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# The Indivisible 2030 Agenda. Systems analysis for sustainability

David Collste

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# **The Indivisible 2030 Agenda**

## **Systems analysis for sustainability**

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### **L'Agenda 2030 indivisible**

### **La durabilité au prisme de l'analyse systémique**

**Stockholm University, Stockholm, Sweden**  
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(CERDI)

This dissertation is presented and defended on Thursday June 3, 2021, for a double doctorate degree in Sustainability Science, awarded by Stockholm University, and in Economics, awarded by the University of Clermont Auvergne, through a bilateral cotutelle agreement, by

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# Abstract

In 2015 the United Nations adopted the 2030 Agenda with 17 global sustainable development goals (SDGs) to shift the world onto a sustainable path. By referring to the SDGs as indivisible, the Agenda emphasises the interdependence of social and ecological concerns. But what does it mean that the goals are interdependent and how is indivisibility to be handled in research and implementation?

In this dissertation, I investigate how models and participatory methods grounded in systems thinking can be used to facilitate the understanding and realisation of the 2030 Agenda. The dissertation explores and examines: (a) how system dynamics models can be used to represent integrated goals and their synergies at multiple levels, (b) how human well-being can be more inclusively integrated into systems models, and (c) how systems approaches can help to bridge local aspirations to global sustainability goals, incorporating multiple values and worldviews in the operationalisation of the Agenda.

This thesis comprises four papers. **Paper I** explores the interdependence of different 2030 Agenda goals through the use of a national-level system dynamics model applied to Tanzania to analyse anticipated social and economic impacts of substantial investments in photovoltaic capacity. Model simulations indicate that, in addition to building more sustainable energy systems, the investments in photovoltaics positively affect life expectancy, years of schooling as well as access to electricity. Furthermore, progress in these dimensions leads to broader system-wide impacts. This indicates that identifying policy synergies across sectors before policies are implemented can provide important insights for achieving the 2030 Agenda. In **Paper II**, we present a method for identifying policy synergies and assessing them quantitatively. The developed synergy approach is then operationalised over three case studies representing Côte d'Ivoire, Malawi and Senegal. In order to further explore the synergies and interdependencies between different human well-being goals, **Paper III** studies data on the achievement of SDGs 1- 7 in seven world regions and the world as a whole. In an analysis of the correlations between these SDGs and GDP per person, we find uniform patterns for all regions above a certain income threshold. This indicates that there is an income

level at which human needs and capabilities are achieved, consistent with the Easterlin's paradox of life satisfaction. In order to address the importance of including diverse perspectives, **Paper IV** investigates how the pursuit of the 2030 Agenda can be grounded in local worldviews. The paper introduces a stakeholder-based approach grounded in systems thinking for visioning and exploring sustainable development pathways to meet the SDGs. The approach focuses on identifying divergences and convergences across scales and worldviews about how to implement the Agenda. The paper presents a case study, the 2018 African Dialogue on the World in 2050, which deliberated on how transforming the agricultural and food systems in African regions could lead to achieving the SDGs in an integrated manner, comparing local perspectives to global sustainability trajectories.

The dissertation concludes with three main insights:

1. System dynamics models can highlight 2030 Agenda links and facilitate a shift to a more inclusive development discourse grounded in systems thinking.
2. The human well-being SDGs 1 to 7 offer a way of including more complex measures of well-being in models that can be relevantly quantified.
3. In order to democratise the 2030 Agenda discourse, it must be acknowledged that there are multiple possible pathways to meet global goals and diverse voices need to be heard.

Overall, this thesis contributes to the academic debate about the use of systems approaches to implement the 2030 Agenda in the Anthropocene.

It also provides tools and analyses to help resolve policy challenges of the 2030 Agenda's implementation, by informing how strategies can be more efficient and sustainable.

**Key words:**

2030 Agenda, Sustainable Development Goals, SDGs, synergy, integrated policy, systemism, planetary boundaries, policy coherence, system dynamics, participatory approach, human well-being

# Résumé

En 2015, les Nations Unies ont adopté l'Agenda 2030 avec 17 Objectifs de développement durable (ODD) pour amener le monde sur une trajectoire durable. En conférant aux ODD le caractère indivisible, l'Agenda met l'accent sur l'interdépendance des préoccupations sociales et écologiques. Mais que signifie cette interdépendance et comment gérer cette indivisibilité à la fois dans la recherche scientifique et dans l'implémentation des Objectifs ?

Dans cette thèse, nous avons cherché à comprendre comment les modèles et les méthodes participatives se revendiquant de la pensée systémique pouvaient être utilisés pour faciliter la compréhension et la réalisation de l'Agenda 2030. La thèse entend répondre à trois interrogations : (a) comment la modélisation des systèmes dynamiques peut être utilisée pour représenter des Objectifs intégrés et leurs synergies à plusieurs niveaux ? ; (b) comment le bien-être humain peut être intégré de manière plus inclusif dans la modélisation systémique ? ; et (c) comment les approches systémiques peuvent aider à combler l'écart entre les aspirations locales et les Objectifs mondiaux de durabilité ? Notamment via l'incorporation de valeurs et de visions du monde plurielles.

Cette thèse comprend quatre articles. L'**Article I** explore l'interdépendance de différents Objectifs de l'Agenda 2030 à l'aide d'un modèle de dynamiques de système, développé au niveau national et appliqué à la Tanzanie. Il s'agit d'anticiper l'impact sur la société et l'économie d'investissements considérables dans la production d'énergie photovoltaïque. Les simulations du modèle indiquent qu'en plus de construire des systèmes énergétiques plus durables, les investissements dans le photovoltaïque affectent positivement l'espérance de vie, la durée de scolarisation ainsi que l'accès à l'électricité. De plus, les progrès dans ces dimensions conduisent à des impacts plus vastes à l'échelle du système. Ces résultats suggèrent qu'identifier les synergies possibles entre des politiques dans différents secteurs, avant même la mise en œuvre de ces politiques, peut fournir des renseignements précieux afin d'atteindre les Objectifs de l'Agenda 2030. Dans l'**Article II**, nous présentons une méthode visant à identifier les synergies entre différentes politiques, puis à les évaluer quantitativement. Cette méthode est appliquée à trois études de cas : la Côte d'Ivoire, le Malawi et le Sénégal. Afin d'explorer plus avant les synergies et les interdépendances entre les différents Objectifs liés au bien-être humain, l'**Article III** étudie des données sur le degré d'avancement des ODD 1 à 7, dans sept

régions du monde séparément, et dans le monde dans son ensemble. L'analyse des corrélations entre ces ODD et le PIB par habitant montre certaines constantes qui sont valables pour toutes les régions au-dessus d'un certain seuil de revenu. Cela suggère qu'il existe un niveau de revenu à partir duquel les besoins et les capacités des humains sont satisfaits, conformément au paradoxe d'Easterlin. Afin de prendre en compte l'importance d'inclure diverses perspectives, l'**Article IV** examine comment la poursuite de l'Agenda 2030 peut être ancrée dans des visions du monde locales. L'article introduit une approche basée sur la participation des parties prenantes, qui permet de visualiser et d'explorer différentes trajectoires de développement durable dans le but d'atteindre les ODD. L'article présente une étude de cas, le Dialogue Africain sur le monde en 2050, qui en 2018 a suscité des délibérations sur les orientations futures des systèmes alimentaires dans différentes régions africaines et les a mises en relation avec les trajectoires mondiales en matière de durabilité. L'article conclut que les approches participatives qui intègrent la pensée systémique constituent un moyen prometteur de lier les aspirations locales aux Objectifs mondiaux de l'Agenda 2030.

**Mots clés:**

l'Agenda 2030, Objectifs de développement durable, ODD, synergies, bien-être humain, participation, limites planétaires, cohérence politique

# Sammanfattning

2015 antog Förenta Nationerna Agenda 2030 med 17 globala mål för hållbar utveckling, SDGs. Genom att hänvisa till målen som odelbara understryker agendan hur sociala och ekologiska problem hänger samman. Men vad innebär det att målen är ömsesidigt beroende och hur ska odelbarheten hanteras inom forskning och vid implementeringen av agendan?

I denna avhandling undersöker jag hur modeller och deltagandeprocesser som utgår från systemteorier kan användas för att bidra till förståelsen och förverkligandet av Agenda 2030. Avhandlingen undersöker: (a) hur systemdynamiska modeller kan användas för att representera integrerade mål och synergier mellan dessa på olika nivåer, (b) hur teorier om mänskligt välbefinnande kan bli mer integrerade i systemmodeller, samt (c) hur systemverktyg som innefattar en mångfald av värderingar och synsätt kan bidra till att skapa bryggor mellan lokala ambitioner och globala hållbarhetsmål i genomförandet av agendan.

Denna avhandling består av fyra artiklar. **Paper I** utforskar de ömsesidiga beroenden som finns mellan olika Agenda 2030-mål genom en nationell systemdynamisk modell applicerad på Tanzania. Syftet är att analysera förväntade sociala och ekonomiska effekter av kraftiga investeringar i solceller. Modellsimuleringarna antyder att solcellsinvesteringar, utöver att bidra till ett mer hållbart energisystem och tillgång på elektricitet, också har positiva effekter på förväntad livslängd och antalet skolår. Dessutom leder framgångarna på dessa områden till ytterligare systemmässiga förbättringar. Dessa resultat pekar på att man genom att identifiera synergier mellan olika samhällssektorer innan politiska förslag implementeras kan få viktiga insikter för hur Agenda 2030 kan nås. I **Paper II** presenterar vi en metod för att identifiera policysynergier och utvärdera dem kvantitativt. Den utvecklade synergimetoden operationaliseras på tre fallstudier som representerar Elfenbenskusten, Malawi och Senegal. För att vidare utforska synergier och ömsesidiga beroenden mellan olika mål för mänskligt välbefinnande studeras i **Paper III** data för måluppfyllelse av SDGs 1 till 7 i sju världsregioner och i världen som helhet. I en analys av korrelationerna mellan mål 1 till 7 och BNP-inkomst per person finner vi tydliga mönster för alla regioner över en viss

inkomstnivå. Detta indikerar att det för varje region finns en viss inkomstnivå vid vilken mänskliga behov tillgodoses och mänskliga förmågor uppnås, vilket överensstämmer med nivån för den s k Easterlin-paradoxen om mänsklig lycka. För att betona vikten av att inkludera olika perspektiv vid modellering av hållbarhetsmålen undersöker **Paper IV** hur strävan efter att nå Agenda 2030 kan utgå från världsbilder som finns lokalt. Artikeln presenterar ett intressent-baserat tillvägagångssätt för att skapa visioner och utforska vägar till en hållbar utveckling som inkluderar marginaliserade röster. Fallstudien *The 2018 African Dialogue on the World in 2050*, vilken handlade om framtida vägar för matsystem i olika afrikanska regioner relaterat till globala scenarier för hållbarhet, presenteras. Artikeln drar slutsatsen att deltagandeprocesser som inkluderar olika former av systemteorier är ett lovande tillvägagångssätt för att koppla samman lokala ambitioner med globala mål för hållbar utveckling.

Avhandlingen avslutas med tre övergripande slutsatser:

1. Systemdynamiska modeller kan visa kopplingar mellan olika hållbarhetsmål och bidra till en mer inkluderande diskussion om vad utveckling innebär med rötter i systemtänkande.
2. Indikatorer för hållbarhetsmålen 1 till 7, som är kopplade till mänskligt välbefinnande, påvisar hur mer komplexa mått för välbefinnande, såsom behov, frihet och funktion, kan inkluderas i modeller och kvantifieras på ett relevant sätt.
3. För att demokratisera diskursen om Agenda 2030 behöver en mångfald av röster höras och det behöver förtydligas att det finns olika tillvägagångssätt för att uppnå de globala hållbarhetsmålen.

På ett övergripande plan bidrar denna avhandling till den akademiska diskussionen om användningen av metoder som grundar sig i systemtänkande för att implementera Agenda 2030 i Antropocen. Genom att visa hur strategier för de globala hållbarhetsmålen kan bli mer effektiva och långsiktiga bidrar avhandlingen också till ett förbättrat underlag för politiskt beslutsfattande.

## List of papers

This doctoral thesis consists of a summary and four papers (I-IV). The papers are appended to the end of the thesis and reprinted with permission from the copyright holders.

**Paper I:** Collste, D., Pedercini, M., & Cornell, S. E. (2017). Policy coherence to achieve the SDGs: Using integrated simulation models to assess effective policies. *Sustainability Science*, 12(6), 921–931. <https://doi.org/10.1007/s11625-017-0457-x>

**Paper II:** Pedercini, M., Arquitt, S., Collste, D., & Herren, H. (2019). Harvesting synergy from sustainable development goal interactions. *Proceedings of the National Academy of Sciences*, 116(46), 23021–23028. <https://doi.org/10.1073/pnas.1817276116>

**Paper III:** Collste, D., Cornell, S. E., Randers, J., Rockström, J., & Stoknes, P. E. (in review). Regional Achievements of Well-being SDGs in the Anthropocene. In review for *Global Sustainability*.

**Paper IV:** Collste, D., Aguiar, A. P. D., Harmáčková, Z., Galafassi, D., Pereira, L., Selomane, O., & Van Der Leeuw, S. (in review). Three Horizons for the Sustainable Development Goals: A Cross-scale Participatory Approach for Sustainability Transformations. In review for *Ecology & Society*.

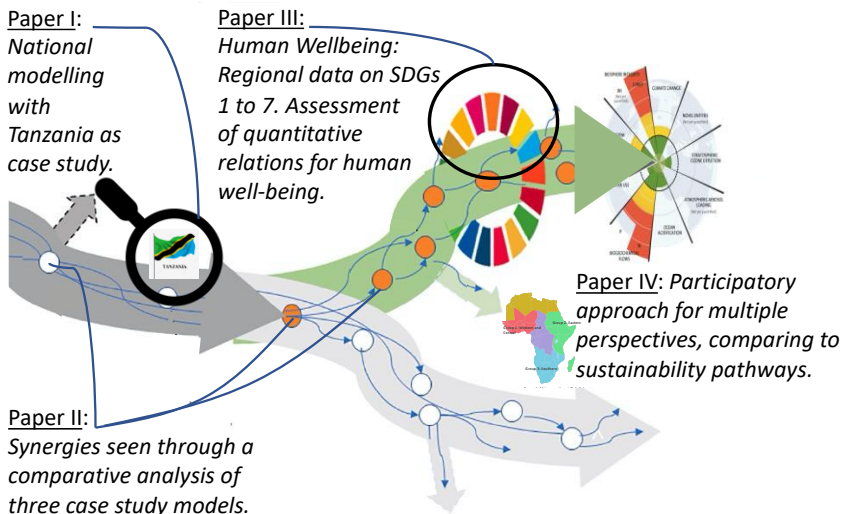
## Contribution to included papers

In **Paper I**, I developed the case study example and designed the research. I performed the modelling together with M.P. I simulated the model and analysed the data. I wrote the paper and received useful directions from the co-authors.

In **Paper II**, I jointly conceptualised and wrote the paper together with the co-authors. My main contributions are in the sections *Method*, *Synergy—A Definition for SDG Analysis*, *A Framework for Analysis of SDG Synergies*, and *Discussion*.

In **Paper III**, I designed the data gathering process together with J.Ra., including choosing the relevant indicators, and transcribing and transforming data to usable formats. I designed the research for the paper, performed the research and analysed the data. I wrote the paper and received useful directions from co-authors.

In **Paper IV**, I contributed to the conception of the work as programme officer for SwedBio. I co-designed the participatory approach and facilitated the pilot case study *the 2018 African Dialogue on the World in 2050*, together with the co-authors. I analysed and interpreted the data. I led the paper development and received useful directions from the co-authors.



A conceptual figure showing the four thesis papers positioning on different aspects of pathways for global sustainability. Adapted from the figure in Aguiar, Collste, Harmáčková, Pereira, Selomane, Galafassi, van Vuuren and van der Leeuw. 2020, that was based on Fazey et al. (2016) and Roy et al. (2018). This figure is discussed as Figure 7.

