Measuring wellbeing in climate and socioeconomic scenarios

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Chapter 1
General Introduction

1.1 Wellbeing within planetary boundaries

Over the past two centuries, humanity has entered an unprecedented phase of global societal changes in population, the economy, and technology and many other factors. Since the nineteenth century, industrialization and its successive waves initiated gradual rises in material living conditions, life expectancy, and education (OECD, 2014). After conflict and unstable phases characterized by the Great Depression and world wars, global development entered a distinct period regularly referred to as the "Great Acceleration" or "Anthropocene" (Crutzen and Stoermer, 2000; Kindleberger, 1986; Steffen et al., 2015a).

This post-1950 period saw rapid industrial expansion, economic growth, increases in global trade, and rising consumption. The growth model deepened reliance on fossil fuels and large-scale resource extraction, leading to land-system transformation and intensified ecological pressures.

The post-war period also saw large increases in average living standards. However, inequalities started to rise from the 1980s onwards and starting from the 1990s, environmental burdens also started to shift geographically due to globalization (Jansen et al., 2024a; Piketty, 2017). Escalating greenhouse gas emissions, biodiversity loss, air pollution, and extreme weather events reveal a growing tension between socioeconomic progress and ecological sustainability (Calvin et al., 2023; Rockström et al., 2009; Sakschewski et al., 2025; Steffen et al., 2015b).

Human development in the twenty-first century thus unfolds within a tightening planetary envelope. Global surface temperature in 2011-2020 was about 1.1°C higher than in 1850–1900 pre-industrial baseline (IPCC, 2023). Further warming could be inevitable even under ambitious mitigation pathways. While recent years have already reached the 1.5°C level of global warming for short periods, long-term warming would further result in more frequent climate hazards (e.g., heat waves and altered precipitation patterns) and sea-level rise (Hoegh-Guldberg et al., 2019; IPCC, 2022; World Meteorological Organization, 2025).

Planetary boundaries indicate the biophysical limits of Earth's natural systems and define a "safe operating space" for humanity (Steffen et al., 2015b). The planetary boundaries framework indicates that human activities have already pushed seven of nine boundaries from climate change and land-system change to ocean acidification (Sakschewski et al., 2025). Transgressing these boundaries destabilizes ecological systems that underpin human societies. Importantly, these systems do not operate in isolation. For example, climate change can accelerate biodiversity loss through shifting temperature, while land-system change and ecosystem degradation could weaken the capacity of natural systems (e.g., forests, wetlands, and coastal systems) to help moderate extreme events. These interacting environmental pressures are increasingly recognized as a systematic threat to population, society, and economy (Richardson et al., 2023; Romanello et al., 2021; Whitmee et al., 2015).

The environmental shifts also coincide with major socioeconomic changes. Rapid urbanization concentrates people and infrastructure in areas where heat, air pollution, and flood risks are intensified. By 2050, about two-thirds of the population is projected to live in cities (UN DESA, 2019). Meanwhile, ageing is reshaping age structures in many regions, influencing labor markets, fiscal sustainability, and health-care systems (Chen et al., 2020). Inequalities within and between countries directly reflect who is exposed, who is sensitive, and who can adapt under climate change (Bangalore et al., 2016; IPCC, 2023; Diffenbaugh & Burke, 2019). The compound risks with climate and socioeconomic trajectories are unevenly distributed, thus can disproportionately affect vulnerable populations and exacerbate pre-existing disparities.

These environmental and social crises challenge the narrative of pursuing endless economic growth (Hoekstra, 2019; Kallis, 2011). This is not a new debate. Back in 1972, the Limits to Growth report warned that exponential expansion cannot continue on a planet with finite resources (Meadows et al., 1972). Later, the Brundtland Report introduced the concept of sustainable development and brought environmental considerations to formal political discussion (WCED, 1987). More recently, the Sustainable Development Goals and the planetary boundaries framework have reinforced the need to move towards sustainable development beyond economic growth (Rockström et al., 2009; UN DESA, 2024). Frameworks such as Doughnut Economics describe a “safe and just operating space” in which societies secure social foundations for everyone without exceeding ecological ceilings (Raworth, 2017).

