularly given the limited data available to run more complex models.

2.2.2. Roadless areas

In addition to maintaining carbon stocks, the conservation of nature crucially contributes to biodiversity goals by providing habitats for wildlife, which is explored in this analysis. Initially, a variety of indicators of ecological integrity and biodiversity were considered for this analysis, such as critical habitat coverage, occurrence of endangered species, and species extinction risk. However, global indices (e.g., the Species Threat Abatement and Restoration metric, species range rarity, the Biodiversity Intactness Index; Scholes & Biggs 2005; Mair et al. 2021; IUCN 2023) were too coarse in resolution to meaningfully discern and prioritize nature opportunities for Hong Kong. Similarly, the use of citizen science data (e.g., sightings on eBird or iNaturalist) to plot the occurrence of endangered species was deemed unsuitable due to a high sampling bias towards areas with high levels of human traffic. Ultimately, an analysis of roadless areas was deemed the most suitable proxy under the given constraints, particularly since this analysis has not yet been conducted for Hong Kong.

Roadless areas are commonly defined in literature as land areas that are 1 km or more away from roads (Ibisch et al. 2016). Land units that are farther from roads are, on the whole, less affected by direct and indirect environmental impacts such as deforestation, noise pollution, and wildlife mortality from car collisions, thereby serving as a proxy for landscapes that are of relatively higher ecological quality (Trombulak & Frissell 2000; Laurance & Balmford 2013; Selva et al. 2015). Following methods from existing studies (Trombulak & Frissell 2000; Selva et al. 2015; Ibisch et al. 2016), roadless areas were identified by extracting land areas around a 1-km buffer surrounding Hong Kong's road network (HK Government 2024c). The resulting roadless areas identified were mapped relative to PAs, defined by the World Database on Protected Areas (WDPA) and the Hong Kong AFCD (HK Government 2023; UNEP-WCMC & IUCN 2024), to identify the proportion of roadless areas without conservation protection status.

2.2.3. Coastal flood risk

The final component of the mapping analysis aimed to identify areas where ecosystem services associated with climate risk mitigation or adaptation would be most needed. In Hong Kong, the combination of increasingly intense monsoon seasons and the expansion of real estate development along coastal areas has placed flooding and inundation as a highly material climate risk (Singh & Cai 2023; Lai et al. 2023). The World Resources Institute (WRI) Aqueduct Coastal Inundation Hazard map was used to identify vulnerable coastal areas by selecting a high-impact, low-probability event (100-year flood return period) and a high-emission scenario (RCP 8.5), demonstrating an upper-bound projection for future risks. The resulting flood risk areas were spatially mapped across Hong Kong's coastline, highlighting where water flow regulation or flood control ecosystem services would be most beneficial for surrounding ecosystems and urban settlements.

2.3. Scenario modelling for 2030

Scenario modelling was used to investigate shifts in the identified ecosystem services under future urbanization pathways. Using the 2020 LULC layer as a baseline, five scenarios were constructed to simulate a variety of land use and development pathways for 2030 (described in Table 1). The scenarios were developed to capture the local land use and development context of Hong Kong, such as major urban development projects outlined by the Planning Department, and local geographic conditions that influence patterns of urban expansion. At the same time, the scenarios also drew upon conceptual elements of the globally recognized Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSPs) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Nature Futures Framework (NFF) (Calvin et al. 2023; Kim et al. 2023). The IPCC SSPs were referenced for their projections of socioeconomic development at the global and regional scale in relation to greenhouse gas emission pathways (Calvin et al. 2023). The NFF was referenced to develop the 'optimistic' scenarios for sustainable development, capturing different value systems and societal goals that may shape positive futures for nature and society (Pereira et al. 2020). The scenarios were designed to explore a range of potential futures for Hong Kong's urbanization, climate change adaptation, and nature conservation agendas. While some scenarios may seem extreme or hypothetical, they were intentionally designed to examine a broad range of potential future outcomes. The alignment of SSPs with NFFs is based on conceptual parallels between global socioeconomic trajectories and nature-related priorities, recognizing that various combinations of global and local choices can be made. Assumptions are derived from available data and literature, with an understanding that real-world feasibility or plausibility may vary. For each scenario, a new LULC layer was constructed according to the defined parameters (Table 1).

Table 1. Description of five future land use scenarios for 2030, ranging from low to high levels of urbanization and commitment to maintaining natural ecosystems: 1) Green Opportunities, 2) Halting Expansion, 3) Planned Urbanization, 4) Urban Expansion, and 5) Maximum Urbanization. The scenarios considered local urban expansion agendas, such as plans for major development areas, as well as conceptual references to global scenario frameworks (i.e., the IPCC SSPs and IPBES NFF scenarios).

Scenario name	**Description**	**Conceptually influencing SSP or NFF**	**Details and assumptions**
Green Opportunities	Any non-urban modified land is restored to its natural state	NFF 'Nature for Nature': preservation of nature's diversity and functions is of primary importance SSP1 'Taking the Green Road': a gradual shift towards a more sustainable path, emphasizing environmentally and socially inclusive development. CO_2 emissions reach net zero around 2050.	Based on historical maps and surveys characterizing the vegetation and ecology of Hong Kong, the natural land cover state was designated as shrubby grassland (Boyden et al. 1981; Jim 1986; Liang et al. 2022). Assumes that all other land use types remain the same as the 2020 baseline
Halting Expansion	No further urban intensification takes place beyond 2020	NFF 'Nature for Culture': a focus on shifting social mindsets to connect cities to nature through green buildings, community gardens, and biodiverse urban spaces. SSP2 'Middle of the Road': socioeconomic and technological trends do not shift markedly from historical patterns, with some improvements in resource and energy use. CO_2 emissions reach net zero around 2075.	Assumes that all land use types remain the same as the 2020 baseline.

Planned Urbanization	All planned developments for 2030 are greenlit	NFF 'Nature for Society': nature is optimized for the ecosystem services provided to people, including incentives for urban farming and ecotourism. SSP3 'Regional rivalry': competition among regions shifts a focus to domestic or regional resources and security, environmental goals are not a priority. CO_2 emissions peak in 2050 and gradually reach net zero by 2100.	All 'Major Committed/Planned Development Areas' outlined in the *Hong Kong 2030+ Strategic Plan* are converted to urban areas (HK Development Bureau 2021). Existing green urban areas are not altered, but new urban areas are converted directly to the urban land cover type.
Urban Expansion	All non-urban land areas are urbanized, excluding protected areas (PAs)	NFF: N/A, scenario does not portray a pathway towards a desired future for nature and society. SSP4 'A Road Divided': socioeconomic stratification within and across countries, with high investment in technology development. CO_2 emissions double by 2100	Excludes areas that are deemed geographically infeasible for construction (i.e., those with a slope greater than 30 degrees) and PAs. Assumes that new urban areas are converted directly to the urban land cover type. PAs were defined by the WDPA and AFCD, and zoning laws were defined by the Hong Kong Town Planning Board.
Maximum Urbanization	All non-urban land areas are urbanized, irrespective of current zoning criteria	NFF: N/A, scenario does not portray a pathway towards a desired future for nature and society. SSP5 'Fossil-fuelled development': rapid technological progress, high consumption and economic growth is pursued with a low regard for global environmental goals. CO_2 emissions triple by 2075.	Includes PAs or nature reserves, excludes areas that are deemed geographically infeasible for construction (i.e., those with a slope greater than 30 degrees), beaches and rocky shores, and existing green urban areas. Assumes that new urban areas are converted directly to the urban land cover type.