## Related publications outside the thesis

### Peer reviewed articles

Aguiar, A. P. D., **Collste, D.**, Harmáčková, Z. V., Pereira, L., Selomane, O., Galafassi, D., Van Vuuren, D., & Van Der Leeuw, S. (2020). Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. *Global Environmental Change*, *65*, 102198. <https://doi.org/10.1016/j.gloenvcha.2020.102198>

Downing, A. S., Bhowmik, A., **Collste, D.**, Cornell, S., Donges, J. F., Fetzer, I., Häyhä, T., Hinton, J., Lade, S. J., & Mooij, W. (2019). Matching scope, purpose and uses of planetary boundaries science. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/ab22c9>

Engström, R. E., **Collste, D.**, Cornell, S. E., Johnson, F. X., Carlsen, H., Jaramillo, F., Finnveden, G., Destouni, G., Howells, M., Weitz, N., Palm, V., & Fuso-Nerini, F. (2021). Succeeding at home and abroad—Accounting for the international spillovers of cities’ SDG actions. *npj Urban Sustainability*, *1*(1). <https://doi.org/10.1038/s42949-020-00002-w>

Randers, J., Rockström, J., Stoknes, P.-E., Goluke, U., **Collste, D.**, Cornell, S. E., & Donges, J. (2019). Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability*, *Vol 2*, E24. <https://doi.org/10.1017/sus.2019.22>

Schneider, A., Hinton, J., **Collste, D.**, González, T. S., Cortes-Calderon, S. V., & Aguiar, A. P. D. (2020). Can transnational corporations leverage systemic change towards a ‘sustainable’ future? *Nature Ecology & Evolution*, *4*(4), 491–492. <https://doi.org/10.1038/s41559-020-1143-4>

### Other peer reviewed publications

**Collste, D.** (2020). New Economic Paradigms. In *Encyclopedia of the World's Biomes* (pp. 296–302). Elsevier. <https://doi.org/10.1016/B978-0-12-409548-9.12446-7>

**Collste, D.** (2021). Modeling Korpi and Palme's 'Paradox of Redistribution and Strategies of Equality'. In R. Y. Cavana, B. C. Dangerfield, O. V. Pavlov, M. J. Radzicki, & I. D. Wheat (Eds.), *Feedback Economics: Economic Modeling with System Dynamics*. Springer. <https://www.springer.com/gp/book/9783030671891>

Diemer, A., **Collste, D.**, & Spittler, N. (2020). Systemic Issues and Multi-Stakeholders Partnerships for Achieving Sustainable Development Goals. In W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Encyclopedia of the UN Sustainable Development Goals* (pp. 1–14). Springer International Publishing. [https://doi.org/10.1007/978-3-319-71067-9\\_72-1](https://doi.org/10.1007/978-3-319-71067-9_72-1)

## Co-authored reports

Aguiar, A. P., **Collste, D.**, Galafassi, D., Harmáčková, Z., HOUNGBEDJI, K., Mesfin, M., NDAHIRO, D., PEREIRA, L., SELOMANE, O., & VAN DER LEEUW, S. (2019). *The Second African Dialogue on the World in 2050—How to attain the SDGs within planetary boundaries: Agriculture and food systems. Report on a Multi-Actor Dialogue for TWI2050, 30—31 October 2018, Kigali, Rwanda*. Sustainable Development Goals Center for Africa and SwedBio/Stockholm Resilience Centre at Stockholm University. [https://swed.bio/wp-content/uploads/2019/02/7017-0034-2nd-TWI2050-dialogue\\_report\\_WEB.pdf](https://swed.bio/wp-content/uploads/2019/02/7017-0034-2nd-TWI2050-dialogue_report_WEB.pdf)

Galaz, V., **Collste, D.**, & Moore, M.-L. (2020). Planetary Change and Human Development. Background paper to the 2020 Human Development Report: The next frontier: Human Development and the Anthropocene [Unpublished manuscript, Stockholm Resilience Centre, Stockholm University].

Karangwa, C., Mesfin, M., Dubois, T., Henao, L., Mutune, J., NDAHIRO, D., SEMPEHO, G., **Collste, D.**, CORNELL, S. E., & MELLEGÅRD, V. (2018). *The African Dialogue on the World in 2050: How can agriculture contribute to meeting the SDGs?* <https://swed.bio/reports/report/dialogue-workshop-report-african-dialogue-twi2050/>

Randers, J., Rockström, J., Stoknes, P. E., Golüke, U., **Collste, D.**, & CORNELL, S. E. (2018). Transformation is feasible: How to achieve the Sustainable Development Goals within Planetary Boundaries. A report to the Club of Rome, for its 50 years anniversary 17 October 2018. Stockholm Resilience Centre. <https://www.stockholmresilience.org/publications/artiklar/2018-10-17-transformation-is-feasible---how-to-achieve-the-sustainable--development-goals-within-planetary-boundaries.html>

TWI2050 - The World in 2050. (2018). Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. IIASA. <https://doi.org/10.22022/TNT/07-2018.15347>

TWI2050 - The World in 2050. (2019). The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report prepared by the World in 2050 initiative. IIASA. <http://dx.doi.org/10.22022/TNT/05-2019.15913>

TWI2050 - The World in 2050. (2020). Innovations for Sustainability: Pathways to an efficient and sufficient post-pandemic future. IIASA. [10.22022/TNT/07-2020.16533](https://doi.org/10.22022/TNT/07-2020.16533)

## Contents

1.	Introduction, research aim and contributions .....	14
1.1	Research aim .....	15
1.2	Summary of thesis contributions .....	16
1.3	Structure of the kappa .....	19
2.	Research context and background .....	21
2.1	The emergence of an interdependent social- ecological Earth system view .....	21
2.2	Intergovernmental responses: Historical background to the 2030 Agenda .....	23
2.3	The 2030 Agenda: Universal, transformative, and indivisible .....	25
2.4	Criticisms of the 2030 Agenda and how science can contribute .....	26
2.5	Human well-being and sustainability in the 2030 Agenda context .....	28
2.6	Modelling the 2030 Agenda .....	32
3.	Theoretical framing: Systemism .....	35
3.1	Systemism to align knowledge and action for the 2030 Agenda .....	35
3.2	The system dynamics perspective .....	37
3.3	Social-ecological systems, resilience and development .....	40
3.4	System boundaries: Systemic triangulation for 2030 Agenda studies .....	41
4.	Contributions: Systems analysis applications .....	45
4.1	Research in transdisciplinary sustainability projects .....	45
4.2	Conceptual framework .....	46
4.3	Overview of research methods and data sources .....	49
4.4	System dynamics modelling for the 2030 Agenda .....	51
4.5	Participatory approach grounded in systems thinking – Three horizons for the SDGs (3H4SDG) .....	54
5.	Summaries of the thesis papers .....	56
5.1	Paper I: Policy coherence to achieve the SDGs .....	56
5.2	Paper II: Harvesting synergy from sustainable development goal interactions .....	59
5.3	Paper III: Regional Achievements of Well-being SDGs in the Anthropocene .....	61
5.4	Paper IV: Three Horizons for the Sustainable Development Goals .....	63
6.	Discussion and conclusion .....	66
6.1	Key insights .....	66
6.2	Implications for practice and policy .....	68
6.3	Ethical reflections .....	68
6.4	Personal reflections on my research journey .....	70
6.5	Financial support .....	72
	Literature cited .....	73
	Index .....	85
	Thank you .....	88

Papers I to IV follow, separated by orange-coloured sheets.

” The interdependencies among peoples and nations over time and space are greater than commonly imagined. Actions taken at one time and on one part of the globe have far-reaching consequences that are impossible to predict intuitively, and probably also impossible to predict (totally, precisely, maybe at all) with computer models.”

Meadows, D. H., Richardson, J. M., & Bruckmann, G. (1982).  
*Groping in the dark: The first decade of global modelling*. Wiley.

## 1. Introduction, research aim and contributions

The 2030 Agenda is the international community’s response to the unprecedented social-ecological challenges of the 21<sup>st</sup> century. It presents the most comprehensive global roadmap adopted since the UN Charter. The Agenda responds to society’s demands for international coordination to sustainably ensure human well-being for all, and in harmony with nature.

That the 2030 Agenda is referred to as indivisible signifies the goals’ integrated nature and marks a historic shift for the UN towards “one sustainable development agenda” (Biermann et al. 2017 p. 26). The Agenda is also the most ambitious effort yet of goal-setting at the centre of global policy (ibid.). Indivisibility reflects that there are inherent interdependencies between the goals and the actions needed to achieve them. But how is this indivisible agenda and the interdependent goals to be handled, scientifically and practically? This dual challenge requires approaches that reflect the increasingly complex interdependencies between human well-being and its foundation, the biosphere (Folke et al. 2016).

Implementing the 2030 Agenda’s Sustainable Development Goals (SDGs) in ways that take their inherent systemic interdependencies into consideration requires policy coherence for sustainable development (OECD 2015). Policy coherence for sustainable development also needs to incorporate human dependence on Earth’s life-supporting systems (Griggs et al. 2013), as well as

impacts on the Earth system from human production and consumption systems. These impacts are becoming increasingly significant in the *Anthropocene*, the geological epoch in which humans and societies “have become a global geophysical force” (Steffen et al. 2007 p. 615). Living in the Anthropocene necessitates recognising the risks of current socio-economic developments causing systemic deterioration of the biophysical environment that could trigger large-scale Earth system shifts, with potentially devastating consequences for humanity (Steffen et al. 2018).

**For science**, the interdependent nature of the SDGs in the Anthropocene imposes a challenge of providing relevant frames for comprehending the goals, their linkages and the complex processes of change involved in implanting and achieving them. To respond to this challenge, the goals should be approached in a systemic rather than sectoral fashion, and ideas for action should be put in the context of systems-oriented approaches. As C. S. Holling explains:

” Both the science of parts and the science of the integration of parts are essential for understanding and action. Those more comfortable in exercising only one of these have the responsibility to understand the other. Otherwise the science of parts can fall into the trap of providing precise answers to the wrong question and the science of the integration of parts into providing useless answers to the right question.” (Holling 1998).

**Systems approaches** focus on the interlinkages between parts and how the nature and structure of these interlinks give rise to outcomes. They thus belong to what Holling refers to as the “science of the integration of parts”. The systems approaches applied in this thesis also recognise the importance of how systems are understood by the different actors within them. Systems approaches can be applied for improving theoretical understanding, and for informing real-world action, and are often situated in the cognitive intersection of knowledge and action. They have long been used for an integrated understanding of the world system. Well-known examples include the global integrated system models applied in *The Limits to Growth* (Meadows et al. 1972, 1974, 1992, 2004) and *International Futures* (Hughes 1999, 2019), but systems methods are also used in works that support local engagement in sustainability transformations (see, e.g., Holling 1978).

## 1.1 Research aim

Since 2016, when I began working on this dissertation - less than a year after the 2030 Agenda agreement was signed - there has been an enormous increase in the academic literature on different aspects of the 2030 Agenda and its implementation. This includes research investigating interactions between goals and targets (see Bennich et al. 2020 for a review of this literature), as well as

research focusing on science that supports improving national implementation of the Agenda (see reviews by Allen et al. 2016, 2018, and 2021a). These recent reviews have identified research gaps that should be filled to provide better understanding of the Agenda and to guide its implementation. Key gaps identified include; a lack of methods that improve the understanding of interlinkages between SDGs (Allen et al. 2018, 2021a), the lack of systems thinking and integrated analytical approaches and models (Allen et al. 2018), a lack of systems approaches that cover the full Agenda (Bennich et al. 2020), and the lack of participatory methods informed by systems thinking (Bennich et al. 2020). This thesis contributes to filling these identified gaps in the current research discourse on the 2030 Agenda. Specifically, this dissertation aims to demonstrate:

*How models and participatory approaches grounded in systems thinking can highlight interdependencies between goals, and contribute to bridging global sustainability knowledge and the decision-making arenas of the 2030 Agenda.*

In line with this aim, in this work I have explored and examined:

- A. How system dynamics models can be used to represent the complexity of interactions between SDGs, both qualitatively and quantitatively (Papers I and II)
- B. How human well-being can be (re-)conceptualised for integration in systems models, in the context of world-Earth modelling of SDG pathways (Paper III)
- C. How systems approaches can help to bridge local aspirations to global sustainability goals, incorporating multiple values and worldviews in the operationalisation of the Agenda (Paper IV).

## 1.2 Summary of thesis contributions

My research explores the intersection between the knowledge producing processes of global sustainability research, and the actions necessary to achieve global sustainability goals, e.g., in the form of policy implementation. This form of **knowledge-action interface** can, according to Cash et al. (2003), be explored with different types of ‘boundary objects’, including models and scenarios, as I do in this dissertation. Exploring the knowledge-action interface can allow research to more effectively contribute to translating knowledge to action (Cornell et al. 2013).

The main scientific contribution of this thesis is showcasing the use of systems approaches in understanding the indivisibility prescribed by the 2030 Agenda. To fully take on a systems approach to the 2030 Agenda necessitates both obtaining a **general systems understanding** that recognises the complexity

of the Agenda's social, economic and environmental goals, and applying systems methods to gain **specified systems understanding**. In particular, global systems models have tended to integrate economic and environmental aspects, while leaving social aspects and human well-being comparatively poorly rendered. Systems approaches serve different purposes, including helping the user to see and understand system components and their interconnections as well as guiding actions to improve outcomes. Taking concrete, actionable steps that are informed by systems thinking requires comprehending what systems thinking implies. Given that the Agenda is referred to as indivisible and the integrated challenges that the global society is facing today, systems thinking that better captures societal goals is not a choice but a necessity.

Below follows a brief introduction to the contributions made by the different thesis papers.

**Paper I** demonstrates how integrated simulation models can be used to analyse progress on the SDGs at a national level. The study embarks from an existing version of the Threshold 21 model, a system dynamics model designed to support integrated long-term national development planning (see Barney 2002). In the paper, we analyse anticipated health and educational impacts of substantial investments in photovoltaics capacity in a pilot case study model of Tanzania. We systematically map out how mutually reinforcing causal relationships between SDG 3 on healthy lives, SDG 4 on education, and SDG 7 on energy, can give rise to system-wide improvements in electricity access, life expectancy and schooling. We expand the Threshold 21 model with a new causal structure incorporating links between electricity access and health and educational outcomes. We also quantify these links and discuss how qualitative understanding of causal links can be relevantly translated to a quantified model with a higher level of abstraction. The model simulations and results are the first application of the *Threshold 21 integrated SDG model*, iSDG.

**Paper II** presents a generalisable approach for quantitatively estimating synergies between policies for SDG implementation. The possibility of identifying probable SDG synergies before implementing 2030 Agenda policies can facilitate the harmonisation of policies and improve their collective impacts. In the paper, we present a method for identifying synergies and assessing them quantitatively, as well as a framework for categorising these synergies. The synergy approach that is laid out is operationalised in three case studies representing Côte d'Ivoire, Malawi and Senegal. The case study simulations indicate that strategies for SDG implementation can be significantly improved, and more SDGs achieved, if synergies are considered in the SDG planning. My main contributions to the paper are first, conceptualising the synergies

approach, second, comparing it to other tools for identifying synergies, and, third, highlighting the uniqueness as well as limitations of the approach.

**Paper III** analysis how human well-being can be conceptualised in world-Earth models. World-Earth models are an emerging class of stylised dynamic global social-ecological system models that seek to incorporate more human aspects than earlier models. Human well-being is often referred to as the overarching aim of societies, specifically in relation to sustainability. Despite being a societal aim, human well-being is rarely relevantly incorporated into world modelling as these tools often focus predominantly on energy and material flows. Human aspects that are incorporated in these models are either demographic (i.e., population sizes) or economic aggregate incomes (i.e., GDP measures). In Paper III, we conceptualise human well-being in terms of the achievement of the 2030 Agenda's human well-being goals, SDGs 1 to 7. We study regional historical data on progress on these SDGs and relate this data to the corresponding levels of GDP per person as measured by purchasing power parity (PPP). We also contextualise the seven SDGs with reference to theories of well-being: preference satisfaction theory, life satisfaction approaches, human needs, and the capabilities approach. In the data, we observe stark regional differences of SDG attainments: the patterns of human well-being for the world as an aggregated whole has developed differently from its seven regions, with implications with respect to scale for the future use of world-Earth models in discussions of global sustainability. This work has contributed to the development of the Earth3 model (Randers et al. 2019), where the regional relationships were used to calibrate the model links between GDP per person levels and human well-being outcomes.