The central task of twenty-first-century development should no longer be centered on the acceleration of economic output. Instead, it is to secure sustainable and inclusive wellbeing to ensure that current and future generations can flourish within planetary boundaries.

1.2 Wellbeing in climate and socioeconomic models: Major Challenges

The societal challenge of shifting from the current growth-based model towards a pathway that prioritizes wellbeing within planetary boundaries is fundamental. However, this is too broad a question for a single PhD thesis. The scope of this thesis is therefore restricted to the analysis of wellbeing in climate and socioeconomic models. These models play an important role in shaping climate policies and societal narratives about the urgency and the solutions to climate change, one of the most important planetary boundaries.

The Intergovernmental Panel on Climate Change (IPCC) relies heavily on scenario-based modeling analysis to assess emission pathways, climate impacts, and mitigation strategies that inform international policies (Calvin et al., 2023). The Representative Concentration Pathways (RCPs), which specify trajectories of greenhouse gas concentrations and associated radiative forcing, are combined with Shared Socioeconomic Pathways (SSPs), which define alternative socioeconomic futures (e.g., demographics, economic development, technological change, and so on) as climate-socioeconomic scenario framework (Moss et al., 2010; Riahi et al., 2017; Vuuren et al., 2011). This combined SSP-RCP framework constitutes the Scenario Model Intercomparison Project (ScenarioMIP) and underpins climate simulations and mitigation analyses in the Coupled Model Intercomparison 6 (CMIP6) (Eyring et al., 2016; O'Neill et al., 2016).

The Integrated Assessment Models (IAMs) such as IMAGE, REMIND, MESSAGE-GLOBIOM, GCAM, and AIM constitute an essential part of the climate projections (Baumstark et al., 2021; Calvin et al., 2019; Fujimori et al., 2017; Krey et al., 2020; Vuuren and Stehfest, 2021). IAMs couple energy, land-use, economic, and environmental systems to generate internally consistent long-term mitigation pathways under alternative scenarios (Harfoot et al., 2014; Vuuren et al., 2012). In IPCC assessments, ensembles of IAM outcomes play a central role in evaluating the costs, trade-offs, and feasibility of long-term mitigation portfolios under alternative policy assumptions.

While IAMs are powerful tools for climate mitigation analysis, they remain limited in addressing the broader challenge of secure wellbeing within planetary boundaries. The limitation is presented in 4 important ways: First, most IAMs have incorporated a growth-centered economic paradigm. Second, the political, social, and institutional dynamics required for structural transitions are absent. Third, multidimensional wellbeing is not explicitly represented within these models. Fourth, feedback mechanisms linking climate change to socioeconomic determinants of wellbeing are rarely incorporated.

1.2.1 Growth focus

The first challenge concerns the central role of economic growth in current scenarios. The SSPs narratives project continued GDP growth throughout the twenty-first century, differing in magnitude but not in direction (Dellink et al., 2017a). Long-term income convergence and productivity growth are embedded as core structural assumptions, and GDP trajectories are centered as primary drivers of emissions and mitigation costs in IAMs (Koch and Leimbach, 2023). The current SSPs, therefore, do not incorporate new perspectives like post-growth and degrowth. Post-growth centers around sustainable and inclusive wellbeing, emphasizing sufficiency and ecological limits (Jackson, 2021). Degrowth frameworks intentionally seek downscaling in high environmental impact activities, especially in rich countries, with social changes in shorter working hours, maximum income and commons-based provisioning (Hickel et al., 2022; Kallis et al., 2020; Martínez-Alier et al., 2010). Such pathways are not currently explored under the SSPs architecture, though recent research argues that such pathways may facilitate mitigation while maintaining or even improving wellbeing (Hickel et al., 2021).