The changes to the ecosystem services from the 2020 baseline were then quantified for each future scenario to illustrate shifts in nature and climate outcomes. The LULC layers for each scenario were used as inputs to the InVEST Carbon Storage and Sequestration model to estimate future gains or losses in carbon storage for 2030 compared to the 2020 baseline. Additional climate change mitigation benefits of nature conservation, modelled through the protection of Hong Kong's currently unprotected roadless areas, were calculated under each scenario. Furthermore, the risks of coastal flooding to urban populations were quantified by calculating the proportion of urban areas located in flood risk zones for each scenario.

2.4. Opportunities for nature-based solutions

The result of all three analytical components that encompassed carbon storage, roadless areas, and coastal flood risk were combined to identify potential priority areas for implementing coastal and terrestrial NbS. The area of overlap between three spatial layers was quantified: the upper quartile of carbon storage pixels (denoted 'high carbon' areas), roadless area pixels, and coastal areas within at-risk flood zones (denoted 'flood risk' areas). Areas that had the highest potential for NbS implementation were indicated by those that had overlaps between these prioritization layers. These areas were specifically indicated by characterizing any 500 x 500-meter pixels that matched at least two out of three of the following criteria: a) flood risk area; b) a roadless area; c) had at least 50 percent coverage of high carbon storage areas. The criteria fulfilled by each area would help inform the type of NbS opportunities that would be most applicable for implementation, and could range from coastal flooding adaptation solutions to terrestrial habitat conservation strategies.

3. Results

3.1. Mapping ecosystem services

Carbon: The estimated current carbon storage capacity for Hong Kong was 10.9 megatonnes of carbon (Mt C) as of 2020. Areas that were forested, particularly PAs in the eastern and central areas of New Territories (e.g., Sai Kung, Ma On Shan, Sha Tin), had higher per-hectare storage capacities. Mai Po was identified as an area of particularly high carbon storage on the northwestern shoreline of New Territories (Figure). Situated on an estuary leading to Deep Bay, Mai Po is partially designated as a Wetland of International Importance under the Ramsar Convention (the Mai Po Nature Reserve) and is largely characterized by mangroves, estuarine sedges, and seagrass beds. Areas with the lowest carbon storage were urban areas and built-up land, particularly in business districts (e.g., north coast of Hong Kong Island, Kowloon) and reclaimed lands (e.g., Chek Lap Kok, coasts of Kowloon).

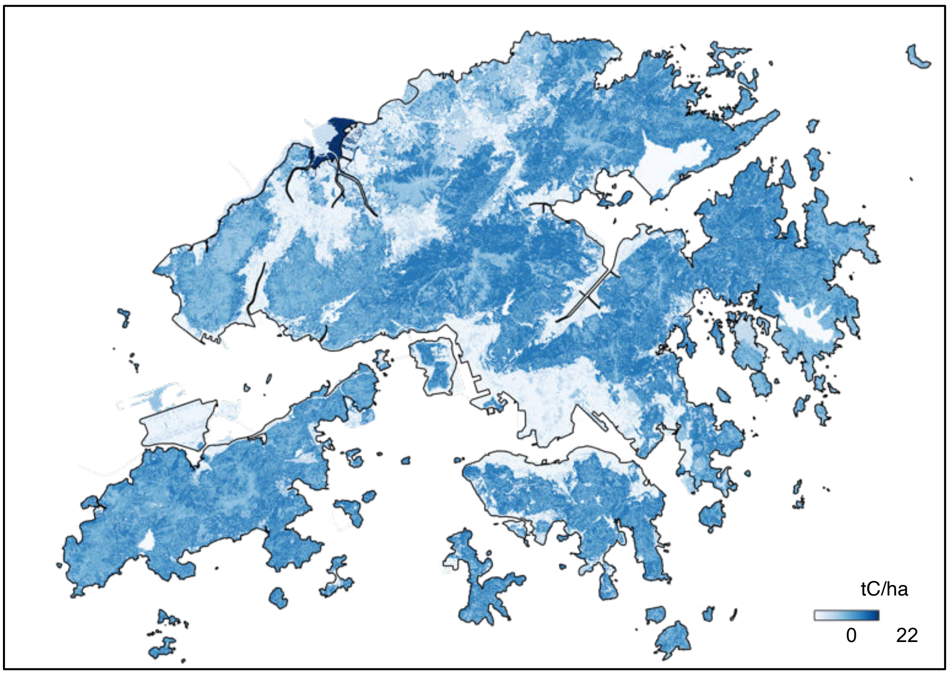


Figure 4. Carbon storage map of Hong Kong shown in tonnes of carbon per hectare (t C/ha), calculated from a 2020 baseline LULC layer. The total carbon storage capacity was estimated at 10.9 Mt C, with the mangroves and estuarine vegetation of Mai Po having the highest per-hectare carbon storage. Other areas with high carbon storage were those that have a high vegetation cover of woodland, grassland, and shrublands, while areas with the lowest carbon storage were urban land cover.

Roadless areas: A total of 176 km^2 in roadless areas was estimated for Hong Kong, making up about 16 percent of the city's total land surface. Most of the roadless areas were concentrated in the eastern parts of New Territories, portions of Lantau Island, and other outlying islands. These areas are largely dominated by shrubby grassland and some woodland, which may have existed in different distributional proportions prior to Hong Kong's past century of development and urbanization (Boyden et al. 1981). Overlaying these results with PA boundaries showed that 75 percent of roadless areas are already protected (132 km^2), particularly the largest roadless areas in the eastern New Territories (Figure 5). This is much higher than the global coverage of roadless areas by PAs (9.3 percent), and particularly promising given that the Asian continent has particularly low coverage of protected roadless areas of high ecological value (Ibisch et al. 2016). The remaining 25 percent (approx. 44 km^2) of roadless areas that are not protected are in outlying islands that are comparatively less built-up. There are several roadless areas on smaller outlying islands that are currently not under any PA designation or conservation zoning under statutory plans, such as Tung Lung Chau, Beaufort Island, and Tiu Chung Chau. Additionally, some roadless areas are in areas designated as Sites of Special Scientific Interest (SSSI) but do not have any conservation protection status, such as Sunshine Island, central Lantau Island, and southwestern Lamma Island. Within PAs themselves, less than a third of the parks were found to be roadless (31 percent, 132 km^2).

Coastal flood risk: Mapping coastal flood risk revealed that the western coastlines of Hong Kong are more at-risk compared to eastern coastal areas (Figure 5). The largest area of coastal inundation susceptibility was in the northwest coast of New Territories at the mouth of Deep Bay, which is also where the Mai Po Nature Reserve is located. Another identified area of vulnerability was the north side of Lantau Island, which is a reclaimed portion of land where the Hong Kong International Airport (HKIA) is situated. Other areas of risk emerged along artificially reclaimed western portions of the Victoria Harbor. The areas that had low flood risk were generally sheltered in large bays or inlets on east-facing coastlines (e.g., Tolo Harbour, Port Shelter, Cheung Sha, Tai Tam Bay).