**Paper IV** brings a cross-scale outlook and focuses on differences in values and worldviews in relation to 2030 Agenda implementation. Global pathways generated in international sustainability studies are contrasted to narratives that are prevalent among regional stakeholders in relation to food systems in Sub-Saharan African regions. The paper embarks from the need to embed the pursuit of the 2030 Agenda in worldviews “on the ground”. It both recognises and promotes the importance of convergences and divergences in perspectives. In order to relevantly incorporate diverse perspectives, we argue for the need to increase participation of people that are not heard in global sustainability studies. We therefore propose a participatory approach that builds on the widely used Three Horizons framework for foresight and transformation. The approach is also demonstrated in relation to a case study, *the 2018 African Dialogue on the World in 2050*, which serves as a pilot for other regional multi-stakeholder discussions in support of SDG implementation. The Dialogue deliberated on how transforming the agriculture and food systems in regions of Africa could contribute to reaching the SDGs in an integrated man-

ner. Local pathways were then compared to global narratives about sustainability. The paper details the premises and steps of the developed Three Horizons for the SDGs (3H4SDG) approach and highlights its methodological advancements. We also summarise the results from the pilot application of the approach, which highlighted multiple and contrasting perspectives on the implementation of the Agenda. The paper concludes that participatory approaches grounded in systems thinking represent a promising way to link local aspirations with 2030 Agenda goals and global sustainability pathways.

### 1.3 Structure of the kappa

Figure 1 presents an overview of the thesis contribution and kappa structure. Following this introduction, Section 2 provides the research context of the knowledge-action interface of the 2030 Agenda including a historical background to the 2030 Agenda and the state of the art of modelling in support of sustainability. In Section 3, I set out the theoretical frame of the thesis, focusing on ‘systemism’. In Section 4, I present the thesis’ contributions in the form of systems analysis applications and explain how the papers fit together and contribute to aspects of the knowledge-action interface. In Section 5, I summarise the dissertation papers, and in Section 6 I discuss and conclude the paper results.

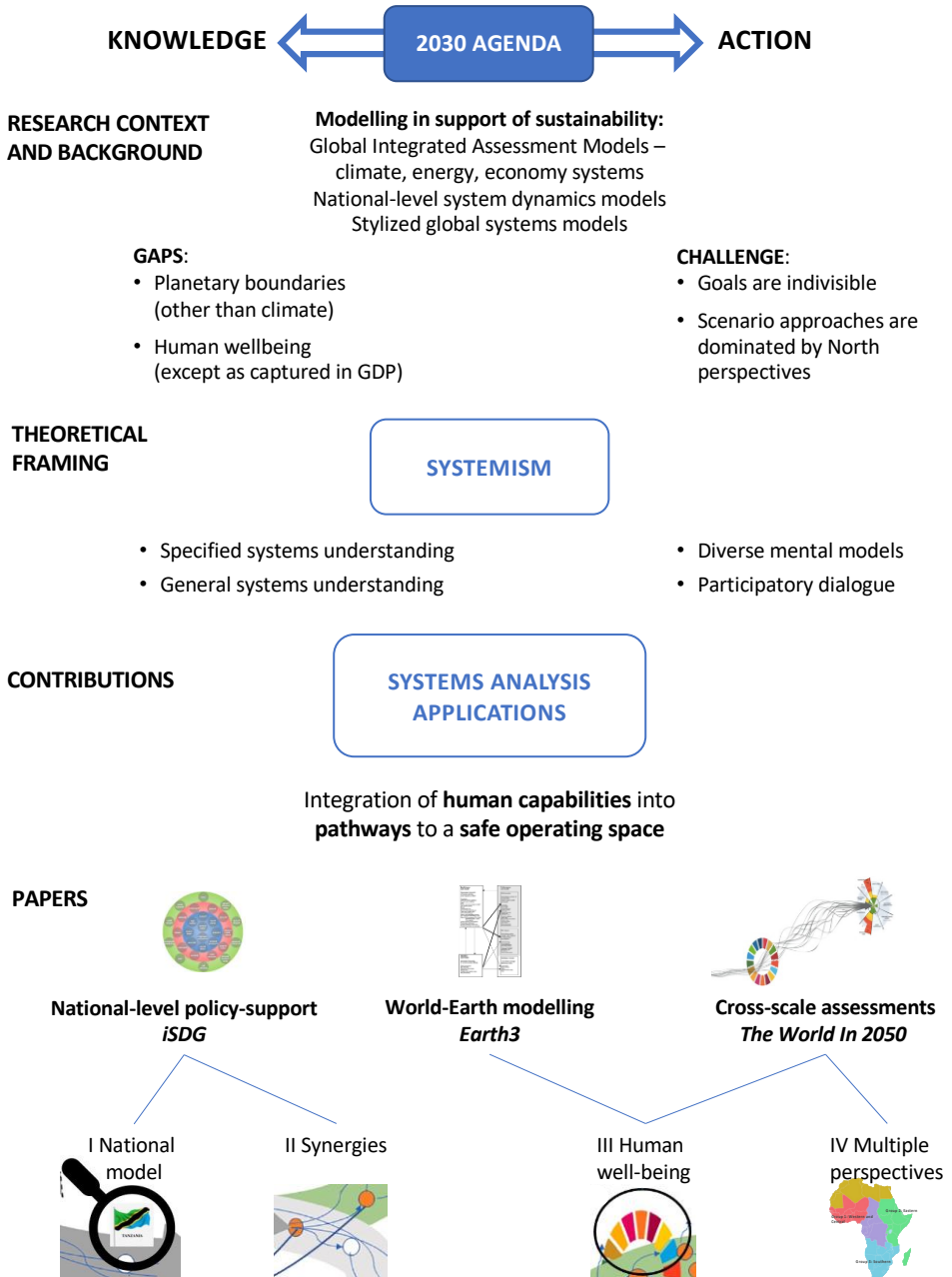


Figure 1: Overview of the thesis contribution and kappa structure.

## 2. Research context and background

In this section, I present a historical account of the interdependent social-ecological Earth system (2.1) and the policy responses from an intergovernmental viewpoint (2.2) – arriving at the 2030 Agenda based on the three aspects: that the Agenda is referred to as universal, transformative, and indivisible (2.3). I thereafter discuss criticism against the Agenda and how science can contribute (2.4), as well as the constituents of human well-being and sustainability that are central to the thesis papers (2.5). The section ends with a description of current modelling practices in support of sustainability (2.6).

### 2.1 The emergence of an interdependent social-ecological Earth system view

In the 1960s and the 1970s, concerns were rising over the environmental consequences of increases in material throughput, fuelled by rapidly growing global economies and populations. These concerns included environmental problems caused by the use of chemicals and pollutants (note Rachel Carson's *Silent spring* from 1962), population growth (Ehrlich 1971), and the wider “predicament of mankind” (The Club of Rome 1970). The predicament of mankind incorporated intertwined problems at the aggregated world level, including e.g. widespread poverty, growing malnutrition, and environmental deterioration and was jointly put together in a document to the Club of Rome (1970). The concern about the “predicament of mankind” led the newly established Club of Rome to invest in the first world-level simulation models, presented in Jay W. Forrester's *World Dynamics* (1971) as well as the report *The Limits to Growth* (DH Meadows et al. 1972). *The Limits to Growth* was based on a computer-based stylised global world model, World3 (DL Meadows et al. 1974), which linked human development, including population and material throughput, to environmental limits.

The World3 model outputs presented in *Limits to Growth* anticipated that humanity would run into ecological limits within the coming century, i.e., in the 21<sup>st</sup> century, if no significant radical societal changes to counteract this development would be taken (the computer simulation ran from 1900 to 2100). According to the study, the limits will either have the form of sources, i.e., limitations in the use of non-renewable resources such as oil or coal, or, they will have the form of sinks, i.e., caused by the limited absorptive capacity of the Earth in handling different forms of environmental pollutions such as greenhouse gases. The system dynamics method that was used for these first world models, further presented in Section 3, has developed closely alongside the last 50 years of discussions on sustainable development (Pedercini et al. 2020

presents an overview of contributions from the system dynamics field to sustainable development discussions).

The early 1970s was also the time for James Lovelock and Lynn Margulis' Gaia hypothesis. The hypothesis suggests that all living organisms interact with their non-living surroundings on Earth in forming a self-regulating complex system that has maintained the conditions for life (Lovelock 1972, Lovelock and Margulis 1974).

In the 1980s, the International Geosphere-Biosphere Programme (est. 1987), IGBP, was founded, dedicated to the study of phenomena of global environmental change, informed by the feedbacks between life and its abiotic surroundings. This was an early initiative setting the foundation for what has come to be called Earth system science (NASA 1988, Lawton 2001). Following these developments, the first assessment reports of the Intergovernmental Panel on Climate Change (IPCC) were published in the early 1990s (IPCC 1992, 1996). The assessment laid out the scientific basis for the possibility of hazardous human interference in the global climate system due to anthropogenic carbon emissions leading to average temperature rise (Cornell et al. 2012). Since then, the growing understanding of Earth system processes has also brought an increased interest in ways to integrate social and bio-geophysical phenomena.

It is now widely acknowledged that the Earth system has become human-dominated (Steffen et al. 2004). In this context it has been suggested that humanity has entered the Anthropocene (Waters et al. 2016, Subramanian 2019) – the geological epoch in which humans and societies “have become a global geophysical force” (Steffen et al. 2007 p. 615). This implies a need to find ways to live responsibly, acknowledging human dependencies on a functioning Earth system, and its societal implications (Hamilton 2017).

Theories of social-ecological systems have helped in our understanding of the Earth system (Holling 1986). Social-ecological systems are systems where human societies and ecological systems are integrated, with reciprocal feedback and interdependence (Folke et al. 2010). Theories of social-ecological systems emphasise *resilience*, defined as the capacity of a system to absorb changes, but also to reorganise when facing disturbances to retain the same functions (Folke et al. 2010, Walker and Salt 2012). Reduced resilience implies increased vulnerability of the system to disturbances which can risk causing a collapse. Social-ecological systems and resilience perspectives are further presented in Section 3.

Attempts to define the resilience of the Earth system incorporate identifying critical Earth system processes that are key to human flourishing. It is within

this context that a ‘safe operating space for humanity’ has been defined in terms of nine planetary boundaries (Rockström et al. 2009a, 2009b, Steffen et al. 2015). The boundaries mark out the biogeochemical conditions of the Holocene – the relatively stable geological epoch that has provided favourable conditions for agriculture and complex societies to flourish. Breaching these boundaries implies increasing risks for the Earth’s life-supporting systems, driving the Earth system into a new state that is ecologically vulnerable and hence unfavourable for human flourishing. Global biophysical models and integrated assessment models have been developed mainly for climate processes and their economic impacts, but not the wider human-caused challenges highlighted in the planetary boundaries framework. Thus, stylised world-Earth models are needed for the analysis of interactions of global environmental changes with human well-being.

## 2.2 Intergovernmental responses: Historical background to the 2030 Agenda

International political discussions have over the past 50 to 60 years gradually responded to the global environmental crises and the increased understanding of human and Earth system interdependencies. Since the formation of the United Nations in the aftermath of the Second World War, the organisation has expanded its agenda beyond its core focus on international security and human rights, to include global developmental, environmental and climate concerns. The first UN conference on the ‘human environment’ was held in Stockholm in 1972. The conference concluded with the following statement:

“To defend and improve the human environment for present and future generations has become an imperative goal for mankind – a goal to be pursued together with, and in harmony with, the established and fundamental goals of peace and of world-wide economic and social development” (United Nations, 1973).

The 1972 Stockholm conference was followed up in Rio de Janeiro in 1992 with the UN Conference on Environment and Development. The outcome - the Rio Declaration - was a short document with 27 principles that emphasised the interrelations between human development and the environment. The Declaration also highlighted that:

“the major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialized countries” (United Nations, 1992).

The Rio outcomes were heavily influenced by the Brundtland Commission’s report ‘*Our common future*’, which defined the term sustainable development as “development that meets the needs of the present without compromising

the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987).

In 2001, UN Secretary-General Kofi Annan convened the Millennium Summit during which member countries agreed on eight Millennium Development Goals (MDGs), to be reached by 2015. Although the MDGs included one goal on environmental sustainability, they were predominantly human-centred, including goals on hunger, education, gender equality, child mortality, maternal health, HIV/AIDS and malaria, and global partnership for development. The MDGs were a big achievement for a global mobilisation to achieve social priorities (Sachs 2012). However, a critique of the MDGs notes that the goals were often seen in isolation incorporating siloed approaches to reach them (Rippin 2014). Beyond the date when the MDGs were to be achieved, new global priorities were to be formulated under the headline of a ‘Post-2015 development agenda’.

20 years after Rio, a second conference was held in 2012, Rio +20. The Rio+20 outcome document was titled ‘*The future we want*’ (United Nations 2012) and included an agreement to develop a set of ‘Sustainable Development Goals’, SDGs.

The 2030 Agenda is thus an outcome of the two parallel negotiation processes: ‘the Post-2015 development agenda’ (United Nations 2013), negotiating the MDG follow-up; and the ‘SDGs’ – building on the agreement from the Rio+20 conference. The reconciliation of the two processes has been widely seen as a success for integrating environmental sustainability into a broader poverty- and development-oriented framework (Biermann et al. 2017).

The 2030 Agenda negotiations have been recognised for being both inclusive and innovative (Biermann et al. 2017). They included sessions of stakeholder stocktaking, and researchers were invited to give presentations during the preparations for the negotiations (Chasek et al. 2016). Although the 2030 Agenda reflects decades of multilateral negotiations and shares many characteristics with earlier UN resolutions, the Agenda is unique in two ways. Firstly, it marks the most ambitious effort yet to place goal-setting at the centre of global policy (Biermann et al. 2017). Secondly, it marks a historic shift towards *one sustainable development agenda* that integrates social and economic development with environmental sustainability (ibid.). Related to this, it is noteworthy that the 2030 Agenda resolution incorporates systems terms, e.g. by referring to the SDGs as “interlinked”, “integrated” and “indivisible”, and it includes the statement that the “The survival of many societies, and the biological support systems of the planet, is at risk.” (United Nations 2015).

## 2.3 The 2030 Agenda: Universal, transformative, and indivisible

The 2030 Agenda incorporates 17 SDGs with 169 targets and 231 indicators (the indicators were agreed two years later, United Nations 2017). Importantly, the Agenda also includes a preamble and a declaration including three aspects. The Agenda is referred to as being universal, transformative, and indivisible<sup>1</sup> (Mohammed 2015, United Nations 2015).

That the Agenda is referred to as being *universal* implies that the SDGs, unlike the MDGs, apply to all countries: “These are universal goals and targets which involve the entire world, developed and developing countries alike.” (United Nations 2015). It is, therefore, possible to compare the achievements of goals between different countries and world regions, at least for a subset of indicators for which data is available. Examples of such comparisons are the national level focused *Index and Dashboards Reports* (Sachs et al. 2016, Schmidt-Traub et al. 2017). In Randers et al. (2018, 2019), we also made regional forecasts of SDG achievements. Universality also enables studying interrelations between countries and regions, e.g. in the context of spillovers (in Engström, Collste, Cornell et al. 2021, we discuss spill-overs from cities SDG actions that have impacts beyond national borders). Because social and environmental conditions vary, much of the 2030 Agenda implementation must be contextualised and interpreted in relation to local conditions and understood in the context of locally prevalent narratives (van der Leeuw 2020b). Furthermore, Leach et al. (2010) argue that there are different contextual views on sustainability. To interpret the 2030 Agenda implementation in local contexts, it is therefore important to recognise these “multiple sustainabilities” (Leach et al. 2010 p. 42). Otherwise, the Agenda risks being seen as imposed from the outside and irrelevant to local decision-makers as well as citizens.

The 2030 Agenda is also presented as *transformative*: “In these Goals and targets, we are setting out a supremely ambitious and transformational vision.” (United Nations 2015). The term ‘transformation’ has been defined as “a fundamental change in the structures, cultures, and practices of a societal system, profoundly altering the way it functions” (de Haan and Rotmans 2011). As referred to above, there has been a significant shift across the scientific community recognising that human activities are driving Earth towards a hazardous future that will make current ways of living impossible, and therefore transformations are needed (see, e.g., IPCC 2014, IPBES 2019). For a further discussion on the needs for transformation and what they imply in the 2030 Agenda context, see Linnér and Wibeck (2019).

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<sup>1</sup> These aspects were, e.g., highlighted by Amina Mohammed, the UN Secretary-General’s Special Adviser on Post-2015 Development Planning (Mohammed 2015).