1.2.2 Lack of transition dynamics

Shifting society's focus to wellbeing within planetary boundaries requires profound social, institutional, and political transitions. Yet achieving these transitions is a challenge in itself. Slow progress in climate mitigation underscores the difficulties. Besides climate mitigation itself, the environmental impacts are also mediated by socioeconomic and political factors that shape vulnerability and adaptation (Lamb and Steinberger, 2017). The stalled progress is due to opposing powers such as fossil fuel interests and institutions that resist systemic change. Socio-technical transition theories explain this as struggles between radical niche innovations (e.g., community sufficiency projects) and locked-in regimes (Geels, 2019). Power asymmetries and incumbent interests could further block required changes (Scoones and Stirling, 2020; Stirling, 2011).

Social tipping points research suggests that a portion of around 25% committed actors could already trigger systemic shifts, as shown by Centola et al. (2018) experimentally. Overcoming such challenges is central to securing wellbeing under climate change. However, while these dynamics are included as predefined narrative conditions, they are not explicitly modeled within SSP-based frameworks as endogenous mechanisms.

1.2.3 Lack of wellbeing quantification

The SSPs and IAMs frameworks underpin IPCC mitigation pathways characterize "development" primarily through population and GDP trajectories, which drive energy demand and land use (Cuaresma, 2017; Koch and Leimbach, 2023). This reflects the success of Gross Domestic Product (GDP) within national accounting and policy practice since its historical institutionalization in the mid-twentieth century (Coyle, 2016; Max-Neef, 1995; UN, 1953, 1953; US BFDC, 1934). Consequently, multidimensional wellbeing is not a core model variable in most SSP implementations and process-based IAMs. This omission matters because the relationship between GDP and wellbeing is not linear, especially at higher income levels (Frey and Stutzer, 2000; Hickel et al., 2021; Kahneman and Deaton, 2010). Only a narrow set of wellbeing-related impacts is commonly quantified (notably GDP, food security, and temperature-related mortality), while many other wellbeing dimensions with available empirical quantification, including mental health, infectious disease, labor productivity, and conflict, are either absent or only partially represented in these climate models (Schrijver et al., 2025).

1.2.4 Lack of climate-wellbeing feedbacks

Within the SSPs and IAMs frameworks, some key socioeconomic variables (e.g., population, education, and GDP) are quantified but typically are treated as exogenous inputs to IAMs which then lead to greenhouse gas emissions (O'Neill et al., 2016; Schrijver et al., 2025). This structural separation leaves socioeconomic trajectories to evolve largely independently of environmental degradation. The endogenous modeling of dynamics linking environmental change to socioeconomic trajectories is lacking. Therefore, explicit feedback from environmental change to socioeconomic indicators and ultimately to wellbeing are rarely represented. Instead, climate-related impacts on wellbeing determinants (e.g., health) are often assessed as post hoc, by linking IAM-based climate outputs to separate impact models or demographic projections (Silva et al., 2016; Yue et al., 2024). This limits the potential and capacity of IAMs to produce internally consistent outcomes and to inform integrated sustainability strategies (Liu et al., 2025; Schrijver et al., 2025).

This is not an exhaustive list of critiques of current integrated modeling assessment frameworks. Beyond the limitations discussed above, IAMs and current scenario frameworks also face other criticisms like limited representation of behavioral dynamics and challenges related to transparency, interpretation, and communication of results (Gambhir et al., 2019; Keppo et al., 2021).

1.3 Emerging methodological directions in the literature

Recent methodological developments have begun to address the challenges identified above. This section reviews advances related specifically to two areas: incorporating wellbeing and integrating climate-wellbeing dynamics in climate models. In particular, recent developments in wellbeing metrics, scenario frameworks, and modeling tools provide a foundation for quantitatively projecting wellbeing under global climate and socioeconomic scenarios. While addressing growth focus and the lack of transition dynamics remains crucial for strengthening research on future development pathways, these issues are beyond the scope of this thesis.

Specifically, this thesis examines how wellbeing can be measured beyond GDP and how wellbeing can be projected under environmental change. The scope of this thesis hence lies in strengthening data, indicators, and scenario-based modeling frameworks.