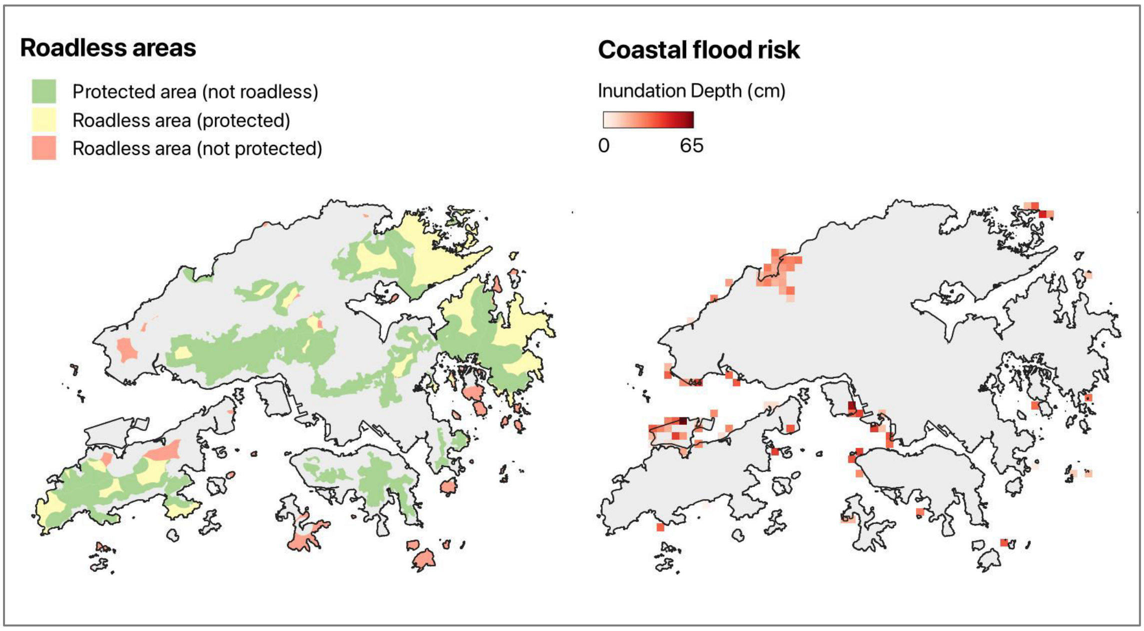


Figure 5. Map of roadless areas (right) and coastal flood risk areas (left) in Hong Kong. Roadless areas are those that are more than 1 km away from roads, representing higher potential to be valuable for biodiversity. Protected areas (green) have been overlaid to depict roadless areas that are currently protected (yellow) and roadless areas that are not protected (red). Flood risk areas show coastal inundation hazard for 100-year floods in 2030, under a RCP8.5 warming scenario (source: WRI 2020).

3.2. Scenario modelling

The five future land use change scenarios encompassed varying degrees of development and urbanization (Figure 6), resulting in gains and losses in estimated carbon storage capacity in relation to the 2020 baseline (Table 2). The Green Opportunities scenario returned all modified non-urban land to shrubby grassland, but this only resulted in a 2.5 percent (6.81 Mt C) increase in carbon storage capacity in relation to the baseline. No changes to carbon storage were modelled in the Halting Expansion scenario, given that baseline levels of land use were maintained without any additional modifications. Under the Planned Urbanization scenario, the conversion of natural land cover types to expand urban areas – largely in Kowloon and the New Territories – resulted in a 6.4 percent projected reduction (–0.65 Mt C) in total carbon storage. With further urbanization modelled under the Urban Expansion scenario, particularly along coastlines, total carbon storage was estimated to decrease by 66.2 percent (–6.54 Mt C). Finally, under the most extreme scenario of urban expansion, Hong Kong's carbon storage capacity is estimated to undergo a 168.1 percent reduction (–4.05 Mt C) in the case where all feasible land cover types are converted to urban areas.

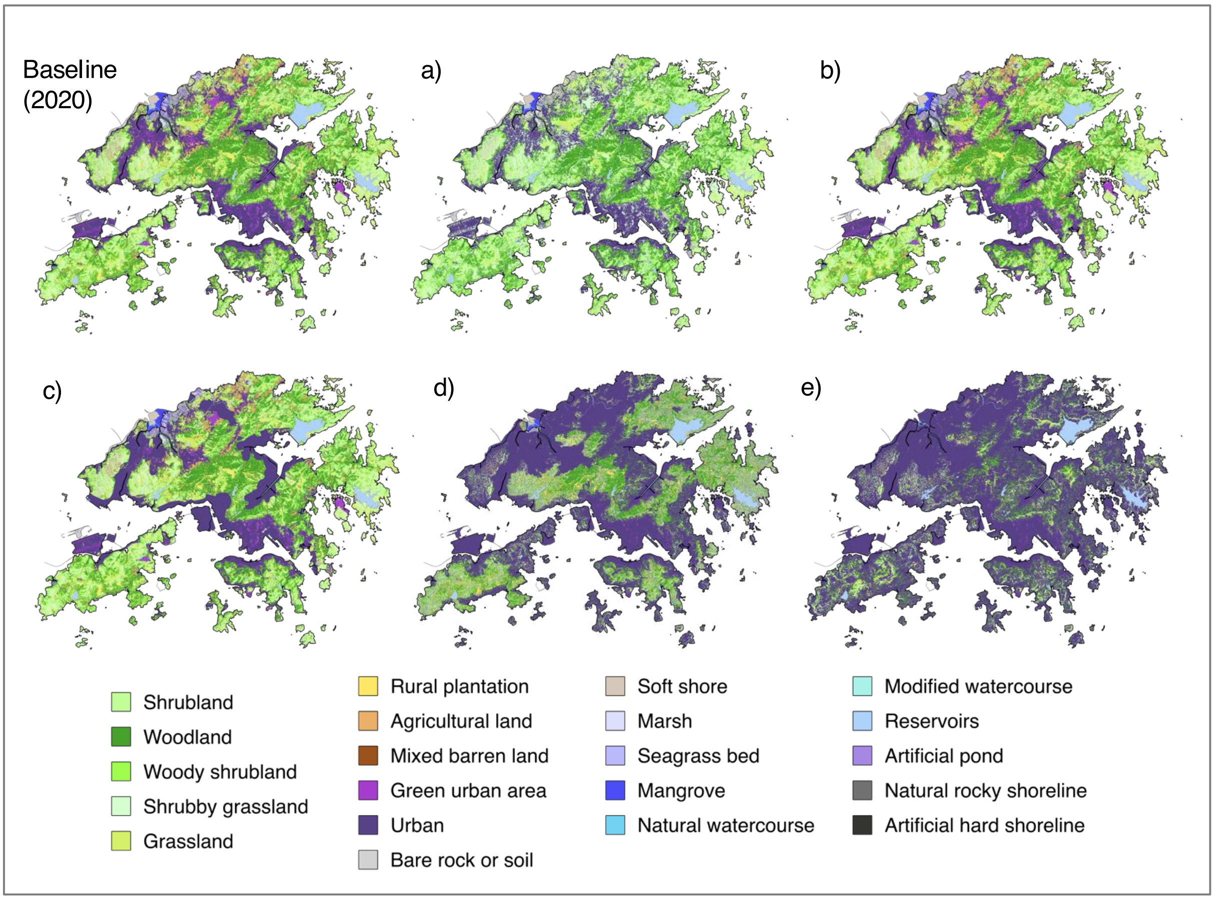


Figure 6. LULC maps of Hong Kong modelled under five future development scenarios for 2030, depicting increasing levels of urban expansion: a) Green Opportunities, b) Halting Expansion, c) Planned Urbanization, d) Urban Expansion, and e) Maximum Urbanization.