The final of the three aspects of the Agenda referred to here, and the focus of this thesis, is that the goals are ‘*indivisible*’ and ‘*integrated*’. The 2030 Agenda states that the goals “(...) are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental.” (United Nations 2015). The emphasis on the indivisible and inter-linked nature of the goals reflects a recognition that they depend on each other for the achievement of the Agenda as a whole – that the goals are interdependent. This challenge siloed approaches for goal implementation that focus merely on one target, i.e., that overlook the many interlinks between goals. Integration is a focus for much of the 2030 Agenda research to date (see the review of this literature presented in Bennich et al. 2020). But there are many ways in which the integration can be handled. There is here a risk of ‘*integration*’ only involving mapping interaction between and across diverse sets of goals and targets without paying enough attention to the causal structure of the underlying systems. To avoid this risk, one should engage with the structural assumptions underlying hypothesised causal relations in the context of development planning and sustainability pathways. This is one of the core issues I address in this thesis.

## 2.4 Criticisms of the 2030 Agenda and how science can contribute

There is already a critical discussion around various aspects of the 2030 Agenda. A central critique points out that while the SDGs incorporate, and in principle reconcile, environmental sustainability with aspects of human development, they do not sufficiently account for environmental aspects. For example, Zeng et al. (2020) argue that what is referred to as the three dimensions of sustainable development - the economic, social, and environmental - are unbalanced in the Agenda. They compare SDG indicators to a suite of external measures of biodiversity and conclude that while most countries are progressing well towards fulfilling environmental SDGs, these SDGs have little relation to the countries’ actual environmental performance. The authors warn that “If this continues, the SDGs will likely serve as a smokescreen for further environmental destruction throughout the decade.” (Zeng et al. 2020 p. 795). Similarly, the Global Footprint Network show that countries with the highest rankings on the Sustainable Development Goals Index that estimates countries’ gaps towards achieving the SDGs (Schmidt-Traub et al. 2017), are also among the countries with the highest Ecological Footprints (Global Footprint Network 2016).

In line with this critique, the transformative aspect of the 2030 Agenda has been questioned. Hickel (2019) studies the SDGs by looking at the compatibility of realising SDG 8, which includes targets on aggregate global economic

growth, and the environmental SDGs 6, 12, 13, 14, and 15. Based on empirical observations, Hickel argues that it is not feasible to combine economic growth with reductions in resource use and CO<sub>2</sub> emissions. He concludes that SDG 8 violates the sustainability of the Agenda as a whole and suggests removing the aggregated growth target. In the same vein, both Victor (2019) and van der Leeuw (2020a) criticise the Agenda for incorporating a notion of ‘progress’ defined as improvements in terms of growth of the Gross Domestic Product. Weber and Weber (2020) argue that the Agenda rests on a notion of sustainability informed by ecological modernisation theory. This theory is based on privileging economic growth over social and environmental concerns (Weber and Weber 2020). Victor (2019) argues that moving towards this narrow definition of progress may neither be feasible nor appealing for all regions of the world.

Researchers have also asked “transforming to what?” Weber (2017) examines the Agenda and associates its formation with a macro-political framework mirroring the present global power structure, that privileges the upholding of “commercial law as the ordering principle of development” (Weber 2017 p. 407). She contends that this is “(...) not the kind of transformative process that critical scholars and social movement activists might anticipate (...)” (Weber 2017 p. 401). Further, Briant Carant (2017) studies the evolution from MDGs to SDGs by use of critical discourse analysis and argues that crucial voices are missing in the SDGs, including those raised by the World Social Forums – an annual meeting of civil society organisations with the motto ‘Another World is possible’. Instead, she argues, the Agenda is dominated by two kinds of rhetoric: neo-liberal in parts, Keynesian elsewhere – but neither is transformational (Briant Carant 2017). Easterly, criticising the Agenda from another perspective refers to the 2030 Agenda as “Senseless, Dreamy, Garbled” (Easterly 2015) and claims that it is both utopian and meaningless. Furthermore, he associates it with what he refers to as “the decline and fall of hopes for Western aid” (Easterly 2015).

Given that the Agenda was developed in multilateral negotiations, it is perhaps not realistic to expect that it fully reflects the views of social movement activists and the World Social Forums, as Briant Carant (2017) and Weber (2017) emphasise. Although the goals and resolution writing process incorporated a significant amount of stakeholder stocktaking processes and input from scientists, it was the UN member states that in the end agreed on the resolution text. The Agenda is therefore a compromise between the views of the different member states. The ‘progress critique’ raised by van der Leeuw (2020a), Victor (2019) as well as Weber and Weber (2020) reflects the difficulty to reconcile the radical societal transformations that are needed to reverse pressures on critical Earth system processes and ensure human well-being, with political

realities as seen through the eyes of policy makers and UN diplomats. By suggesting 17 goals on human well-being and environmental concerns, the Agenda expands the focus from one sole economic indicator such as GDP, to a broader understanding of social-ecological development. Although the Agenda itself will be unlikely to produce necessary transformations, it can nevertheless be seen as an important step towards the recognition of social-ecological interdependencies. Improvements in systemic understanding could in a longer perspective contribute to the societal transformations needed.

## 2.5 Human well-being and sustainability in the 2030 Agenda context

### 2.5.1 Human well-being

There are many definitions for human well-being. In this thesis, I have chosen to focus on two main approaches: ‘human needs’ and the ‘capabilities approach’. I have chosen these two approaches because they are inclusive of multiple aspects of human well-being, and are not limited to simplified indicators such as preference satisfaction or consumption. They also coincide with targets and indicators of the 2030 Agenda (United Nations 2015). These two approaches are briefly presented below.

*Theories of human needs*, including the listing of what these needs are, were developed in the 1980s and early 1990s by Doyal and Gough (1984, 1991) and Max-Neef (1989, 1991). These theories propose minimum levels of fundamental provisions that should be met for all people. They take basic human needs to be universal and reject subjectivist and relativist approaches to human well-being. Max-Neef contributed to the theory of human needs by distinguishing between ‘fundamental needs’ and ‘needs satisfiers’ (Max-Neef 1991). While food, liquid, and shelter constitute fundamental human needs, the kinds of food, liquid, and shelter that are used to satisfy the needs may be culturally contingent. As mentioned above, the most widely accepted policy definition of sustainable development comes from the Brundtland commission’s report and is expressed in terms of “meeting the needs”.

*The capabilities approach*, also referred to as the *human development approach*, was developed by Amartya Sen and Martha Nussbaum (Sen 1985, 2001, Nussbaum and Sen 1993, Nussbaum 2011). It conceives human well-being in terms of people’s substantive freedoms, referred to as ‘capabilities’. The capabilities approach thus enriches theories of human needs by emphasising freedom as core to what human well-being entails. According to the human capabilities approach, well-being is judged by people’s capabilities to achieve outcomes that they themselves value “and have reason to value” (Sen

2001 p. 291). The addition “have reason to value” means that a person’s preferences do not necessarily correspond to what is valuable for a person. The theory can thereby be distinct from subjectivist and relativist notions of well-being. The capabilities approach has influenced discussions on international development and contributed to the inception of the UNDPs Human Development Reports in the 1990s (United Nations 1990).

In comparison with human needs, capabilities have been criticised for being difficult to measure. As capabilities are not the outcomes of people’s choices, such as educational attainment or health outcomes, but rather, their actual freedoms to choose, there is no direct way to measure them. Martha Nussbaum has nevertheless presented a list of 11 core capabilities, but these are not as concretely defined in indicators as Max-Neef and Doyal and Gough’s human needs. Amartya Sen has opposed listing what capabilities incorporate.

It is worth mentioning that both Sen and Nussbaum emphasise the relationships between humans, non-human beings and nature. As one of the core capabilities, Nussbaum has listed: “Other *species*. Being able to live with concern for and in relation to animals, plants, and the world of nature” (Nussbaum 2011 p. 34). Furthermore, she refers to the capabilities of non-human animals, which is one of the reasons that she prefers the notion of the ‘capabilities approach’ rather than the ‘human development approach’ (Nussbaum 2011).

### 2.5.2 An embedded view of sustainability

As emphasised in the introduction, in the Anthropocene, socio-economic developments risk causing systemic deterioration of the biophysical environment. Such deteriorations have the potential to trigger large-scale Earth system shifts that could undermine human civilisation (Steffen et al. 2018). It is in this context that Griggs et al. (2013) proposed a definition of sustainable development that embarks from, and goes beyond, the Brundtland definition. Griggs et al. (2013) define sustainable development in the Anthropocene as “Development that meets the needs of the present while safeguarding Earth’s life-support system, on which the welfare of current and future generations depends” (Griggs et al. 2013 p. 306).

Griggs et al.’s definition of sustainable development is congruent with the embedded or nested view of sustainable development that is prevalent in ecological economics. Ecological economics emphasises that the economy and society are both embedded in, and dependent upon, the biosphere, with the explicit notion that social and economic development takes place within environmental boundaries (e.g., as set out in seminal work by Daly 1991, and Boulding 1966). This is often illustrated simply in the form of a set diagram, with three

concentric circles: the outer being the environment, within which is society, and within the society is the economy, see Figure 2a.

To reconcile the embedded view of sustainable development with the 2030 Agenda, researchers have proposed different conceptual illustrations of the 2030 Agenda that have become influential in many societal, business, and policy contexts (Figure 2b-d).

Rockström and Sukhdev introduced the SDG wedding cake, Figure 2b (from Folke et al. 2016). The figure categorises the 17 SDGs in the three nested categories of the biosphere, society, and economy. By showing the biosphere as the foundation for the whole Agenda, the figure illustrates that achieving all goals depends on safeguarding Earth's life-support systems. The figure thereby represents a valuable communication tool that helps to handle the insufficient incorporation of ecological concerns in the 2030 Agenda.

The initiative *the World in 2050* (TWI2050: [twi2050.org](http://twi2050.org)) has chosen to combine the decadal ambition of the 2030 Agenda's SDGs with the long-term perspective of planetary boundaries. It provides a forum for structuring and synthesising use-oriented research by scientists worldwide who are involved in developing integrated model-based assessments of scenarios and pathways. Figure 2c, that inspired the cover of this thesis, illustrates the TWI2050 notion that the fulfilment of the 2030 Agenda has to take place within the planetary boundaries: targets to restore or reduce pressures on the latter are put on a longer time horizon, to be reached by 2050. Note also that the many trajectories in the TWI2050 figure incorporate the view that there may be many possible paths to reaching the SDGs within planetary boundaries (see the earlier comment on there being multiple sustainabilities, Leach et al. 2010).

A related image, Figure 2d, represents the concept of doughnut economics that was developed by Kate Raworth (2012, 2017). The "doughnut" portrays both the environmental ceiling of a safe and just operating space for humanity, and the social foundations. The doughnut's environmental ceiling is defined by the planetary boundaries, and the social foundations is based on the agreed priorities of the world's nations, initially for the Rio+20 conference and more recently in the SDGs themselves: including, e.g., health, education, and energy. This framework has now been used in many participatory processes (Doughnut Economics Action Lab: <https://doughnuteconomics.org>), and the indicators of the social foundations have also been quantified (including at the national level by O'Neill et al. 2018).

In my thesis, the 2030 Agenda is handled within a unified framework of an embedded view of sustainability – that is illustrated in several ways by the portrayed figures. The World in 2050 diagram, Figure 2c is however closest

to my operationalisation of the Agenda as it illustrates dynamic patterns of development towards the 2030 Agenda and the safe operating space, and illustrates the many possible ‘sustainabilities’. Two of the thesis papers, Papers III and IV, were written in the context of the World in 2050 initiative. Furthermore, the Millennium Institute that holds the iSDG model used in Papers I and II, is part of this initiative.

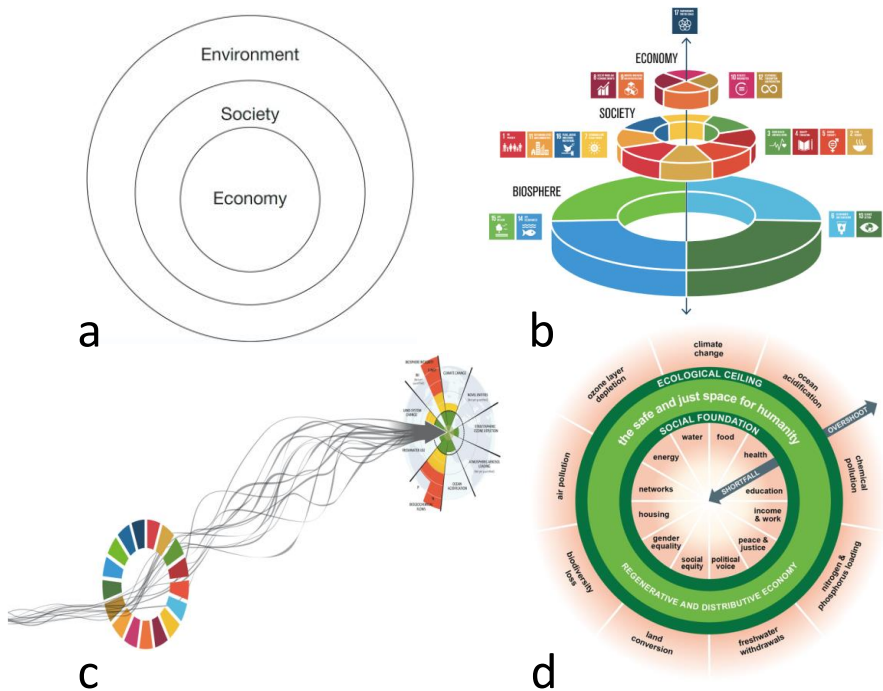


Figure 2 (a, b, c, and d): Four conceptualisations. 2a illustrates the ecological economics notion of the economy and society as embedded in the environment, 2b illustrates the 17 SDGs in a similar framework (Azote for Stockholm Resilience Centre). 2c illustrates a figure from the World in 2050 initiative (Illustration copyright: J. Lorkantz/Azote) and 2d is Kate Raworth’s doughnut (CC BY-SA 4.0).

## 2.6 Modelling the 2030 Agenda

Several frameworks have been suggested to operationalise and implement the 2030 Agenda in ways that acknowledge the Agenda as being indivisible. By the end of the SDG negotiations, the UN Department of Economic and Social Affairs had already developed SDG network diagrams based on analysis of key terms in the respective goal formulations (Le Blanc 2015). Another early semi-quantitative framework was proposed by the International Council for Science, ICSU. The framework includes ranking connections between indicators from -3 representing cancelling relationships to +3 representing that two indicators are indivisible (Nilsson et al. 2016). This approach was further developed using cross-impact matrices and network analysis to explore the interactions (Weitz et al. 2018). The SDG interlinkages tool from the Institute for Global Environmental Strategies maps and assigns the strength of links between SDGs (Zhou and Moinuddin 2017). However, none of these frameworks allow for the simulation of policies and the quantitative assessment of possible outcomes of different policies. Therefore, models referred to as Integrated Assessment Models, IAMs, have been suggested to contribute to SDG policy analysis and implementation – significantly so by the World in 2050 initiative (TWI2050 - The World in 2050 2018).

The first IAMs were built in the 1980s in relation to the establishment of the IPCC. The spatial scope of IAMs is typically global, with a few world regions. Their strength lies in covering important linkages related to the energy-water-land-climate nexus (TWI2050 - The World in 2050 2018, van Soest et al. 2019), with a focus on economic parameters (Castro and Jacovkis 2015). Typically, IAMs are built around economic general equilibrium models to which components are added to account for impacts on climate variables (Pedercini et al. 2020). That is, rather than building on the early stylised global system models such as the World3, IAMs were built on climate-economy relationships, and extended from more sector-specific models (Castro and Jacovkis 2015). The different sectors of the IAMs can be either hard or soft linked. Hard linked means that there are couplings within the same model and direct feedbacks between sectors, while soft links typically incorporate two separate models run in parallel with a few parameters that are the output of one sector model being incorporated into another.

The purpose of IAM-based analyses is typically to reduce environmental impacts at a minimised economic cost. Therefore, current IAMs are not incorporating many aspects of human systems - except when it comes to GDP (Zimm et al. 2018, van Soest et al. 2019). They might be extended to cover more of the SDGs, but this would require major advances (TWI2050 - The World in 2050 2018). The SDGs pose challenges to this class of models in terms of

issue coverage, i.e., several SDGs are not captured at all, and also of interconnections between SDGs (Hughes 2019). Criticisms against IAMs include that they are sensitive to the choices of some key economic modelling parameters. Models are typically sensitive to the damage functions: the relationship between an increase in temperature and its simulated effects on GDP. The models are also sensitive to the choice of discount rate, i.e. how much future losses are valued in relation to the present (Pindyck 2015). Because of their heavy focus on climate change, the issue areas that are linked and the type of interconnections are limited (TWI2050 - The World in 2050 2018, Hughes 2019). These limitations include both the coverage of human well-being aspects of SDGs, and in covering the broader environmental understanding beyond climate, e.g., as posed by the planetary boundaries. A further limitation is that there is a paucity of connections between the few existing social components, i.e. GDP, and ecological components (Costanza et al. 2007, Hughes 2019).