1.3.1 Concepts and measurement of wellbeing and sustainability

Over the past decades, a wide range of “Beyond-GDP” initiatives emerged to measure sustainable and inclusive wellbeing, rather than economic growth. Milestones include the Brundtland Report (WCED, 1987), the Stiglitz-Sen-Fitoussi (SSF) report (Stiglitz et al., 2009), the UNECE CES recommendations (UNECE, 2014), the OECD Better Life Initiative (OECD, 2011), and the UN Sustainable Development Goals (UN DESA, 2024).

The proliferation of schools of thought from these initiatives lays the conceptual foundation for sustainable and inclusive wellbeing and its determinants across disciplines. Five key scientific schools of thought convey the understanding of wellbeing from different aspects and are well recognized in the field, including subjective wellbeing, welfare economics, needs theories, the capabilities approach, and ecological approaches (Jansen et al., 2024b). Subjective wellbeing—drawing on life satisfaction, hedonic (affect), and eudaimonic (meaning and purpose)—emphasizes individuals’ self-evaluations of quality of life (Clark et al., 2018; Diener, 2009; Diener et al., 2018; Henderson and Knight, 2012; OECD, 2025; Ryan and Deci, 2001). Welfare economics conceptualizes wellbeing through utility and resource allocation, often monetizing welfare-related factors and highlighting trade-offs as presented in the Genuine Progress Indicator (Cobb et al., 1995; McCombie, 1983; Nordhaus and Tobin, 1972; Slycken and Bleys, 2024). Needs theories identify requirements to lead a fulfilling life like health and safety (Doyal and Gough, 1984; Max-Neef, 2010; Max-Neef et al., 1991; Nussbaum, 2003), while the capability approach defines wellbeing in terms of people’s ability and autonomy to achieve valued ways of living (Anand et al., 2005; Sen, 1993; Sen and Sen, 1988). Ecological approaches argue that human flourishing must occur within planetary boundaries and, as illustrated by the Doughnut framework, within a safe operating space that combines ecological ceilings with social foundations (Dodds, 1997; Meadows et al., 1972; Raworth, 2017, 2012; Rees, 1992; Rockström et al., 2009; Steffen et al., 2015b).

Sustainability, while central to ecological approaches, is itself conceptually contested and evolving. Previous concepts focus on the substitutability between natural and man-produced capital, including “weak” (allowing substitution) and “strong” sustainability (emphasizing non-substitutability, critical natural capital, and biophysical limits such as planetary boundaries) (Leach et al., 2010; Neumayer, 2003; Rockström et al., 2009; Steffen et al., 2015b). Beyond the concepts, various sustainability paradigms propose distinct drivers of environmental degradation and corresponding transformation pathways from nature protection, green economy, earth stewardship to degrowth (Dasgupta, 2021; Folke et al., 2009; Martin et al., 2024; Martínez-Alier et al., 2010; Rozzi et al., 2015; UNEP, 2010).

In parallel, the uptake of wellbeing and sustainability initiatives among institutions and scholars has accelerated the development of Beyond-GDP metrics over the past decades (European Commission et al., 2025; HLEP, 2022; Meadows et al., 1972; UN, 2001; UNU-IHDP, 2012). These metrics has been promoted to provide comprehensive quantitative assessments of multiple dimensions across wellbeing and sustainability (Jansen et al., 2024b; Kwatra et al., 2020; Liu et al., 2024; World Bank, 2024). Notable examples include the Human Development Index (UNDP, 2020), the Sustainable Development Goals framework (UN DESA, 2024), and various composite indicators measuring subjective wellbeing, inequality, and environmental sustainability (World Bank, 2023).