The potential carbon storage gains offered by the simulated conservation or rewilding of unprotected roadless areas varied under the different land use change scenarios (Table 2). In scenarios with a relatively high level of land protection and restoration in place, such as the Halting Expansion and Green Opportunities scenarios, further carbon storage benefits were marginal. However, in scenarios that simulate large-scale expansion of urban areas, the protection of roadless areas offered carbon storage benefits between 0.5 and 1.2 Mt C. These benefits were particularly pronounced in the Maximum Urbanization scenario, which resulted in a 23.2 percent gain in carbon storage estimated from the protection of roadless areas. Only a small number of roadless areas directly overlapped with areas designated for planned urban development, with the exception of a portion of Lamma Island that is under consideration to be developed into residential housing and recreation facilities (HK Development Bureau 2021). However, the planned 2030 developments would generally expand many urban boundaries to directly border PAs and roadless areas, increasing their vulnerability to anthropogenic disturbances from urban settlements.

With respect to coastal flood risk, the proportion of at-risk areas that were urban ranged from 39.6 percent under the Green Opportunities scenario to 93.0 percent under the Maximum Urbanization scenario (Table 2). The Green Opportunities scenario had approximately 32km^2 of urban land area within coastal flood risk areas, whereas the Maximum Urbanization scenario had more than double the exposure (76km^2). Most at-risk urban areas identified were situated in coastal areas designated for new urban development, particularly along Chek Lap Kok, Tuen Mun, and western edges of the Victoria Harbor, suggesting the necessity for risk exposure mitigation in these areas.

Table 2. Summary of the ecosystem services and risks modelled under 2030 land use change scenarios: the estimated total carbon storage capacity, carbon storage benefits from the protection of roadless areas, and coverage of urban areas in flood risk zones. The 2020 baseline carbon storage (10.86 Mt C) was used to calculate the percentage change in carbon storage in 2030 for each scenario.

2030 land use change scenario	Total carbon storage, 2030 (Mt C)	Difference in 2030 total carbon storage from 2020 baseline (Mt C, %*)	Total carbon storage, 2030, with roadless area protection (Mt C)	Change in 2030 total carbon storage with roadless area protection (Mt C; %†)	Area of urban land cover in flood risk zones (km^2)	Proportion of flood risk zones that are urban land cover (%)
Green Opportunities	11.15	0.28 +2.5%	11.15	0.0082 +0.07%	32.34	39.57
Halting Expansion	10.86	0.00 0.0%	10.87	0.0080 +0.07%	37.48	45.86
Planned Urbanization	10.21	−0.65 −6.4%	10.25	0.033 +0.33%	40.44	49.47
Urban Expansion	6.54	−4.33 −66.2%	7.12	0.59 +8.27%	69.94	85.56
Maximum Urbanization	4.05	−6.81 −168.1%	5.28	1.22 +23.20%	76.00	92.98

*Percentage change was calculated as follows: $100 \times (C_f - C_b)/C_f$; where C_f = 2030 carbon storage and C_b = 2020 baseline carbon storage

†Percentage change was calculated as follows: $100 \times (C_r - C_f)/C_r$; where C_r = 2030 carbon storage with roadless area protection

3.3. Towards nature-based solutions

The three spatial layers depicting carbon storage, natural habitats, and coastal flood risk were combined to indicate potential priority areas to implement NbS (Figure 7). In total, 68.77 km^2 were identified as priority areas, which were either: roadless & high carbon areas (12 locations, totalling 61.88 km^2) or high carbon & flood risk areas (1 location, totalling 6.89 km^2). The Mai Po Nature Reserve emerged as the only area that was both high carbon and a flood risk zone. It also borders three urban development areas planned under the *2030+ Strategic Plan*: Kwu Tung North New Development Area (NDA), Fanling North NDA, and the Fanling-Sheung Shui New Town (HK Government 2021b). The largest roadless areas were also those that overlapped with high carbon storage areas, namely in eastern and northeastern New Territories and parts of Lantau Island. While they currently lie within existing PAs, the areas in Lantau border built-up areas or areas designated for new urban developments (HK Government 2021b). There were no areas of overlap between all three prioritization layers, nor areas that were both roadless & flood risk areas. However, certain islands had relatively high coverage of all three within a close range (i.e., Lamma Island and Lantau Island).

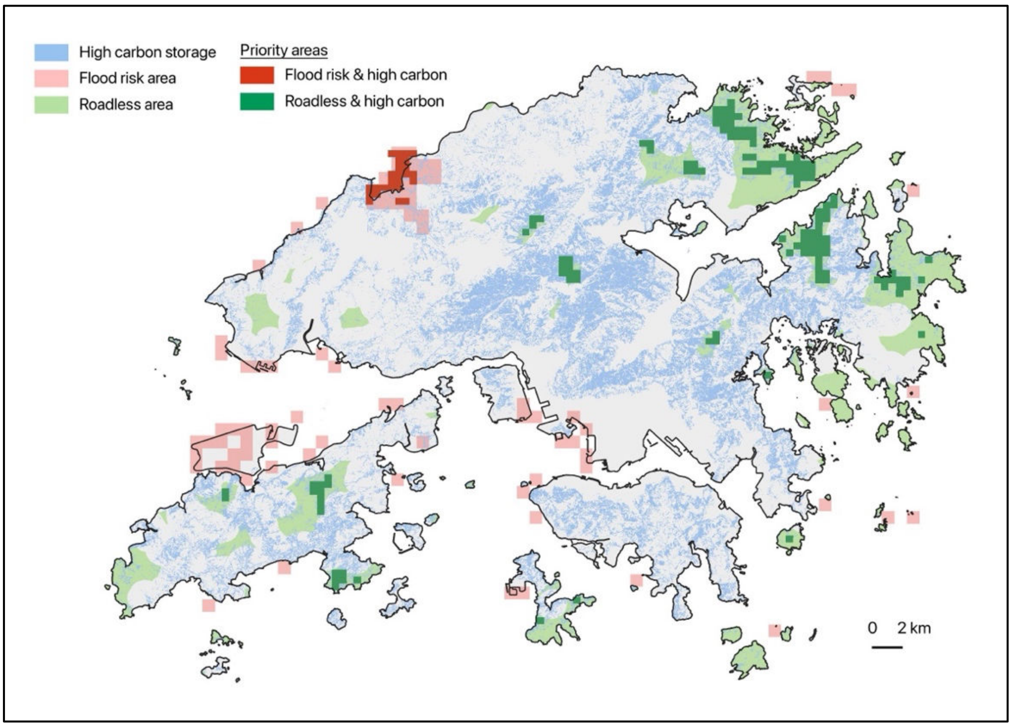


Figure 7. Map overlaying flood risk zones, roadless areas, and areas of high carbon storage to identify high-priority areas for nature-based solution. Priority areas are defined as those where two of the three prioritization layers overlap above a certain threshold in a 500 x 500-meter pixel: a) flood risk areas that overlap with areas of high carbon storage covering at least 50% of the pixel; b) roadless areas that overlap with areas of high carbon storage covering at least 50% of the pixel.