Alternatives to the IAMs include more tightly integrated models that incorporate more SDG indicators, such as those in the system dynamics tradition of World3 and beyond. In a study on the coverage of current IAMs, van Soest et al. (2019) emphasise three models that cover the SDGs more extensively: iSDG, International Futures, and Earth3. iSDG is the further development of the Threshold 21 model (Barney 2002, Pedercini 2007) and is the model used in Papers I and II. It is a system dynamics model based on country data and a flexible structure, further explained in Section 4. International Futures is based on a mix of methods, including system dynamics, with a fixed model structure and international data (Hughes 2019). Earth3 is a simple global systems model to which Paper III has contributed (Randers et al. 2019).

Integrated global models, whether IAMs or models from the system dynamics tradition, include many different assumptions. For scientific rigor, it is thus important that the models are communicated transparently and that key limitations of the models are made clear. Then other researchers can run the same models with different assumptions and study their sensitivity to different inputs. Unfortunately, this is not always the case (Castro and Jacovkis 2015, Pindyck 2015). Furthermore, to promote model transparency, value judgments in relation to the models (for example, the decision of what discount rate to use) and the biases of the modellers should also be openly discussed (Meadows et al. 1982, Meadows and Robinson 1985). Value judgments and biases may influence model results. With this in mind, it can be seen as problematic that most global modellers are from universities and research institutions in the Global North. There is a risk of bias, i.e., that perspectives and values prevalent in large parts of the world beyond the Global North are lacking representation. This calls for methods that can incorporate different perspectives, and that do not avoid value divergences. A multitude of values and perspectives can enrich the discussion and contribute to broader spectra of views on

the future of the world-Earth system, and potential sustainability solutions. This need for a multitude of values and perspectives is the rationale behind the participatory approach presented in Paper IV. In Aguiar et al. (2020), we compare divergences and convergences between the results from the 2018 African Dialogue on the World in 2050 presented in Paper IV, and global sustainability narratives.

This thesis contributes to modelling and analyses in support of the 2030 Agenda by presenting model applications and discussing their use – significantly when it comes to incorporating human dimensions (Papers I, II and III) – and by presenting ways to incorporate a wider spectrum of global divergent views by suggesting a participatory method to enrich the global pathways discussion (paper IV). This is further explained in the following sections, beginning with the thesis’ theoretical framing.

### 3. Theoretical framing: Systemism

The papers in this dissertation all present various systems-thinking approaches. I have chosen to situate them within the broader frame of *systemism*. Below, I introduce this theoretical approach and discuss how it aligns knowledge and action for the 2030 Agenda. I also introduce the perspectives of *system dynamics*, *social-ecological systems* and *resilience thinking* as well as boundary critique as these serve as conceptual foundations for my research.

#### 3.1 Systemism to align knowledge and action for the 2030 Agenda

Systems thinking and systems analysis incorporate various theoretical approaches, methods and tools in order to understand interdependencies. In a seminal paper, philosopher Mario Bunge argues that *systemism* provides an alternative to *individualism* and *holism* and implies a different worldview and research approach to understanding social reality (Bunge 2000).

In an individualist perspective, the world is understood by referring to individual actors or the atomistic parts of the study subject, e.g., individual preferences in a market economy. According to Bunge (2000), such a perspective overlooks the structures of systems or sets of connections. In its radical versions, individualism disregards the existence of social entities such as families, networks, and parties.

Holism is also limited, according to Bunge, and lacks explanatory power. Holism gives attention to "...imaginary collective entities such as collective memory, national spirit, and nations that allegedly hover above individuals." (Bunge 2000 p. 147). The focus on such social entities comes with a risk of missing how the actions of individuals can spread and feedback to social entities.

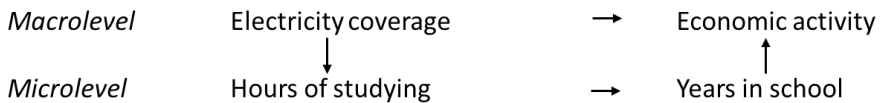
Systemism, according to Bunge, provides the only viable way to understand reality. According to systemism, everything is either a system or an actual or potential component of a system. Bunge refers to systemism as the worldview and methodological approach within natural sciences in general, enabling the integration of mathematics, physics, chemistry as well as technology; he also argues that social studies should apply systemism (Bunge 2000). In line with other systems thinkers, Bunge says systems have systemic, emergent, features that their components lack. Because of this, research that deals with system components, e.g., a causal relationship between two variables, should be put

in the context of integration of components into wholes. One could here draw a parallel to Holling’s observation that:

“the science of parts can fall into the trap of providing precise answers to the wrong question and the science of the integration of parts into providing useless answers to the right question.” (Holling 1998).

Systemist research approaches do not only focus on bivariable causal connections, but also consider wider webs of causal connections, spanning micro and macro levels, that together make up wholes as well as parts of the systems.

An example of a systemist tool presented by Bunge is what he refers to as the Boudon-Coleman diagram, Figure 3. Boudon-Coleman diagrams illustrate the alternation between different scales of analysis within a systemist study. Figure 3 illustrates the iteration between macro- and micro level phenomena with an example taken from my case study of electricity access in Tanzania of Paper I. The diagram displays a macrolevel phenomenon (electricity coverage), the microlevel consequences of changes in individual behaviour (students having access to electric light being able to study later at night and progress further in their education) and the emergent macrolevel phenomena (more years of schooling causes an increase in economic activity).



*Figure 3: A Boudon-Coleman’s diagram, illustrated with an example of macro- and microlevel relationships between energy, education and work and economic activity discussed in Paper I.*

Thus, it seems that systemism offers a useful approach for analysing the interdependencies and dynamic interrelations of the 2030 Agenda goals across scales and between social and biophysical systems, helping to explain how these systems co-evolve and adapt to each other.

There is, however, a wide variety of traditions and approaches that categorise themselves as systems approaches, or apply perspectives from a systemic worldview. Ramage and Shipp (2020) present a selection of these approaches, embarking from 30 prominent systems thinkers from various traditions, including cybernetics, general systems theory, soft and critical systems, complexity theory, and learning systems. These systems approaches differ in both their study objects as well as their methodologies. Some of them, especially

the soft systems approaches and critical systems, focus on social aspects of systems, for example the functioning of organisations. Others, such as general systems theory and system dynamics, focus on concepts and principles that are broadly applicable to all kinds of systems, both natural and social.

When it comes to bridging natural science concepts and social science concepts, such as is done in this thesis, it is important to acknowledge their separate characters. While the objects of natural science are socially defined (e.g., as ‘planetary boundaries’) but naturally produced, objects of social science are both socially defined and socially produced. In the social sciences, conceptualisations are both part of the research process and the research object (Danermark and Ekström 2019). New experiences and new knowledge can thereby change how people act. Within the understanding of social-ecological systems, as utilised in this thesis, the role of social constructs, meanings, and values are important to acknowledge alongside natural science concepts (Westley et al. 2002). In the system dynamics tradition that is explained in the subsection below, social constructs are referred to as *mental models* (Forrester 1987).

### 3.2 The system dynamics perspective

The system dynamics tradition serves as my main methodological educational background. Therefore, in my research I bring what Bert de Vries in his textbook *Sustainability Science* refers to as “the system dynamics perspective” (de Vries 2013 p. 14). My work is however also influenced by the social-ecological systems and resilience perspectives that are presented in the following section.

System dynamics is a systems analysis approach for studying dynamic patterns of systems, i.e., how variables such as population, interest rate or water in a lake are changing over time. Within system dynamics, these patterns are referred to as their **behaviours** (Sterman 2000, Meadows 2008). With this approach, the behavioural patterns are seen as the outcomes of interrelations between system components that are connected in causal relationships, referred to as the **system’s structure**. The system dynamics approach places a certain emphasis on circular causality, i.e., how chains of cause-and-effect relationships return to the initial variable. These are referred to as **feedback loops**. The approach embarks from the assumption that the world is “composed of closed, feedback-dominated, non-linear, time-delayed systems” (Meadows and Robinson 1985 p. 38).

The system dynamics approach was developed by Jay W. Forrester at MIT in the 1950s and 60s (see his own perspective on the development of the field in Forrester 2007). In line with this approach, models are constructed as representations of corresponding real-world systems, and are used to facilitate

learning about them - by referring to the causal structure and resulting behaviour of the model representations. System dynamics applications typically use cognitive maps such as causal loop diagrams that accentuate the loop structure of the system, and stock and flow diagrams, which also highlight the nature of variables as accumulations (stocks) and rates (flows), respectively. In mathematical terms, system dynamics models consist of series of integral equations, dealing with stocks or accumulations; and derivatives, which deal with the system's flows.

System dynamics practitioners operate across disciplines. They often quickly apply quantification measures, including tentative estimates where data is lacking. This is because quantitative modelling and simulation are argued to bring rigor and clarity to systems thinking as it forces the systems thinker to be mathematically explicit. This encouragement of quantifying, argues Forrester (1994), is something that other systems thinking approaches such as soft operations research lack. Practitioners typically iterate between the systems diagrams and the simulations in order to better understand both the behavioural patterns and the hypothesised causal structure of the system under study (Homer 1996). Once confidence is gained in the model structure, the models are then used to explore different what-if questions.

Figure 4 illustrates the different degrees of formalisation in typical system dynamics applications. Underneath the figure are questions that guide the critical assessment of modelling choices. Note that in the development of system dynamics models, steps are iterative and system dynamics practitioners do not necessarily engage with all degrees of formalisations, and some will remain at the qualitative end of the spectrum.

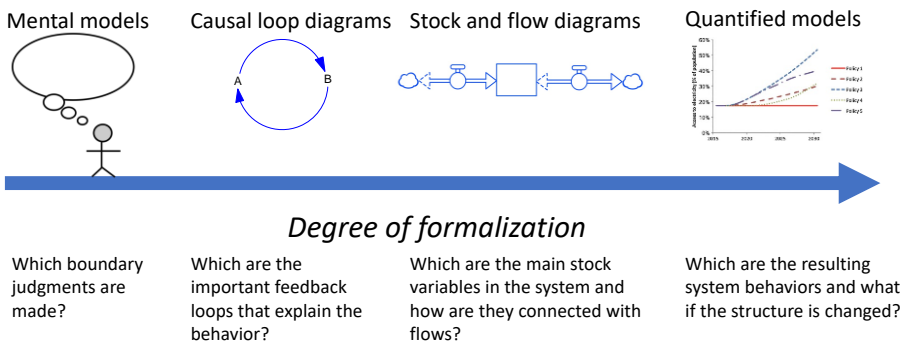


Figure 4: Mental models and formal models: An illustration of the different degrees of model formalisations in system dynamics.

The system dynamics approach specifically emphasises the importance of model structure. This is because the aim of a model is not only to replicate system behaviour, but also to represent the causal structure of the system. The model building process, including iterations between the steps in Figure 4, enables bridging both qualitative understanding and quantifications of problems. Validation of system dynamics models is based on their usefulness with respect to a purpose (Barlas and Carpenter 1990). Formal aspects of model validation in the system dynamics approach incorporate both *structure validity* and *behaviour validity* (Barlas 1996). Structure validity refers to validating the causal structure a model, that is represented by causal relationships in the form of stocks, flows, and causal links. Behaviour validity refers to the resulting simulated model behaviour, compared with the observed behaviour of the real system.

The system dynamics tradition also emphasises the role of people's understanding of systems, their mental models, in explaining how they act and influence a system. System dynamics tools can be understood as methods for handling, testing, and scrutinising these mental models. In modelling projects, differences between people's understandings may be explored by modelling their assumptions and then analysing and comparing the resulting behaviours. This enables the use of a model to both illuminate these differences and to study their hypothesised function for the behaviour of the system. For modelers to be open to different systems understandings and simultaneously to not miss what may be crucial to explain a system's behaviour, system dynamics researchers often combine information gathering from quantitative databases with stakeholder interviews. System dynamics models are also sometimes developed in processes that involve stakeholder groups in participatory modelling, combining learning and action (see the books *Group Model Building*: Vennix 1996, as well as *Mediated Modeling*: van den Belt 2004).

Boundary judgments are critical and emphasised in the system dynamics field. Boundary judgments define what is included and excluded in an analysis and is further deliberated upon in Section 3.4. Many system dynamicists propose distinguishing variables into three categories: endogenous, exogenous, and excluded or omitted (Meadows and Robinson 1985, Sterman 2000, Ford 2010). Endogenous variables are central to the system that is modelled, as they are the variables thought to explain the 'inner workings' or endogenous sources of how a system behaves. Exogenous variables are those that affect the system from the outside rather than being generated from within. Excluded or omitted variables are variables that might have a bearing on the system but the choice is made *not* to include them in the specific model.

A system dynamics modeller strives to explain the behaviour of systems by referring to variables that are endogenous to the model. This can result in a bias towards explanations of system behaviours that are rooted in their causal structure (Meadows 1976), instead of focusing on, for example, the potential variability or divergence of parameter values. This emphasis on explanation through causal structures also relates to the typically longer time horizon of system dynamics models, compared to modelling paradigms that have shorter time horizons (e.g., econometrics, input-output, and optimisation modelling). With longer time horizons, there is more time for feedback loops to affect the system behaviour. These two aspects are directly relevant to modelling for the 2030 Agenda.

### 3.3 Social-ecological systems, resilience and development

Research on social-ecological systems often emphasises the integrated and interdependent character of humans-in-nature (Berkes and Folke 1998). Social-ecological systems are both complex and adaptive systems. The complex nature of such systems refers to the fact that they have independent and interacting components resulting in emergent behaviour that cannot be predicted. Variations and novelty are added to the system, and system components are continually adapting to their surroundings and the behaviours of other system components (Levin 1998). The longer term perspective on change that is studied in social-ecological systems research is what necessitates the understanding of feedbacks (Walker and Salt 2006), corresponding to reasoning within system dynamics approaches for the use of long-term behavioural patterns.

Social-ecological systems researchers emphasise the need to adaptively manage social-ecological systems, as their behaviours can only be anticipated to a limited extent (Armitage et al. 2007). To manage the uncertainty and emergent behaviours of systems, attention is given to building resilience. As mentioned in the introduction section, resilience is the capacity of a system to absorb changes, but also to reorganise when facing disturbances to retain the same functions (Folke et al. 2010, Walker and Salt 2012). It can be useful to distinguish two complementary aspects of resilience: specified and general resilience. Specified resilience is the resilience of some specified part of a system to a particular disturbance. General resilience is the capacity of a system that allows it to adapt and reorganise when faced with a variety of disturbances, including novel ones that the system has not previously experienced (Walker and Salt 2012).

Social-ecological systems research emphasises the distinct features of social and ecological system components respectively (Westley et al. 2002). Distinct features of social systems that are emphasised include “symbolic construction

or meaning” (Westley et al. 2002 p. 119). These constructions, with strong parallels in the concept of mental models in the system dynamics approach (Forrester 1987), affect the behaviours of individuals and societies and, thus, potentially, social-ecological system outcomes.

Social-ecological systems and resilience perspectives emphasise dynamical aspects of sustainable development. For example, Reyers et al. (2018) argue that the nature of development challenges is co-evolving and social-ecological. The interdependencies between biodiversity, ecosystem services and human and societal dimensions of development are in focus (Reyers and Selig 2020). In our background report to the UNDP Human Development Report 2020 (Galaz, Collste & Moore 2020), we discuss how such an interdependent understanding of development requires a clear definition of the constituents of its human and societal aspects, e.g., as suggested by the human needs or capabilities approaches outlined above. Lade et al. (2020) propose an extension to resilience theory that draws parallels to the capabilities approach, defining resilience as “*The diversity of pathways available to an agent or agents*”. They argue that for an individual agent, this diversity of available pathways is similar to Sen and Nussbaum’s notion of ensuring an individual’s capabilities.