Though wellbeing and sustainability are inherently multidimensional concepts encompassing diverse aspects of human flourishing, the concepts converge to three domains of wellbeing, inclusion and sustainability (Jansen et al., 2024b). First is the current level of wellbeing, capturing average outcomes of a nation such as longevity, learning, material living standards and subjective wellbeing. Second is inclusion, which concerns how those outcomes are distributed within and between nations. Averages can conceal large disparities by income, gender, age, or place. Third is sustainability, which is about the current conditions that affect the wellbeing of future generations (EGWM, 2024; HLEP, 2022; OECD, 2024; Stiglitz et al., 2009; UNDP, 2020; UNECE, 2014). Together, this framework grounds a harmonized language to synthesize the diffused metrics for sustainable and inclusive wellbeing (Hoekstra, 2019; Irlan et al., 2024; Jansen et al., 2024b).

1.3.2 Health as a core dimension of wellbeing under climate change

Among the various dimensions of wellbeing, health occupies a foundational role. As climate change increasingly threatens wellbeing, health outcomes provide a direct and quantifiable interface between environmental change and human wellbeing (Romanello et al., 2023; Whitmee et al., 2015; WHO, 2021). The quantification of health impacts captures both exposure to climate-related hazards and underlying socioeconomic vulnerability. The consequences for health-related wellbeing are multifaceted and operate through direct and indirect pathways (Pottier et al., 2021; Wardekker et al., 2012). Heat exposure elevates mortality and morbidity, especially among older adults, and is intensified by urban heat-island effects (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2021). Air quality co-evolves with climate and energy systems: fossil-fuel combustion and biomass burning drive fine particulate matter pollutants and ozone exposures that contribute to millions of premature deaths and reduce life expectancy (IHME, 2024; Lelieveld et al., 2015). Water and food security are threatened by droughts, floods, and temperature extremes, with escalating effects for nutrition and infectious disease (Romanello et al., 2024). Extreme events damage housing, health facilities, and infrastructure, disrupting access to care and causing displacement. Indirectly, climate shocks also reduce labor productivity and labor capacity (Burke et al., 2015; Dunne et al., 2013; Kjellstrom et al., 2009). These effects are unevenly distributed globally. Regions with high exposure and disadvantaged communities with low adaptive capacity in low- and middle-income countries face greater health burdens and fewer resources to manage them (Bangalore et al., 2016; IPCC, 2023; Diffenbaugh & Burke, 2019). Without deliberate policy, differences in exposure, sensitivity, and adaptation would widen the inequalities in wellbeing.

1.3.3 Climate and socioeconomic scenarios and models

Climate projections are largely based on predefined scenarios to explore potential pathways towards sustainable development. A set of climate and socioeconomic scenarios has been developed and adopted by the climate community over the past decades (Moss et al., 2010; O'Neill et al., 2020). The Representative Concentration Pathways (RCPs) have been designed to describe a series of different radiative forcing levels under emission trajectories in the future (Moss et al., 2008; Vuuren et al., 2011). The RCPs serve as the scenario backbone for climate analysis in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). More recently, the Shared Socioeconomic Pathways (SSPs) have been developed to provide internally consistent narratives and quantitative trajectories for socioeconomic aspects such as population, education, income, and inequality (O'Neill et al., 2017; Riahi et al., 2017). For the Coupled Model Intercomparison Project Phase 6 (CMIP6), the Scenario Model Intercomparison Project (ScenarioMIP) links SSPs with RCP to underpin the climate projections in the IPCC Assessment Report 6 (AR6) (Eyring et al., 2016; O'Neill et al., 2016). Recent studies have developed SSP-consistent quantifications of various socioeconomic indicators, including life expectancy, educational attainment and GDP per capita, which represent the determinants of wellbeing. This SSP-RCP framework could serve as a scenario-consistent foundation for wellbeing projections under climate change context (Dellink et al., 2017b; Jiang and O'Neill, 2017; KC and Lutz, 2017; O'Neill et al., 2016; Rao et al., 2019; Riahi et al., 2017; Sellers, 2020).