4. Discussion

4.1. Land use trade-offs

The scenarios modelling of land use change for Hong Kong demonstrate several important outcomes with respect to natural carbon storage benefits. Firstly, Hong Kong is near the upper limits of the carbon storage benefits that can be achieved from preserving existing natural land cover under current development circumstances. The CAP outlines goals to reduce Hong Kong's per capita carbon emissions to 3.3–3.8 tonnes by 2030, with 2022 per capita emissions currently at 4.55 tonnes (HK Government 2021a, 2024a). On a per-capita basis, Hong Kong's natural ecosystems provide 1.44 tonnes per capita in carbon storage, demonstrating the importance of preserving and enhancing these carbon stores to achieve the city's net zero targets within the coming years. This is seen from the marginal additional gains in carbon storage that resulted under the Green Opportunities scenario. These outcomes are aligned with the results found in studies from the neighbouring Guangdong–Hong Kong–Macao Greater Bay Area and Guangdong Province, which show that policies to protect woodland and grasslands adjacent to urban areas help maintain and improve regional carbon storage (Xu et al. 2016; Wang et al. 2023). Further gains in carbon storage could be implemented through the installation of complementary green infrastructure, such as the addition or enlargement of urban green spaces (e.g., peri-urban parks, gardens, green walkways), construction of green roofs, walls, or road barriers, and replacement of impermeable pavements with permeable alternatives (Cortinovis & Geneletti 2018). These solutions have commonly been recommended as 'low-regret' measures for climate adaptation and mitigation and are increasingly being adopted in urban planning processes globally (Dodman et al. 2023).

On the other hand, Hong Kong's relatively advantageous baseline state of natural carbon storage also indicates the potential to lose significant carbon storage capacity under future scenarios that involve urban expansion. The estimated losses associated with greenlighting existing 2030 development plans in the Planned Urbanization scenario are already more than double what could be gained in the Green Opportunities scenario. The scenarios modelling even more ambitious urbanization illustrate far bigger losses in carbon storage as urban land cover replaces grasslands, shrublands, and forested areas. The projected reductions in these carbon sinks would be difficult to reverse ex-post; it is particularly challenging to restore fully urbanized areas back to natural land cover types that possess their full carbon storage capacity (Hobbs et al. 2009; Standish et al. 2013). The dichotomous trade-off between urbanization and environmental goals demonstrated in the land use scenarios are seen not only in Hong Kong, but elsewhere globally. The expansion of urban areas for residential and commercial real estate development directly competes with the preservation of natural ecosystems that are of high carbon value. The cities of Guangzhou and Hangzhou in mainland China, for instance, experienced substantial losses of vegetation carbon storage over the course of rapid urbanization between 2000 and 2012 or 2015 respectively (Xu et al. 2016; Wang et al. 2021). During this time, the conversion of wetland and cropland into urban areas resulted in 'irreversible' impacts on regional carbon balances. The environmentally detrimental land use trajectories experienced by neighbouring cities highlight the need for Hong Kong to prioritize the preservation of ecosystem services when managing present and future urban development agendas (Wang et al. 2021).

The land use scenario modelling results suggest that Hong Kong should approach future land development with caution if it seeks to maintain the climate mitigation benefits of its natural areas for net zero goals alongside its urban development plans. Instead, areas that are already developed could be re-developed and intensified to fulfil growing built environment needs. At the same time, green infrastructure and urban NbS offer opportunities to increase Hong Kong's carbon storage capacity and work towards nature positive outcomes within the built environment. This approach, aligned with land sparing principles and IPBES NFF 'Nature for Society' values, would allow for a certain degree of additional urban development without expanding onto natural habitats (Pereira et al. 2020; Balmford 2021). In circumstances where additional land must be cleared for development, it would be important to strategically avoid areas that are significant positive contributors to climate and biodiversity outcomes. Areas in Hong Kong that are also highly exposed to climate- and nature-related risks should further inform this selection process. These locations were identified as those that maximize nature and climate benefits whilst also having high risk exposures for infrastructure, principal among these being Mai Po (Figure 7). Implementing a prioritization framework would act as a step towards incorporating nature and climate perspectives into decision-making processes for the built environment from which they are largely excluded (Ekins et al. 2003; Solecki et al. 2015; Longato et al. 2023). This is important not just for achieving global biodiversity and climate goals, but also for leveraging the broad range of ecosystem services offered by intact and well-maintained natural landscapes.

4.2. Maximizing climate-nature opportunities

The trade-offs and complexities associated with future land use change are further exemplified in the evaluation of potential opportunities for NbS implementation. The analysis of roadless areas, which represent parcels of land that are best positioned to benefit biodiversity if preserved and restored, revealed swathes of land in the New Territories and outlying islands that could be prioritized for conservation management. This is particularly true of portions of roadless areas that are not yet included within country parks or conservation areas (e.g., the roadless areas located in unprotected SSSIs), which would be particularly vulnerable to future encroachment from human development (Gong et al. 2020). Roadless areas that are located in PAs but directly border urban settlements are also at risk of greater disturbance from human activities that may compromise the provision of ecosystem services (Zeng et al. 2005; Hansen & DeFries 2007). Furthermore, the carbon benefits modelled from the conservation of roadless areas in Hong Kong demonstrate their importance in not just nature preservation, but also for climate change mitigation. A key limitation, however, is that roadless areas contain walking paths, hiking trails, and unpaved village lanes that may still be impacted by pedestrian disturbances, motorbike traffic, or artificial lighting and railings that could fragment wildlife populations (Li et al. 2010; Lowry et al. 2013). Roadless areas are also still subjected to the diffuse and long-ranging environmental impacts from urban areas, such as light pollution and air pollution. Hong Kong’s roadless areas thus may not be as disturbance-free as areas that satisfy roadless criteria in other contexts. Nevertheless, these areas demonstrate a valuable opportunity to efficiently and effectively avert losses in biodiversity through their protection, and to enhance biodiversity through changes in management strategies. The contribution of roadless areas to wildlife habitat connectivity and climate change mitigation could be enhanced by converting paved paths to permeable surface, reducing the footprint of manmade lighting and railing structures, or removing roads altogether (Li et al. 2010).

Beyond habitat conservation, the importance of considering the joint nature and climate benefits stemming from ecosystems also applies to climate risk adaptation and impact mitigation. As seen in the mapping of coastal flood risk, the largest vulnerable area in Hong Kong was in Mai Po. This is also the site of ongoing plans for the Northern Metropolis urban development project, which aims to develop a 30,000 hectare 'holistic metropolis' with both commercial and residential real estate developments (HK Government 2021c). Results from this climate risk analysis, however, suggest that the high exposure to flood risk would be disadvantageous for real estate developers along many dimensions: higher insurance premiums, larger infrastructure maintenance costs, and risks to community safety. In addition to these risks, this location houses the Mai Po Nature Reserve, containing globally significant habitats for endangered migratory bird species and other biodiversity. Mai Po was also the only priority area identified in the analysis with overlaps in high carbon storage and flood risk areas. Rather than housing more built-up areas surrounding the nature reserve, Mai Po would be more optimally utilized as a site of wetland restoration to protect surrounding areas from flooding. Doing so is supported from not just the perspective of maximizing synergistic nature and climate benefits, but also for the purpose of safeguarding existing infrastructural assets and community wellbeing. At the very least, new and existing developments would need to implement green infrastructure or NbS to address their high exposure to flood risks.