The strong emphasis on emergence and uncertainty differentiates the social-ecological systems approach from more deterministic systems approaches. Within the system dynamics approach, the emphasis on structure driving system behaviour leads to the study of past behaviours with the implication that these structures can - at least partially - also explain future behaviours. However, if emergent features are dominating the system’s behaviour, this handling may be problematic – and one may also have to study anticipated future system structures (Collste and Bennich in prep.). While system dynamics methods contribute with ways of mapping, modelling and simulating integrated systems, social-ecological systems and resilience thinking provide tools and perspectives to engage with their complex natures, emphasising uncertain and emergent features. Perspectives from both system dynamics and social-ecological systems can contribute to better navigating sustainability, including the ambitions set out in the 2030 Agenda.

### 3.4 System boundaries: Systemic triangulation for 2030 Agenda studies

An important aspect in all systems studies is the conceptualisation phase, where the boundary of a system is defined (Forrester 1994). It sets the frame for the whole endeavour. The judgments of system boundaries incorporate which ‘facts’ and ‘values’ are to be considered, and which are excluded. Meadows and Robinson (1985) argue that the choice of boundaries is the most

important aspect influencing the outcome of a modelling process. In the system dynamics field, system boundaries are generally set by referring to a reference mode of how one or several key variables behave over time.

Engaging with and discussing the setting of boundaries in system studies has more generally been referred to as *boundary critique*, a term introduced by Ulrich (1996) and used by Midgley et al. (1998) (a wider discussion of “boundary critique” and comparisons between different approaches can be found in Midgley 2000). Critical systems heuristics developed by Ulrich (2003) provides tools and conceptualisations for this critical phase – focusing on what the system currently “is” and what it “ought to be”. A key concept in critical systems heuristics is *systemic triangulation* that can be applied systematically for setting boundaries and considering boundary judgments. A main advantage of Ulrich’s systemic triangulation is that it can straightforwardly be applied, understood and explained.

The use of systemic triangulation builds on the understanding that boundary judgments are unavoidable in any systems thinking application. That is to say, no matter whether one critically engages in setting and questioning the scope of a particular study or not, boundary judgments must be made in order to carry out a study. If boundary judgments are not made explicit, or are not discussed up front, there is a risk of missing crucial facts, and not relevantly engaging with the system that is intended for the particular study.

Ulrich’s systemic triangulation (2003, 2005) is illustrated by a triangle with the three corners incorporating ‘system’, ‘facts’ and ‘values’ respectively, see Figure 5. The term ‘system’ represents what is being considered. Outside the systems thinking realm, this word could more generally be replaced by ‘situation’ or ‘issue’. What is considered as the ‘system’ in a particular application is defined by the boundaries of the situation or issue at hand, the *boundary judgments*. What is defined as the ‘facts’ actually incorporates the circumstances that are deemed to be relevant for the study, and are dependent on the observations that are made. Finally, ‘values’ incorporate interests, needs, and aims in a broader framing based on normative evaluations.

Importantly, within Ulrich’s triangle, the three corners can affect one other. If new observations are made that change the relevant facts, they may necessitate a re-evaluation of the boundary judgments and hence a redefinition of what is considered as the ‘system’ under study. Furthermore, Ulrich’s theory states that a re-evaluation of boundary judgments may result from a change in values and goals.



more, this triangle can be used iteratively in order to encourage the consideration of different claims and systems understandings in the applications of system methods. However, it is also important to note the distinct features of the respective corners of the triangle. While values may affect system boundaries, they do not change the ‘facts’, but may change what ‘facts’ are relevant, based on changes in system boundaries. For example, the principle of environmental sustainability may direct our attention to factual evidence such as atmospheric CO<sub>2</sub>, biodiversity, etc., while the value of human well-being might direct our attention towards facts about human needs and capabilities.

Returning to the aim of this dissertation - to demonstrate how models and participatory approaches grounded in systems thinking can highlight interdependencies between goals, and contribute to bridging global sustainability knowledge and the decision-making arenas of the 2030 Agenda, systemic triangulation is particularly useful. It helps to inform how perspectives from different systems traditions can be complementary. While the system dynamics perspective and approach brings a focus on causal interdependencies between different parts of a system and invites the practitioner to specify the system structure, the social-ecological system and resilience perspectives bring a focus on uncertainty and emergence.

## 4. Contributions: Systems analysis applications

In this section, I present the research programs that my thesis papers contribute to. I also give an overview of research methods applied in the four thesis papers.

### 4.1 Research in transdisciplinary sustainability projects

My research presented in this thesis has been designed and implemented within four main working programmes.

The overarching research frame for the thesis has been *Adaptation to a new economic reality*, or AdaptEconII, a project exploring alternative economic ideas that might contribute to a more sustainable and desirable society. The project was funded by the European Union's Horizon 2020 research and innovation programme under a Marie Skłodowska-Curie grant that also funded the first three years of my PhD fellowship. The AdaptEconII project incorporated the use of system dynamics as one of its main approaches.

Papers I and II also specifically contribute to the development and analysis of the Millennium Institute's Threshold 21 model applied to the 2030 Agenda: The integrated Sustainable Development Goal model, iSDG. Paper I was the first peer reviewed publication on the model, which is now being applied in various contexts where it serves as a practical tool to help governments design policies specifically for the SDGs. The model supports the SDG planning process by giving planners the opportunity to experiment with different strategies and policies before decisions are made.

Paper III was written as part of the Earth3 project, a world-Earth modelling and scenario project with the aim of developing pathways in which the SDGs can be reached within the safe operating space as defined by planetary boundaries. The project was supported by the Global Challenges Foundation, and resulted in a report to the 50<sup>th</sup> anniversary of the Club of Rome (Randers et al. 2018). The report was also presented in a TED talk by Johan Rockström (2018). The Earth3 model developed for the project is presented in Randers et al. (2019) and Goluke et al. (2018). Between 2020 and 2022, the Earth3 project is being followed up by a new initiative on transformational economics, Earth4All, led by teams from the Club of Rome, the Norwegian Business School, the Stockholm Resilience Centre and the Potsdam Institute for Climate Impact Research (PIK) (see <https://www.pik-potsdam.de/en/news/latest-news/earth4all-new-initiative-on-transformational-economics>).

Paper IV was written within the World in 2050, TWI2050, a global research initiative in support of a successful implementation of the United Nations' 2030 Agenda. The aim of TWI2050 is to provide knowledge to support the policy process and implementation of the SDGs. The initiative was jointly launched by the International Institute for Applied Systems Analysis (IIASA), the Sustainable Development Solutions Network (SDSN), and the Stockholm Resilience Centre (SRC) and has resulted in three annual reports to which I have contributed as co-author (TWI2050 2018, 2019, 2020). However, a gap identified in the early meetings of the initiative was the lack of African presence and perspectives. Therefore, with support from the Swedish International Development Cooperation Agency (Sida) through SwedBio, two African Dialogues were held in Kigali, Rwanda. One was held in 2017 (SDGC|A and SwedBio 2018) and one in 2018 (Aguar et al. 2019). The aim of the dialogues was to increase the plurality of perspectives that would also feed in to the systemic and integrated analyses of the TWI2050 project. Paper IV was written in conjunction with the 2018 African Dialogue on the World in 2050.

## 4.2 Conceptual framework

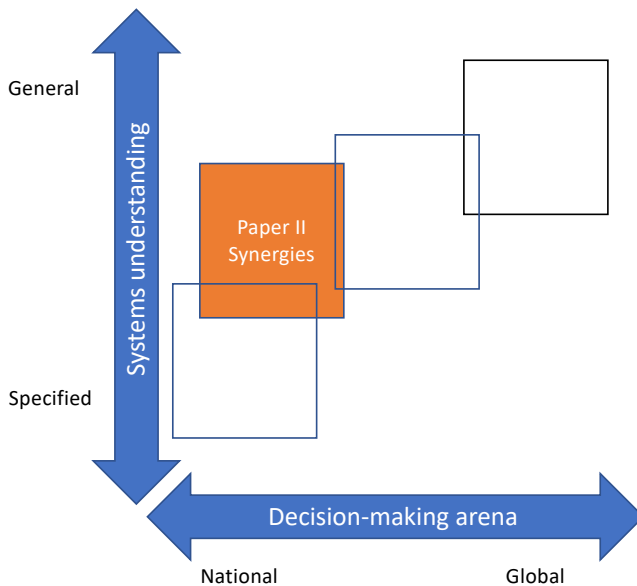
This thesis is situated within the **knowledge-action interface** of the intersection of different understandings of systems and different policy arenas (Cash et al. 2003, Cornell et al. 2013). The papers in this dissertation span both **specified** and **general systems understanding**, as illustrated in Figure 6. These are terms that have echo in resilience thinking. In resilience thinking, as briefly explained above, the terms specified resilience (i.e., the resilience of some part of the system to a specified shock) and general resilience (i.e., the general capacity of a system to absorb disturbances, including unforeseen ones, and reorganise), refer to system characteristics. In the context of this thesis, emphasis is placed on both the specified and general understanding of systems.

**Specified systems understanding**, maps out relationships concretely, e.g., for a specific case study. This can be done by presenting a specific hypothesised causal structure that is internally valid. A strength of the specified systems understanding is that it gives a rich enough representation of the system to give actionable insights. At least at the level of the specified case, it can offer concrete steps of policy implementation.

**General systems understanding** is generalisable knowledge that is valid across different realms. General systems understanding contributes to knowledge across different cases of the same phenomena. It is therefore more focused on stylised, often simplified descriptions of system relationships. It may incorporate more abstracted generalised level conclusions about behaviours. This general understanding, can be theoretically well-grounded; in the

transdisciplinary contexts of sustainability science, it can integrate theoretic understanding from contributory fields.

In Figure 6, each paper is placed in relation to the vertical axis by their relative contribution to general and specified systems understanding. Paper I leans towards the specified end of the spectrum of systems understanding, illustrated by its position in relation to the vertical arrow. The conditions for the Tanzania case study presented in Paper I may not be generalisable for other countries. Paper III sits firmly at the general end of the spectrum, as it is assessing relationships between income levels and human well-being SDGs that can be generalised across seven world regions. Papers II and IV are placed between general and specified systems understanding. Paper II defines and provides general understanding of synergies in the context of SDGs and how they can be generally applied by exemplifying with three more specific country-level studies. Paper IV highlights the tension between generalised (global) and specified (regional and more context-specific) target-seeking sustainability pathways for the 2030 Agenda, providing practical ways to adhere to plural and divergent worldviews in relation to understanding and developing pathways.



*Figure 6: The four papers in the landscape of the knowledge-action interface of the 2030 Agenda. The papers are laid out in respect to the two dimensions, i.e., the type of systems understanding that they contribute to and the decision-making arena that they contribute to.*

With respect to the action aspects of the knowledge-action interface, the research is relevant to decision-making arenas at national, regional and global levels, represented by the horizontal arrow in Figure 6. Knowledge production about social-ecological systems at these different levels relates to the issue of fit between biophysical systems and institutions (Folke et al. 1998). It is particularly linked to the issue of appropriately fitting the production of knowledge to legislative and administrative processes (this is discussed in Galaz et al. 2008). In the 2030 Agenda context, knowledge production about national decision making is crucial as it corresponds to where many important political decisions are taking place, it has good socio-economic-cultural fit. The 2030 Agenda was also agreed between nation-states. Papers I and II are engaging with the national level of the 2030 Agenda implementation.

However, to better understand macro-level institutional and political challenges posed by the Anthropocene, **global** and **regional** level knowledge production should complement national level understanding. This is in particular important in relation to knowledge production linked to the handling of global and regional commons. Paper IV engages with African sub-regional perspectives and compares these to global model scenarios. It thus encompasses regional and global levels. Paper III also engages global and regional levels, studying general patterns of human well-being.

The 2030 Agenda challenge of ‘indivisibility’ relates to the development of both specified and general systems understanding, and the knowledge production and use of this understanding in relation to decision-making arenas, on the national, regional and global levels. Achieving the globally-defined SDGs requires action at multiple levels. Together, the papers demonstrate how models and participatory methods can both be useful across knowledge aspects and across decision-making arenas of the 2030 Agenda.

### 4.3 Overview of research methods and data sources

All the dissertation papers take an overarching systemist approach by focusing on causal relationships and system-level questions. The dissertation combines methods that provide different but complementary systems-oriented perspectives (Figure 7 and Table 1).

Qualitative and quantitative methods are combined. The entire structure of the SDG goals, targets and indicators is framed as measurable, quantifiable and comparable. However, when it comes to modelling and participatory approaches, choices of system boundaries and which variables to include and which to omit are of paramount importance. Combining both qualitative and quantitative methods contribute to a fuller picture of the 2030 Agenda context and implementation and responds to different parts of the overarching research aim. Figure 7 provides a conceptual overview of the four papers presented in the thesis and the approaches used. The following Table 1 presents a more detailed overview of data types and methods used in the papers.

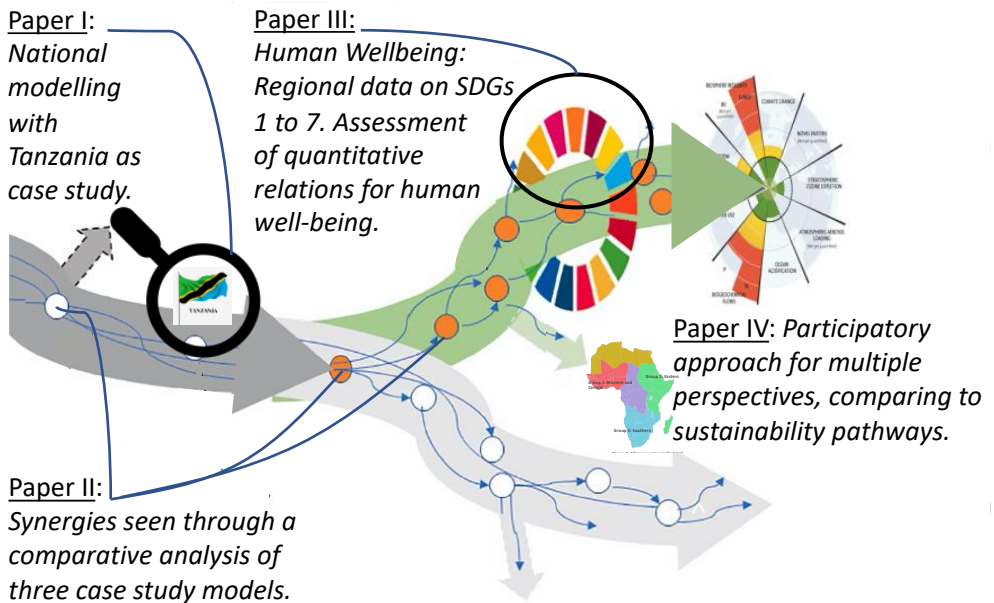


Figure 7: A conceptual figure showing the four thesis papers positioning on different aspects of pathways for global sustainability. Figure adapted from the figure in Aguiar, Collste, Harmáčková, Pereira, Selomane, Galafassi, van Vuuren and van der Leeuw. (2020), that was based on Fazey et al.(2016) and Roy et al. (2018).

*Table 1: A summary of scale, data types, and methods for data collection and analysis used in the papers. Note that for Paper II, modelling appears in the category ‘Data types’, and for Papers I and III in the category ‘Methods for data collection and analysis’. This is because Paper II compares the results from earlier modelling studies, while for Papers I and III, model elements are developed and presented in the papers.*

<b>Publica- tion</b>	<b>Scale of analysis</b>	<b>Data types</b>	<b>Methods for data collection and analyses</b>
<b>Paper I National model</b>	National: Tanzania.	Official international and national data on electricity access, health and education, used to assess causal structure of national iSDG model. Academic and grey literature.	Quantitative system dynamics modelling.
<b>Paper II Synergies</b>	National: Côte d’Ivoire, Malawi and Senegal.	Modelling results from three national iSDG models, presented in the paper.	Comparative analysis across national case studies, methodological discussion.
<b>Paper III Well-being</b>	Regional and global: The World and seven world regions.	National data on socio-economic indicators, collated to regions from international statistical databases.	Assessment of quantitative relations.
<b>Paper IV Multiple perspectives</b>	Cross-scale: African sub- regions based on African Union classifications, and global sus- tainability nar- ratives.	Documentation of a participatory dialogue process, qualitative and semi-quantitative survey data.	Systems oriented participatory process (3H4SDG); participant survey. Synthesis of literature and survey results.

## 4.4 System dynamics modelling for the 2030 Agenda

### 4.4.1 Quantitative national level system dynamics modelling: the iSDG model

Papers I and II both illustrate the use of the national level system dynamics model Threshold 21 iSDG, to express complex relationships among the SDGs, including SDG synergies. Here, I briefly describe this model and reflect on its development and use.