On the modeling side, Integrated Assessment Models (IAMs) couple economy systems with social activities in energy, land-use and technology to capture the human-society-earth interactions and produce internally consistent trajectories of quantitative social and environmental outcomes under alternative development pathways. (Beek et al., 2020; Fujimori et al., 2025; Harfoot et al., 2014; Vuuren et al., 2012). The IAMs are widely used to quantify sustainability challenges such as mitigation pathways, land-use change, and air-quality co-benefits based on a range of scenario frameworks (Calvin et al., 2019; Huppmann et al., 2019). The outputs of IAMs could also sequentially be involved in Earth-system circulation models to simulate atmospheric composition (such as $PM_{2.5}$ and ozone) and climate projections (e.g., temperature and precipitation), and greenhouse-gas emissions (Collins et al., 2017; Riahi et al., 2017; Turnock et al., 2020). Development in such models increasingly supports climate research at finer spatial scales, enabling spatially explicit exposure estimates and assessment (M. Chen et al., 2020; Y. Chen et al., 2020; Wang and Sun, 2022).

1.4 Remaining research gaps

Despite recent methodological progress, a systematic integration of wellbeing and environmental-social feedback into forward-looking, scenario-consistent assessments remains lacking. Existing wellbeing frameworks have largely evolved from social statistics and national accounting systems, emphasizing retrospective analysis rather than projection. Meanwhile, integrated assessment models that inform climate and sustainability policy rarely represent wellbeing beyond income or consumption. Because these traditions developed separately, with different temporal perspectives and indicator systems, their integration into a coherent, scenario-consistent framework remains limited. This disconnection between wellbeing research and scenario-based modeling constrains the assessment of trade-offs and co-benefits between environmental change, social progress, and human health.

In response to these limitations, this thesis identifies four critical data and modeling gaps as follows:

1.4.1 Data accessibility and harmonization

The fragmented landscape of beyond-GDP metrics creates fundamental barriers to comprehensive wellbeing research. Researchers attempting to analyze relationships between economic, social, and environmental dimensions of development must navigate disparate databases with inconsistent terminology, indicator definitions, geographic identifiers, and time coverage. This fragmentation obstructs cross-metric analysis of wellbeing, inclusion, and sustainability and impedes reproducibility. Terminological confusion (e.g., "wellbeing," "quality of life," "social progress," "sustainability") compounds these barriers. A unifying taxonomy and systematic harmonization addressing common geographies, metadata standards, versioning, and interoperable access are largely absent but necessary to enable integrated analysis across multiple disciplines.

1.4.2 Temporal disconnection in wellbeing assessment

Beyond-GDP indicators remain predominantly retrospective measurement tools despite policymakers' need for forward-looking assessments. This temporal gap becomes critical in climate change contexts, where decisions made today will shape wellbeing outcomes decades into the future. The SSP framework provides demographic and economic projections underlying climate and socioeconomic scenarios, yet these data have not been systematically leveraged to project composite wellbeing indicators. Addressing this gap requires both methodological development and critical assessment to evaluate how sustainable and inclusive wellbeing might evolve under alternative climate and socioeconomic scenarios and to compare policy pathways on wellbeing outcomes.

1.4.3 Missing environmental-social feedback in Integrated Assessment Modeling frameworks

Integrated assessment modeling frameworks treat underlying socioeconomic drivers (e.g., demographics and health) as exogenous variables, which creates systematic biases in long-term projections. This modeling approach could potentially produce inconsistent results and limit the understanding of future environment-human development. The scale, spatial pattern, and policy relevance of these biases have not been systematically quantified in a scenario-consistent, global framework. Closing this gap requires methods for endogenizing environmental-health relationships in demographic models while maintaining scenario consistency, and empirical assessment of how feedback integration changes projected outcomes across diverse settings.