In some cases, the identified climate risks have implications beyond the site itself. Most of Hong Kong's at-risk flood zones are reclaimed shorelines, which are limited in their capacity to withstand inundation above a certain vertical limit (van den Belt et al. 2013). One prominent area of flood risk exposure is Chek Lap Kok in Lantau Island, where the HKIA was built upon reclaimed land in the 1990s. The high vulnerability of the HKIA, Hong Kong's only commercial airport, places the broader economy at risk due to the important role that international transit plays in Hong Kong's tourism, business, and shipping sectors. Adding to the city's infrastructural and commercial exposure to flood risk is the ongoing construction of HKIA's third runway on the north side of Chek Lap Kok, the most exposed portion of the coastline (HK Government 2021b). The island is also the site of reintroduction efforts for the Romer's Tree Frog (*Liuixalus romeri*), an endangered species native to Hong Kong (Fung 2015). Given these ecological and infrastructural vulnerabilities, the HKIA offers a prime example of a site where NbS would offers multifaceted mitigation and adaptation benefits such as shoreline protection, carbon sequestration, and natural habitat provision. Existing analyses of nature conservation and restoration opportunities have found that the net economic value of the associated benefits can outweigh private profits made (Bradbury et al. 2021). In the Tong King delta of Vietnam, for instance, the presence of mangroves was found to significantly reduce wave velocity and flow, providing an effective form of protection for surrounding aquaculture farms and commercial developments (Mazda et al. 1997). The Singaporean government has similarly invested into the research and development of 'soft' and 'hard' ecological engineering approaches that will retrofit manmade coastal defence structures with mangroves, sponges, and other intertidal organisms (Friess 2017). In Hong Kong, the proportion of built-up areas within flood risk zones is projected to increase under scenarios of intense urbanization (Table 2), highlighting the importance of NbS in mitigating future risk to commercially and societally important assets.

4.3. Recommendations and future directions

Several key recommendations emerge for Hong Kong. In order to leverage nature and climate opportunities in the coming years, it is paramount to maintain the present proportion of urban land and natural ecosystems without further expansion of built-up areas. The models of future land use change indicate that joint benefits for nature and climate action are greatly reduced when natural habitats are sacrificed for urban expansion. Land developers are therefore encouraged to consider the optimization of existing built-up land or renewal of disused barren land, rather than converting natural habitats. These recommendations align with existing and well-established principles of land sparing and the IPBES NFF 'Nature for Society' values, which could be referenced to further guide decision-making processes (Pereira et al. 2020; Balmford 2021). In pursuit of nature positive and net zero goals alongside further urban development, Hong Kong would need to address not only direct impacts and emissions but also the embedded environmental impacts associated with infrastructural supply chains (Zu Ermgassen et al. 2019). Such actions are outlined in accordance with frameworks such as the Mitigation Hierarchy and ‘No Net Loss’ policies that are being implemented in Canada, Columbia, the UK, and other jurisdictions (Zu Ermgassen et al. 2019; Tarabon et al. 2020).

There are also many opportunities to better adapt existing agricultural and urban landscapes to benefit nature, ranging from small to large spatial scales and levels of investment (Shaikh & Hamel 2023; Prodanovic et al. 2024). Sai Kung and Mai Po were highlighted as areas with the greatest potential for realizing nature-related benefits, suggesting that large efforts should made in urban planning policy to halt and avoid development in these areas. NbS that are designed to ameliorate the impacts of human activity from surrounding urban areas, such as green roofs or rain gardens, would serve as methods to maintain landscape connectivity amidst continued land development (Prodanovic et al. 2024). In modified non-urban landscapes, such as the agricultural areas of New Territories, there are a wide range of sustainable agriculture practices can be implemented to benefit local biodiversity and bolster resilience to climate change (Wezel et al. 2016; Muhie 2022). At the policy level, levers such the ‘urban growth boundary’ approach could be applied to limit the amount of built-up land in a city and its surrounding area, which has been recommended for neighbouring cities in mainland China (Ding et al. 1999; Xu et al. 2016). The analysis of flood risks similarly found Mai Po and Chek Lap Kok to be particularly vulnerable to coastal inundation, suggesting that these two areas would be ideal locations to implement NbS for climate change adaptation to reduce future infrastructural, societal, and commercial risks. Actions could include ecological engineering approaches such as the replacement of seawall portions with mangroves or enhancing the surface texture of existing seawalls to promote habitability for intertidal organisms (Bulleri & Chapman 2010; Lai et al. 2015).

Lastly, it is recommended that greater capacity is developed to measure and monitor biodiversity, ecosystem services and climate risks in Hong Kong, ideally through a centralized platform or taskforce involving multidisciplinary stakeholders. In the interim, carbon storage may act as a useful link that bridges climate risks with nature opportunities, as indicated by the large overlap with roadless areas and flood risk areas identified in the NbS opportunities analysis (Figure 7). The collection of a greater range and granularity of biodiversity data would enable policymakers to employ empirical prioritization methods to inform nature positive and net zero strategies. Systematic conservation planning, for instance, is a process-based framework for locating, designing, and managing priority conservation areas (Margules & Pressey 2000). It has been operationalized for land managers, policymakers, and broader societal stakeholders (e.g., through software interfaces such as Marxan) and has been adapted to include climate change considerations (Watts et al. 2017; Reside et al. 2018). Multi-criteria decision analysis is another relevant method for quantitatively weighing trade-offs, formulating decisions, and testing the robustness of environmental management policies that could be successfully applied in Hong Kong with greater data availability (Adem Esmail & Geneletti 2018). Such frameworks and approaches, using the analyses presented in this study, would be highly applicable to decision-making stakeholders in Hong Kong as the BSAP undergoes review and CAP targets are revisited.

For other urban systems like Hong Kong that seek to align climate and nature policy agendas, several broader lessons can be taken from this study. The use of geospatial scenario modelling has emerged as a useful tool to depict the trade-offs along dimensions that are otherwise difficult to link (Standish et al. 2013; Scott & Rajabifard 2017). The intersection of climate and nature policy agendas with economic development may seem difficult to demonstrate, but scenario modelling of land use change provides a simple and visually powerful way to distil empirical complexities (Liu et al. 2019; Chen et al. 2023; Zhao et al. 2023). Furthermore, despite the many gaps in data that still exist surrounding climate change and biodiversity measurement, this study has demonstrated that there are already ways to operationalize limited data with existing platforms such as InVEST. The types of analyses ultimately selected when replicating this study in a different area, however, will ultimately depend heavily on the local context. For example, a roadless analysis was appropriate for Hong Kong due to its spatial heterogeneity of natural habitats and a lack of granular species-specific data – but this may not be the case for a different urban setting. Given that each geographic context will have its own challenges and circumstantial nuances, consultation and collaboration with local partners is highly important in shaping a robust approach that will yield effective outcomes.