Threshold 21 iSDG builds on the original Threshold 21 model (Barney 2002). iSDG is modelling the society-wide effects of different policy choices, such as investments in different sectors. The model simulates anticipated development over 10 to 30 years into the future. It is designed to assist policy planning and stakeholder interactions by providing a credible representation of real-world development. For a presentation of the historical development of the Threshold 21 model and system dynamics applications in relation to the last 50 years of the international sustainable development discussions, see Pedercini et al. (2020). Barney (2002) presents the founding of the Millennium Institute and the development of the first Threshold 21 models.

The project to develop the iSDG model was led by Matteo Pedercini at the Millennium Institute, as a response to the 2030 Agenda emphasis on indivisibility. The research in relation to Paper I contributed to the model's construction. Unlike the Integrated Assessment Models, IAMs, described in Section 2, the iSDG model is more integrated across sectors and covers aspects of all of the SDGs (Pedercini et al. 2020). The model was developed for analysing anticipated future SDG achievements, incorporating socio-economic, governance and ecological dynamics. The 2030 Agenda focus on integration motivated an increased emphasis on relationships between sectors of the model (e.g., education and health) that are not represented through their effects on aggregate production, GDP. Thus, in comparison to earlier versions of the Threshold 21 model, iSDG incorporates stronger links between various goals. Fig. 2 in Paper I presents an overview of the iSDG model in the frame of the nested framework of ecological economics, earlier presented in Figure 2a in this kappa. In the iSDG model, all 30 sub-sectors are tightly linked by causal relationships that span between and across the sectors.

The iSDG model's user interface is also designed to be accessible to non-modellers. This makes it possible for government officials to use the model for operationalising the 2030 Agenda. All relationships are visually illustrated by causal links and loops. The transparency of the model construction furthermore accommodates the nature of the model as a 'boundary object' that can be used for cooperation between researchers and other stakeholders in the

knowledge-action interface (See also Millennium Institute’s contribution to OECD’s Better Policies for 2016: A New Framework for Policy Coherence: Lindberg 2016).

#### 4.4.2 Quantitative modelling using lower level of complexity – the Earth3 model

Van Soest et al. (2019) identify three models that cover SDGs more extensively than the conventional IAMs. One of these is iSDG and another is Earth3. Paper III was written as part of the development of the Earth3 model, with a focus on the human well-being aspects of the 2030 Agenda. The Earth3 model is an integrated system model of lower complexity designed to include all the SDGs, with reference to metrics of global environmental change that are compatible with the nine planetary boundaries. A sketch of the full model is presented in Figure 8.

Embarking from the earlier work of Randers and Goluke, published in the book *2052- A Global Forecast for the Next Forty Years using a mix of models* (Randers 2013), the modelling linked the core Earth3 model of human activity and its impacts to the 2030 Agenda’s 17 SDGs and planetary boundaries. The Earth3 core sub-model, on the upper left of Figure 8, concentrates on the temporal development of population and aggregate production, GDP. It is combined with a lower complexity Earth system model, the Earth System Climate Interpretable Model, on the lower left of Figure 8, that forecasts biophysical effects of a warmer world (Randers et al. 2016, Randers and Goluke 2020).

Within the Earth3 project, my main responsibility was to develop the SDG and PB modules in the Performance sub-model (shown as the grey shaded area in Figure 8 and the thicker lines). The work included selecting indicators and gathering data from a diverse set of databases including the Penn World Tables, the World Bank Databank and UN population statistics. The data was then collated to represent seven world regions (see the regional division in the supplementary material of Paper III). Furthermore, with inputs from the Earth3 - mainly population and GDP per capita forecasts – the performance of the achievement of SDGs was simulated in the sub-model that I built.

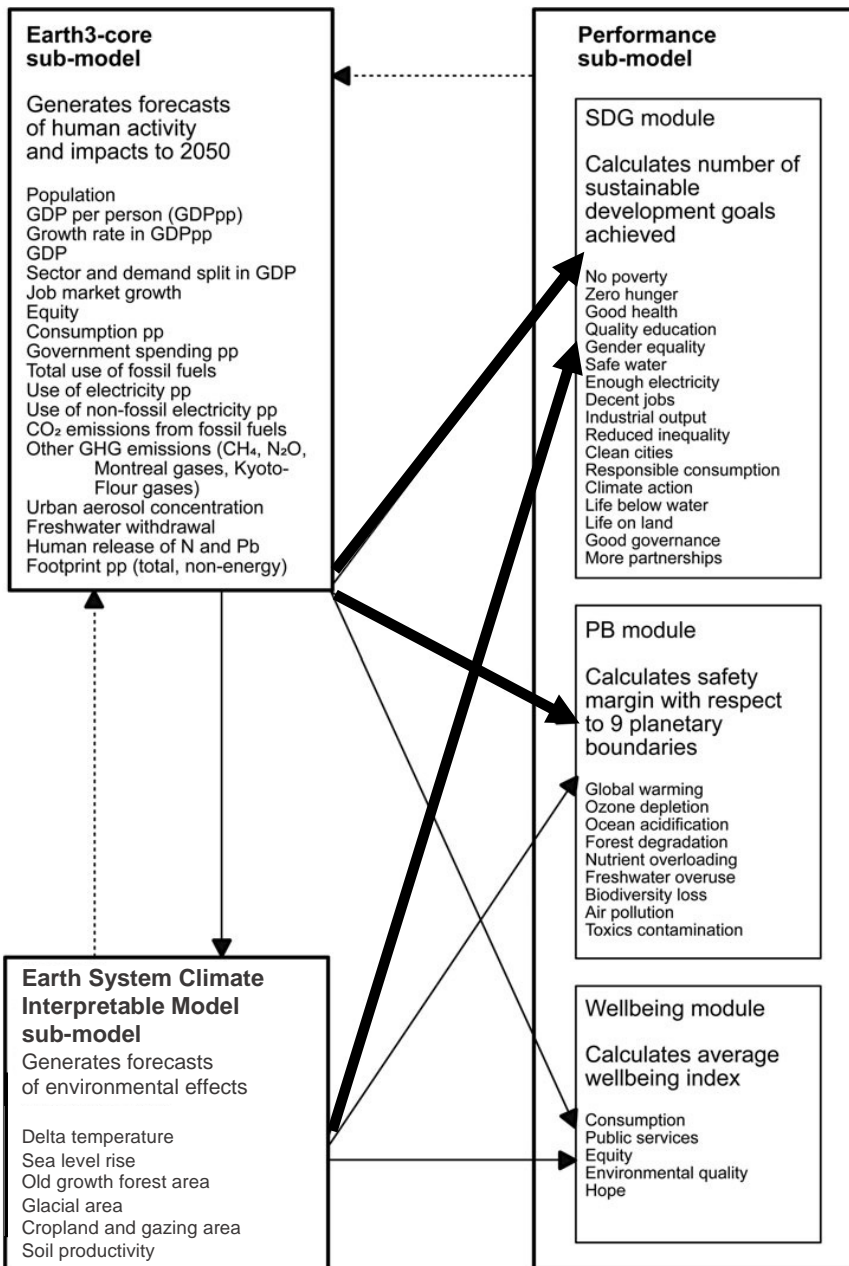


Figure 8: Overview of the Earth3 model system. My contribution is highlighted with the shaded area on the right side of the figure as well as with thick lines. Details in Goluke et al. (2018). Dashed lines indicate where added feedbacks would convert Earth3 into a full system dynamics model. Based on Randers, Rockström, Stoknes, Goluke, Collste, Cornell and Donges. (2019).

How can human well-being aspects be meaningfully incorporated in low complexity world-Earth models of the 2030 Agenda? The linking of the SDG and PB modules with indicators such as population and GDP enabled a simple, straightforward and transparent model structure that can be compared with other Integrated Assessment Modelling approaches. It also encompasses vast simplifications that deserve further deliberation as we discuss in Randers et al. (2019), Collste et al. (2018) and in the supplementary material to Paper III.

Besides developing the Earth3 model, I also contributed to the writing of the project report presented to the Club of Rome (Randers et al. 2018), the accompanying academic paper (Randers et al. 2019) and the technical description of the model (Goluke et al. 2018). I led the documentation of the SDG and Planetary Bouncarie modules, see Collste et al. (2018) that describe, in some detail, their empirical basis including data selection, sources, analysis and forecasting methods.

#### 4.5 Participatory approach grounded in systems thinking – Three horizons for the SDGs (3H4SDG)

Paper IV is based on the development and use of a 2030 Agenda-focused participatory stakeholder approach to enrich global discussions on future sustainability pathways. The research was based on the recognition that there is a lack of diversity in the perspectives of global sustainability pathways, especially those from the Global South (Aguiar et al. 2020). This lack is evident in the Shared Socioeconomic Pathways Narratives (SSPs), used by the IPCC (see, e.g., IPCC 2019), that were initially drafted in a single workshop involving mainly modelling experts from the Global North (O'Neill et al. 2012, 2017). Therefore, there is a risk that crucial views about the future are missing in these projects. As explained through the lens of Ulrich's systemic triangulation (Ulrich 2003), both values and facts contribute to how system boundaries are set for a particular project. This is the case for global models as well as for future scenarios. Results from models may reflect their developers' interests, values and disciplinary orientations (Meadows et al. 1982, Saltelli et al. 2020). In this context, Paper IV focus on filling the gap that was identified in the initiative the World in 2050: improving global target-seeking narratives that are detached from, for example, particular African worldviews.

As a result of participatory dialogues, a wider set of perspectives should be incorporated in sustainability scenarios. The use of participatory modelling, scenarios, and pathways approaches are common in social-ecological systems research (Peterson et al. 2003, Antunes et al. 2006, Leach et al. 2010, Pereira et al. 2020). They are however typically used for local and highly specified contexts. For such contexts, participatory approaches are often seen as a move

away from describing problems, to identifying and propose solutions or possible ways forward based on an improved understanding of possible pathways and feedback from informed stakeholders (Patterson et al. 2017). The methods can thereby more directly “*contribute to real-world sustainability transitions*” (Wiek and Iwaniec 2014 p. 498). In Paper IV, we argue that solutions for challenges discussed in international forums, for example in relation to 2030 Agenda priorities, also need to be contextualised. Furthermore, alternative future pathways discussed in different contexts need to be incorporated in global sustainability discussions.

Paper IV details the participatory approach we developed to facilitate cross-scale interactions with the Agenda and global sustainability pathways. The method is grounded in systems thinking by addressing the integrative and indivisible character of the SDGs. To capture multiple perspectives about how to reach the SDGs, we rely on cross-scale participatory approaches (Biggs et al. 2007, Dutra Aguiar 2015, Folhes et al. 2015). As an overview, the approach consists of several steps:

- a) Using the Three Horizons (3H) framework (Sharpe et al. 2016, Sharpe 2020) to guide the discussion in three steps: (i) future aspirations, (ii) present concerns and (iii) necessary changes to reach the desired future. The 3H diagram that incorporate these three steps facilitates stakeholder interaction and visualisation of the pathways.
- b) When discussing future aspirations and present concerns, we use the dimensions of the Agenda by referring to the 2030 Agenda 5 ‘SDG Ps’: People (SDGs 1-6), Planet (SDGs 13-15), Prosperity (SDGs 7-12), and Peace (SDG 16) and Partnership (SDG 16) (United Nations 2015). The five dimensions are discussed in an integrative way when the stakeholders analyse the deep causes underlying present concerns. These deep causes would, in the language of system dynamics, be translated to the underlying system structure. Only thereafter, the participants discuss the possible actions and transformative changes necessary to overcome the current obstacles and reach the SDGs in an integrated manner, across all dimensions.
- c) The approach also captures multiple perspectives by contrasting global scenario narratives to the results of the discussions for different regions or groups of actors. A diversity of backgrounds in the stakeholder group contributes to finding contrasting perspectives. Divergent perspectives are noted down during the process, and discussed in plenary
- d) Finally, all steps include creative activities to facilitate that the participants take ownership of the process and unleash their imagination. Imagination in participatory approaches contributes to inspiring and empowering the participants (Pereira et al. 2018, 2021).

## 5. Summaries of the thesis papers

### 5.1 Paper I: Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies

Collste, D., Pedercini, M., & Cornell, S. E. (2017) *Sustainability Science* 12(6):921–931. <https://doi.org/10.1007/s11625-017-0457-x>

**Paper I** presents the Threshold 21 iSDG system dynamics model and demonstrates the use and applicability of system dynamics modelling for analysing 2030 Agenda interdependencies. Tanzania was chosen as a pilot case, representing a low-income country in Sub-Saharan Africa. Unlike most applications of the Threshold 21 model (the precursor to iSDG, Barney 2002), this Tanzania model was not commissioned by national decision-makers nor did it include any stakeholder participation. The modelling task was to relevantly represent important causal links across three SDGs, in order to improve the model architecture.

Paper I, studies the consequences of investments in photovoltaics (supporting achievement of SDG 7 on energy), for health (SDG 3) and education (SDG 4), two SDGs that were weakly represented in *Threshold 21*. The paper presents findings of a literature review in which the different relationships were explored. Note that Figure 9 shows an adaptation of the influence diagram presented in our paper that was included in the 2018 UN World Public Sector report (United Nations 2018). The UN report added SDG targets to the figure that we presented in the paper. Translating the many intermediates that are represented in Figure 9 to the Threshold 21 model architecture would be a challenging task, as the model is designed for a more aggregated level of understanding. Instead, the overall tendency of the relationships between electricity access and life expectancy was based on results found in literature.

Paper I also presents the resulting simulations of five scenarios of investments in photovoltaic capacity. Figure 10 shows how different policy options will have different implications for life expectancy over time. These kind of model-generated simulations are less useful on their own than when they are presented alongside the system understanding with the possibility of exposing the assumptions involved. This is why iSDG is used as a discussion tool with an interactive user interface.

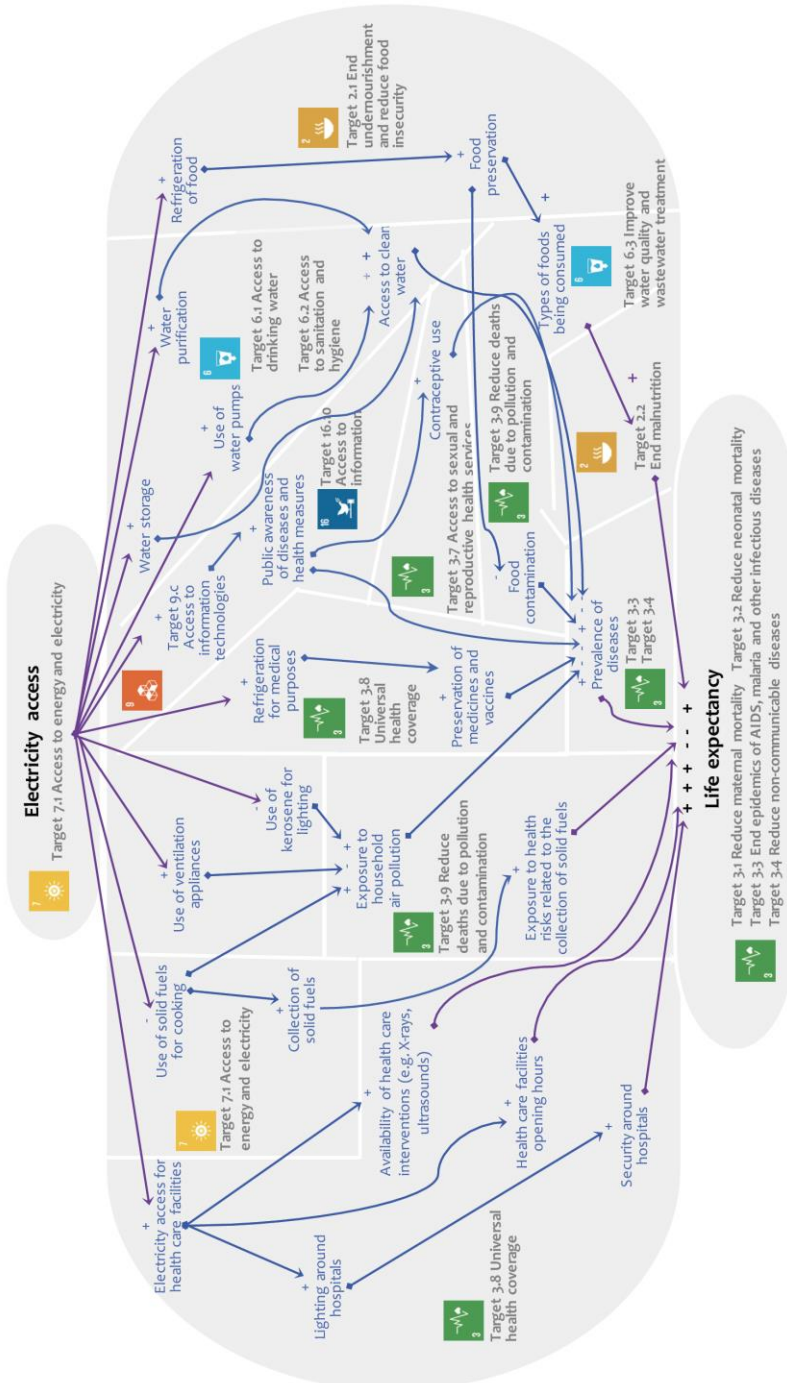
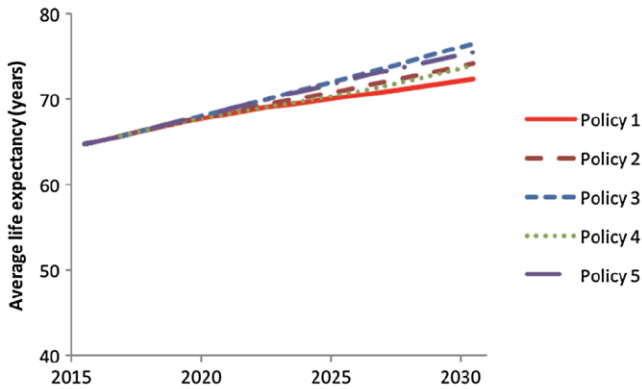


Figure 9: A modified version of Paper 1's Figure 5 with SDG targets superimposed. Reprinted from United Nations 2018.