1.4.4 Increasing need for climate-health projections at finer spatial disaggregation

Urban areas concentrate both climate-health risks and increasing populations requiring protection, yet holistic and standardized methodological approaches for projecting climate-health impacts at a finer scale are limited. Studies employ diverse climate data sources and resolutions, epidemiological model structures, demographic and adaptation assumptions, creating heterogeneity that limits comparability and synthesis. Moreover, critical methodological choices in each modeling step remain guided more by data availability and disciplinary conventions than systematic evaluation of how these decisions affect projection outcomes. Addressing this gap requires a comprehensive synthesis of existing methodological approaches, explicit characterization of how methodological choices drive outcome differences, and development of frameworks guiding next-generation assessments that balance methodological rigor with data constraints.

1.5 Research questions

In response to the research gaps identified above, this thesis centers on the assessment and projection of wellbeing in climate and socioeconomic scenarios, explicitly accounting for feedback between environmental risks under climate change and the societal side. This overarching objective is addressed through four complementary research questions corresponding to the identified gaps. The overall research question focuses on: **How to project wellbeing using forward-looking models in climate and socioeconomic scenarios?**

To answer this overall question, four sub-questions are identified as following:

RQ1 (Chapter 2): How to assess wellbeing systematically using available Beyond-GDP metrics and synthesize them to accelerate interdisciplinary research?

RQ2 (Chapter 3): Can we project wellbeing under different climate and socioeconomic scenarios, and are the Integrated assessment modeling frameworks sufficient for this?

RQ3 (Chapter 4): How does incorporating environmental-social feedback into Integrated assessment modeling frameworks alter wellbeing outcomes under different climate and socioeconomic scenarios?

RQ4 (Chapter 5): What methodological frameworks are needed for robust temperature-mortality projection at the urban scale under climate change?

1.6 Thesis outline

This thesis addresses these gaps through four interconnected studies sequentially: developing a comprehensive harmonized Beyond-GDP database (RQ 1), projecting global wellbeing under SSPs scenarios while identifying feedback limitations (RQ 2), integrating air pollution-health feedback in Integrated assessment modeling frameworks (RQ 3), and synthesizing methodological approaches for climate-health assessments at the urban scale (RQ 4). The research progression builds systematically: from data infrastructure enabling comprehensive analysis, through projection methods revealing modeling gaps, to feedback integration demonstrating how gaps can be addressed, culminating in methodological synthesis providing guidance for future research. The outline of this thesis is illustrated in **Figure 1.1**.

Chapter 2 consolidates the WISE Database of Beyond-GDP metrics by organizing metrics by Wellbeing, Inclusion, and Sustainability (WISE) dimensions, standardization procedures, data harmonization and development of an online visualization tool enhancing accessibility. The chapter proposes the data foundation while overcoming accessibility and fragmentation barriers hindering comprehensive wellbeing research.

Chapter 3 develops and critiques wellbeing projections under various socioeconomic scenarios using HDI as a wellbeing indicator. It reveals divergent wellbeing trajectories depending on socioeconomic pathways and quantifies evolving global inequality in human development. Critically, the chapter highlights a fundamental limitation of environmental feedback on underlying socioeconomic drivers that are absent in the Integrated assessment modeling frameworks. This finding motivates explicit feedback integration in Chapter 4.

Chapter 4 integrates air pollution-health feedback into demographic projections within the SSP framework. The chapter links scenario-specific air pollution concentrations from IAM outputs to cause-specific mortality through risk functions, adjusting SSP demographic projections accordingly. The chapter demonstrates both the feasibility and importance of incorporating environmental-social feedback for realistic long-term health and wellbeing projections.

Chapter 5 reviews methodological approaches for temperature-mortality projections at the urban scale under climate scenarios. Through a PRISMA-guided systematic review, the chapter develops a five-domain framework spanning climate inputs, environmental epidemiology, demographic projections, health impact assessment, and uncertainty analysis. This synthesis provides methodological guidance for spatially explicit assessments, complementing global-scale analyses in earlier chapters.

Chapter 6 summarizes findings across chapters, addresses the overall research question, and discusses broader implications. The chapter discusses innovations and limitations, and outlines directions for future research and health governance domains and proposes a research agenda for continuing integration of environmental and social systems in long-term sustainability assessments.

Figure 1.1 Outline for this thesis.

1.7 References

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