Further research on this topic, particularly in Hong Kong, could include methods to value ecosystem service benefits and climate risks in monetary terms. It is argued by some that that monetary valuation of ecosystem services and natural capital is an important and necessary method to integrate nature into economic and political decision-making processes (Costanza et al. 1997; Helm 2015). Due to several constraints, monetary valuation methods were deemed unsuitable and premature for the context of this study. Firstly, there is not yet a clear consensus on an approach to assign value to nature that is practically feasible and robust from both an economic and ecological standpoint (Turner et al. 2003; Victor 2020). Furthermore, many of the methods available – such as cost benefit analysis or natural capital accounting – require a detailed inventory of environmental resource stocks, flows, and costs for Hong Kong that are yet to be developed. While crude estimates could be drawn from existing literature sources or nearby regions (e.g., via benefit transfer methods), this may produce insights that oversimplify Hong Kong's unique societal and ecological context and offer inaccurate foundations for future decision-making. However, this could serve as a useful area for further research and development, particularly to establish local data collection systems that specifically serve as inputs for natural capital or ecosystem service valuation approaches.

Future work could also evaluate a broader set of ecosystem services and risks beyond those already explored. For example, other types of physical climate risks, such as extreme heat or wildfires, could be mapped in addition to coastal inundation hazard. The inclusion of locally sampled biodiversity data, including in estuarine and marine ecosystems, would also provide a greater range of metrics that could be used to characterize and prioritize nature conservation opportunities. Furthermore, these environmental metrics could also be overlaid with human health indicators to capture the interlinkages with social wellbeing. Studies have calculated a heat-related health index, for example, to map vulnerabilities to extreme heat in urban environments (Hu et al. 2017; Song et al. 2020). Access to nature through urban green spaces is another well-studied indicator for nature opportunities that would be relevant to include in future research (Van Den Berg et al. 2007; Richardson et al. 2012).

Currently, NbS are only just beginning to be explored in Hong Kong through initial scoping of potential case studies (e.g., *Adopting Nature-based Solutions for a Better Hong Kong* 2024). Such exercises will be complemented in the future with empirical and evidence-based approach such as that set forth in this study. The aforementioned areas to expand through further research would ultimately inform a more detailed and quantitative mapping for NbS implementation opportunities throughout Hong Kong, providing a framework for similar urban environments. As data capabilities and analytical rigor of these processes deepen within the Hong Kong context, these can be formalized into systems for natural capital accounting (e.g., the Align Project) or ecosystem service assessment/valuation (e.g., the UK National Ecosystem Assessment, the United Nations SEEA EA framework). The accuracy of future carbon storage estimates would also be improved with primary data collection on different LULC types in Hong Kong, as has been done elsewhere in the region.

4.4. Conclusions

In summary, this study has modelled the environmental trade-offs and opportunities associated with future land use change and urbanization in Hong Kong. Opportunities to maximize ecosystem services from natural habitats were demonstrated by mapping carbon storage and roadless areas, whilst risks associated with climate change were illustrated through coastal inundation hazard mapping. The results clearly exemplified the trade-offs that urban areas will continue to navigate at the interface of economic growth and environmental protection. In particular, Hong Kong is projected to suffer large reductions in climate mitigation benefits if new real estate developments and expansion plans are continued, the impacts of which could not be feasibly reversed. Nature-based solutions emerge as a promising means to bridge environmental goals with needs for urbanization and adaptation in a variety of applications, ranging from the restoration of mangroves for flood protection to the development of urban green infrastructure. The use of interdisciplinary approaches that consider the cross-cutting benefits of action for nature and climate agendas alongside urban growth ultimately illustrates a hopeful transition pathway for sustainable development.

5. Glossary

Term	Definition
Biodiversity	The variability among living organisms, including diversity within species, between species, and of ecosystems (CBD 2011).
Carbon sequestration	The amount of carbon that is absorbed from the atmosphere and stored in a stable and solid form in natural ecosystems (e.g., soils, plants, oceans) over a specified long-term time frame (Burras et al. 2001).
Carbon storage	The amount of carbon that is stored in a natural carbon stock at a given point in time.
Climate risk	The potential negative outcomes associated with the impacts of climate change. It includes dimensions of vulnerability (i.e., the predisposition to adverse impacts), hazard (i.e., the physical impact of the event), and exposure (i.e., the presence of human or environmental systems that may be affected) (IPCC 2012; TCFD 2017; Zscheischler et al. 2018).
Ecosystem services	The goods and services from ecosystem functions that provide direct or indirect benefits to human populations. They can broadly be categorized into provisioning (e.g., food, raw materials), regulating (e.g., air quality regulation, pollination, water purification), cultural (e.g., recreation, aesthetic value), and supporting (e.g., nutrient cycling, photosynthesis) (Costanza et al. 1997; Balvanera et al. 2019).
Natural capital	Aspects of nature that directly or indirectly provide value to people, including ecosystems, species, freshwater, soil, minerals, and natural processes and functions (Natural Capital Committee 2013).
Nature positive	A global societal goal to halt and reverse nature loss by 2030 and achieve full nature recovery by 2050, relative to a 2020 baseline (Locke et al. 2021).
Nature-based solutions	Actions to protect, sustainably manage or restore natural ecosystems that benefit both people and nature (Cohen-Shacham et al. 2016).
Net zero	The balance of anthropogenic emissions of greenhouse gases to the atmosphere with anthropogenic removals over a specified period and baseline (Calvin et al. 2023).

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7. Supplementary material

SM-1. Carbon density values

Note that for the majority of sources referenced for carbon density, values for belowground carbon storage (C_b) were combined with aboveground carbon storage (C_a) and values for soil biomass (C_s) were combined with dead organic matter carbon storage (C_d), hence values for (C_b) and (C_d) were zero in many cases.

Table SM-1. Carbon density values, literature sources, and relevant notes on modifications made to values

Land cover type	Area (ha)	C_a (t/ha)	C_b (t/ha)	C_s (t/ha)	C_d (t/ha)	C_{total} (t/ha)	Source	Notes on additional modifications
Bare rock/soil	3,631.5	14.825	0	93.735	0	108.56	Liu et al. 2019	Values taken from average of 'bare rock' and 'bare land' land cover types
Grassland	8,445.4	10.61	0	97.34	0	107.95	Liu et al. 2019	Values taken for 'low coverage grassland' land cover type
Mangrove	632.2	50.27	0.14	173.12	0	223.53	Liu et al 2014	Values taken for the site with the same dominant species makeup as Hong Kong mangroves (i.e., A. marina and A. corniculatum)
Marsh/reed bed	340.4	4.27	0	59.41	0	63.68	Liu et al. 2019	Values taken for 'swamp' land cover type
Natural rocky shoreline	999.6	6.55	0	95.005	0	101.555	Liu et al. 2019	Values taken from average between 'saline land' and 'bare rock' land d cover types
Other urban area	19,974.0	1.2	0.93	12.48	0	14.61	Deng et al. 2022	Values taken for 'urban land' land cover type
Shrubland	9,901.4	21.07	0	107.2	0	128.27	Liu et al. 2019	Values taken for 'shrubbery' land cover type
Soft shore/beach	801.6	8.58	0	75.11	0	83.69	Liu et al. 2019	Values taken for 'sandy land' land cover type
Woodland	27,491.1	23.12	0	105.46	0	128.58	Liu et al. 2019	Values taken for 'forest land' land cover type

Woody shrubland	13,860.8	19	0	101.14	0	120.14	Liu et al. 2019	Values taken for 'sparse woodland' land cover type
Shrubby grassland	8,530.3	15.19	0	105.18	0	120.37	Liu et al. 2019	Values taken for 'medium coverage grassland' land cover type
Mixed barren land	860.3	9.5	0	84.72	0	94.22	Liu et al. 2019	Values taken for 'other construction land' land cover type
Rural plantation	5,497.4	11.42	0	97.84	0	109.26	Liu et al. 2019	Values taken for 'paddy field' land cover type
Agricultural land	3,985.5	12.19	0	87.03	0	99.22	Liu et al. 2019	Values taken for 'dry farmland' land cover type
Green urban area	3,940.4	8.21	0	83.31	0	91.52	Liu et al. 2019	Values taken for 'residential land' land cover type
Seagrass bed	23.3	0.11	0	0.12	0	0	Jiang et al. 2017	Values taken for mean values for seagrass, converted from Mg/ha
Artificial hard shoreline	160.1	0	0	0	0	0	NA	No carbon storage was assigned for concrete shorelines
Natural watercourse	163.5	0.125	0	0	0	0.125	Deng et al. 2022; Wang et al. 2023	Values taken from average of 'water area' land cover types in two studies
Modified watercourse	190.7	0.125	0	0	0	0.125	Deng et al. 2022; Wang et al. 2023	Values taken from average of 'water area' land cover types in two studies
Reservoirs	2,234.8	0.125	0	0	0	0.125	Deng et al. 2022; Wang et al. 2023	Values taken from average of 'water area' land cover types in two studies
Artificial pond	940.9	0.125	0	0	0	0.125	Deng et al. 2022; Wang et al. 2023	Values taken from average of 'water area' land cover types in two studies

Concluding remarks

This dissertation has explored the trade-offs between urban development and environmental sustainability goals – a challenge that will continue to emerge on local, national, and regional scales as urban populations continue to expand under a changing climate. Using land use change scenarios to model potential future urbanization pathways for Hong Kong by 2030, the associated shifts in ecosystem service provision and climate-related risks are estimated and compared to a 2020 baseline. Without future policies to preserve natural land cover, Hong Kong could suffer large reductions in climate change mitigation, adaptation, and ecological integrity under scenarios of continued urban expansion. The study puts forth nature-based solutions as an opportunity to pursue global net zero and nature positive goals in the context of socioeconomic and infrastructural development needs.

The geospatial approach applied in this study is a novel approach on a topic that has been explored very little in the body of scientific literature for Hong Kong, empirically linking elements of climate change mitigation, nature conservation, and land use change to inform the city's policy. At the same time, the pioneering nature of this study limits the quantitative depth to which the various methodological components could be developed, particularly in comparison to other well-established environmental topics for Hong Kong (e.g., air quality, monsoon dynamics, water pollution; (Cheung et al. 1990; Wong et al. 2001; Ding & Chan 2005). This was evident in the limitations on local ecological data that were available to assess risks and opportunities. In broader academic literature, insights on the linkages between nature and climate policy agendas are also relatively nascent but have been expanding with the increasing application of multidisciplinary and systems thinking approaches. This area will also continue to evolve in real-time with the ongoing implementation global climate and biodiversity outlined in the Paris Agreement and GBF, as well as the re-assessment of adjacent environmental frameworks such as the SDGs. Given this context, the study at hand has much greater scope to improve in quantitative rigor in coming years as: a) greater capacity is built for interdisciplinary ecological data collection in Hong Kong; b) operationalizable frameworks are developed to track and evaluate progress towards global environmental goals; c) more research is conducted in the region on this topic to develop locally relevant insights.

Immediate avenues for next steps stemming from this study are primarily associated with stakeholder engagement to disseminate policy-relevant insights. The recommendations from this study will be presented to the Steering Committee for Hong Kong's ongoing BSAP review, which will culminate in a final report to the Environment and Ecology Bureau. The results from this study will also be communicated to broader stakeholders through multiple avenues:

a) A practical seminar series for Hong Kong's business sector on joint climate and nature sustainability strategy development
b) Collaborative sharing sessions with local think tanks and NGOs on the implementation of geospatial methods for scoping NbS
c) Publication of news articles and blog posts to communicate the results to broader audiences, both locally and globally
d) Presentations at regional and academic conferences to share research with academic communities

Beyond these immediately actionable next steps and those outlined in the Discussion section (pg. 36), there are other areas that future research can explore. The InVEST model used in this study does not include any dynamic modelling of ecological conditions and land market feedbacks, which is a primary limitation of the approach (Armsworth et al. 2006; Larrosa et al. 2019). Future studies that include spatiotemporally dynamic modelling of land use economics and natural carbon storage would provide an opportunity to cross-reference results with those presented in this study, helping determine the context in which more simplistic models like InVEST would be appropriate and effective for decision-making contexts (Rieb et al. 2017). The participation of citizens is also highly important as Hong Kong works develops a prioritization framework for NbS and other environmental policy actions. The collection of local perspectives can help value and prioritize ecosystem services, as well as shape the implementation of NbS, in ways that are not captured by quantitative modelling methods (Faivre et al. 2017; Frantzeskaki 2019). Lastly, future research is needed to replicate similar studies in other urban areas in the East Asia region (e.g., Singapore, Seoul, Tokyo) or locally in the Guangdong–Hong Kong–Macao Greater Bay Area, which would identify areas of regional policy synergy or regionally-specific considerations for net zero and nature positive goals. Opportunities to enhance regional ecological connectivity for both marine and terrestrial habitats (e.g., marine larval flows, migratory flyways) would be particularly pertinent for regional research and policy collaboration.

Hong Kong ultimately serves as a unique case study featuring a highly developed and densely populated urban environment that, at the same time, has preserved a large amount of its natural landscapes. While the recommendations and methodological approach has been tailored to the local context, the underlying themes addressed in this dissertation are of global relevance: the trade-offs between socioeconomic development and environmental outcomes. Looking beyond Hong Kong, the accelerated expansion of urban areas raises questions as to how a balance can be struck between meeting infrastructural needs for human development and doing so in a manner that is safe and just for both human and natural systems. Ultimately, these are fundamental global issues will become ever more salient in the coming years, requiring interdisciplinary approaches that contribute to a growing body of literature and actionable recommendations. It is hoped that this dissertation is one such contribution that will help galvanize future research and policy development in Hong Kong and beyond, demonstrating the synergistic linkages between nature and climate actions, the practical applications of geospatial methods, and the systemic interdependence of social wellbeing and economic stability on ecosystem services.

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Note: This section provides citations for all references made in the Extended Literature Review, Justification of Research Approach, and Concluding Remarks sections. References for the journal manuscript have been included separately on pg. 46.

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Appendix

Appendix I

The Land Use Policy journal's Guide for Authors is provided below. The manuscript in this dissertation has been prepared for submission as a 'Regular Paper' article type.

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Guide for authors

About the journal

Aims and scope

The International Journal Covering All Aspects of Land Use

Land Use Policy is an international and interdisciplinary journal concerned with the social, economic, political, legal, physical and planning aspects of **urban** and **rural land use**. It provides a forum for the exchange of ideas and information from the diverse range of disciplines and interest groups which must be combined to formulate effective **land use policies**. The journal examines issues in geography, agriculture, forestry, irrigation, environmental conservation, housing, urban development and transport in both developed and developing countries through major refereed articles and shorter viewpoint pieces.

Land Use Policy aims to provide policy guidance to governments and planners and it is also a valuable teaching resource.

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