Since the publication of Paper I, the iSDG model has been further developed and applied to other case studies (see, e.g., Millennium Institute 2017, Pedercini et al. 2018, 2019 (Paper II), 2020, as well as Allen et al. 2019, 2021b).



*Figure 10: The simulated behaviour of life expectancy using the entire iSDG model, simulating the results of five different policies. Policy 1 incorporate no expenditure for large scale photovoltaic capacity, Policy 2 represents 1 % of GDP investments from 2016 to 2031, Policy 3 represents 3 % investments. Policy 4 represents gradually increases in investments from 0 % in 2016 to 3 % 2030. Policy 5 represents gradually decreasing investments as percentages of GDP, from 3 % 2016-2020 to 1 % investments 2030-2031. Note that all investment policies (2 to 5) incorporate significant investments in photovoltaic capacity.*

## 5.2 Paper II: Harvesting synergy from sustainable development goal interactions

Pedercini, M., Arquitt, S., Collste, D., & Herren, H. (2019). Proceedings of the National Academy of Sciences 116(46):23021–23028.

Similar to Paper I, **Paper II** also applies the iSDG model but studies more generally how sectoral policies synergise. Synergies arising from the interaction of different 2030 Agenda-related policies result in an overall impact that is different from the sum of the impacts from each policy. Better systemic understanding of such synergies can provide insights that assist in identifying opportunities for cost-effective SDG strategies.

A widely used phrase in SDG research and policy is ‘trade-offs and synergies’, but in general neither of these terms are more precisely defined and used. Paper II brings clarity to the theoretical understanding of SDG synergies by providing a definition of synergy for the 2030 Agenda context: “*2 or more interventions generate synergy when their combined implementation results in progress for an SDG that is greater than the sum of the individual impacts of each intervention.*”

Paper II also defines dyssynergy, which “*occurs when the combined interventions lead to smaller progress than the sum of their individual impacts.*” Dyssynergy is similar to the idea of antagonistic interaction, where one intervention reduces the effects of another. Dyssynergy thus differs from the general understanding of ‘trade-offs’ based mainly on zero-sum competition - where different allocations of finite implementation resources shift the balance of benefits from one sector or context to another. From a social-ecological perspective, dyssynergy implies disruption not just interference.

Formulated as a mathematical equation, anticipated synergy can be calculated as:

$$Synergy = Impact_c - \sum_{i=1}^n Impact_i$$

$Impact_c$  is the impact generated when jointly implementing all policy interventions, and  $Impact_i$  is the impact generated by a single intervention. The resulting value is positive when there is synergy, and negative when there is a dyssynergy.

An example of a synergy is discussed in Paper I: when electricity access is provided, students tend to stay longer in school because it makes it possible to

study at night when it is dark outside. Thereby, policies that provide electricity access synergise with educational attainments. Paper II also gives an example of dyssynergy: when a policy to invest in road infrastructure is combined with a policy of investing in train infrastructure, the marginal effect of the road infrastructure investment decreases if the train infrastructure is targeting the same population that lacks access to transportation infrastructure.

Paper II complements its quantitative assessment of synergies with a qualitative framework for analysing them. The framework proposes five types of mechanisms that give rise to synergy, all of which are grounded in the analysis of the system dynamics model.

- Type I synergies result from a change in the inputs (e.g., in the form of financial resources) that are available for an intervention, caused by the implementation of another intervention.
- Type II synergies arise when the implementation of a policy intervention changes the immediate outcomes of another policy by affecting its enabling conditions.
- Type III synergies take place when an intervention in a given sector affects the target group of another intervention.
- Type IV synergies occur when the cost-effectiveness of progressing on a target indicator changes as the level of the indicator improves, i.e., when the related interventions are characterised by increasing or decreasing marginal returns.
- Type V synergies are a special case of type IV synergies when an indicator cannot exceed a given target value. Together, the two interventions could be more than enough to reach this level, in which case all additional investments would then have no effect on attaining the specific SDG target.

In Paper II, the synergies are quantified based on three pilot case studies where the iSDG model has been applied: Côte d'Ivoire, Malawi and Senegal. The resulting simulations estimate the economic value of synergy in the simulations (see Paper II for simulation results and supplementary material, Pedercini et al. 2019). The paper concludes that effectively harvesting these synergies through policy coherence could provide substantial amounts of resources for further SDG investments.

### 5.3 Paper III: Regional Achievements of Well-being SDGs in the Anthropocene

Collste, D., Cornell, S. E., Randers, J., Rockström, J., & Stoknes, P. E. (in review for Global Sustainability)

**Paper III** focuses on the SDG module of the Earth3 model (Figure 8, above) and explains relationships between human well-being, life satisfaction, SDGs and GDP per person in the Earth3 work. Rather than simply taking GDP as a sufficient indicator of human well-being (as in many integrated assessment models), the paper studies how GDP per person correlates with achievement of a suite of human well-being targets in line with SDGs 1 to 7. This is combined with a representation of different theories of human well-being: preference satisfaction theory, life satisfaction theory, theories of human capabilities and human needs.

The paper includes a simplified representation of the Earth3 model in which all SDGs are incorporated, displayed in Figure 11.

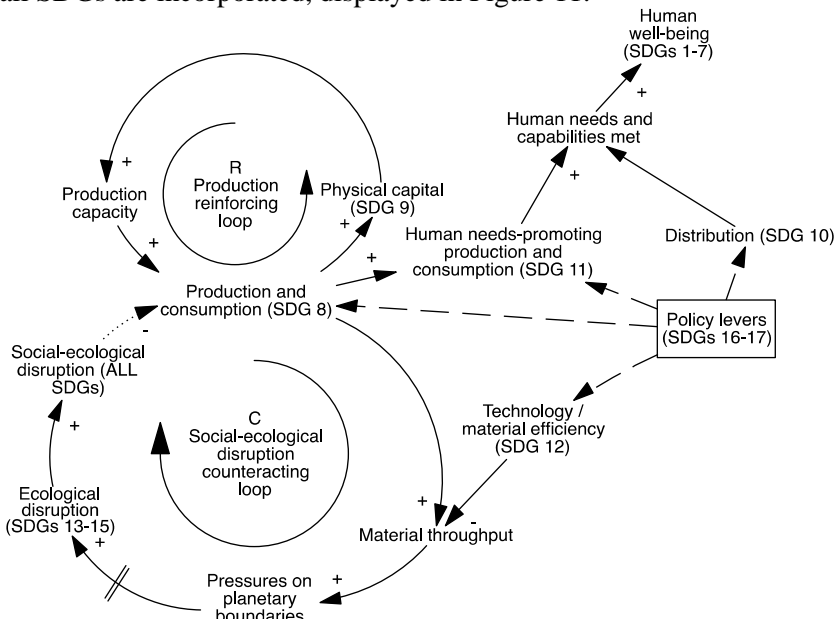


Figure 11: Conceptual sketch of key feedbacks and influences in World-Earth modeling within the Earth3 model. Each arrow represents a causal relationship. The ‘+’ signs at the arrowhead indicate that the effect is positively related to the cause (e.g., an increase in production causes the material throughput to rise above what it otherwise would have been). The ‘-’ signs at the arrowhead indicate that the effect is negatively related to the cause (e.g., a social-ecological disruption causes production to fall below what it otherwise would have been). The top loop is self-reinforcing, hence the loop polarity identifier R; the bottom loop is counteracting (sometimes referred to as balancing), hence the loop polarity identifier C.

From the quantitative data, illustrated by the examples of SDGs 1 and 2 in Figure 12 the paper finds uniform patterns of saturation for all regions above a clear income threshold. Above this threshold, the indicators chosen for SDGs 1 to 7 are achieved, as are the associated human needs and capabilities. The level of GDP per person where SDGs are achieved are consistent with earlier estimates of life satisfaction and the Easterlin paradox (Easterlin 1974, 2003, Easterlin et al. 2010). The level is between 10.000 and 15.000 PPP-adjusted \$2011.

The data also portrays stark differences with respect to scale: the patterns of the world as an aggregated whole (i.e., the pattern that might ordinarily be expected to be included in a world-Earth model) develop differently from all of the world’s seven regions. The general world system understanding differentiates from the specified regions. There are also differences between the regions. In the paper, we argue that these differences between regional patterns can give vital hints on how SDGs can be achieved within Earth’s safe operating space – and how a stationary-state economy could be realised.

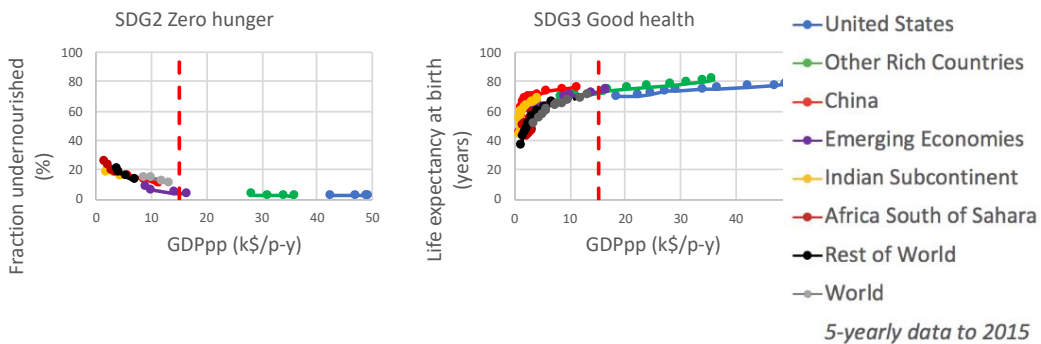


Figure 12: Data sources: All regions develop to increased GDPpp (measured in constant 2011 PPP \$). Vertical line represents GDPpp at 15k. Data sources: adapted from World Development Indicators, The World Bank, World Bank EdStats, UN Population statistics and Penn World Tables.

Paper III differs from the others in *not* being situated in Africa, but its key messages about meeting needs - and about the historical structural differences that need to be overcome for all without accelerating the social-ecological disruption loop - is directly relevant for the challenges of sustainable development, seen as justice challenges not just in economic terms but also with regard to other aspects of well-being.

## 5.4 Paper IV: Three Horizons for the Sustainable Development Goals: A Cross-scale Participatory Approach for Sustainability Transformations

Collste, D., Aguiar, A. P. D., Harmáčková, Z., Galafassi, D., Pereira, L., Selomane, O., & van Der Leeuw, S. (in review for *Ecology and Society*)

**Paper IV** complements the more modelling-intense Papers I to III. It focuses on the need to ground the development of global sustainability scenarios in locally prevalent narratives, as described in Section 4.5. With the research designed in connection to the World in 2050 initiative, the aim was two-fold. Firstly, to contribute with specified systems understanding in the form of scenario elements that could be used in global models. Secondly, to contribute to general systems understanding by constructing a participatory approach that could be replicated in different contexts around the world.

Paper IV details the Three Horizons for the SDGs approach (3H4SDG) in relation to an illustrative case study, the 2018 African Dialogue on the World in 2050. The Dialogue was deliberating on future pathways for food agriculture systems in regions of Africa, in the frame of attaining the SDGs within planetary boundaries. The Dialogue was held in Kigali, Rwanda and had 40 participants (31 stakeholders and 9 facilitators) from 11 different countries, including representatives of national governments, UN organisations, civil society and local communities, academia and research. Table 2 summarises the results of the 3H4SDG approach applied in parallel groups for different regions in Sub-Saharan Africa (See Section 4.5 for a summary of the approach).

Based on the parallel group results, an analysis of convergences and divergences within the groups, and in relation to global narratives, were discussed in plenary. The identified divergent themes included urbanisation, population growth, agricultural practices, and the roles of different actors in the future of agriculture. Box 1 presents examples of the identified divergences and how they can be used to inform the co-design of global target seeking scenarios - which is further explored in the accompanying paper *Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability* (Aguiar, Collste, Harmáčková, Pereira, Selomane, Galafassi, van Vuuren, van der Leeuw 2020).

Table 2: A summary of the four pathways explored during the 2018 African Dialogue on the World in 2050, from which divergences and convergences were extracted.

<b>Pathway and unique features</b>	<b>Future visions</b>
<i>Ubuntu</i> (West and Central Africa): Fully organic and cooperatives dominating.	Agriculture and food systems dominated by farmers' associations and cooperatives. Future characterised by diversity, inclusiveness, and agroecology.
<i>Peaceful and Prosperous East Africa</i> : Divergence between whether small-scale agriculture or large-scale commercial farming is dominating.	Food security assured through either small-scale agriculture or large-scale commercial farming- divergences in group. The scientific community collaborates with the local community to solve problems and community is important.
<i>Urugendo</i> (Southern Africa): Focus on peace as precondition.	Agriculture provides livelihoods, drives the economy and is run by young people. Agriculture is private-led and peace is emphasised as a precondition for a prosperous future. Farmers are organised in cooperatives and there is no hunger.
<i>Rainbow</i> (Sub-Saharan Africa): Strong focus on the role of the governments in providing institutional frameworks and regional partnerships.	An aware and educated society empowers its citizens and promotes home-grown and local knowledge. States are capable with strong institutions that can deliver and are accountable for their citizens. Citizens are actively participating in society and collaboration platforms are provided.

The participant evaluation results indicated that the approach was received positively and perceived as useful, discussing relevant questions and worth applying in different contexts. In the evaluation, participants highlighted that the approach addressed interdependencies and addressed SDGs holistically. Also, participants responses indicated that the process was “*People-led*” and one participant responded that “*communities need to be empowered [through participative processes]*”.

Based on dialogue results and a participant survey, we conclude that participatory approaches grounded in systems thinking represent a promising way to link local aspirations with global goals and global sustainability narratives. 3H4SDG could contribute to better linking and aligning global sustainability pathways to regional and local 2030 Agenda-related worldviews, values and strategies.

**Box 1: Examples of how divergences identified in the Dialogue results can be used.**

Differences between views can be brought to light from the results from the 3H4SDG approach. An example that was discussed in the 2018 African Dialogue on the World in 2050 relates to population. While the sustainability-focused Shared Socioeconomic Pathway 1 (SSP1) proposes low growth of population, some Dialogue participants highlighted population as an asset in rural and urban areas, that promotes food security and consequently the securing of human needs. Differences in emphasis of various factors may be attributed to differences in ‘values’ that also influence which ‘facts’ that are highlighted, in line with Ulrich’s triangle (Ulrich 2003). The figure on the right portrays in **blue arrows** the view that an increased population contributes to a greater ‘work force’ that can bring ‘innovations’ and ‘efficiency’ and thus lower the ‘consumption footprint’ and ‘natural resource use’. The **brown arrow** represents the view that a greater population causes a bigger ‘consumption footprint’.



*To the left: Divergences between the Dialogue results and the Shared Socioeconomic pathways (SSPs) from Aguiar et al. (2020). To the right: the same divergence in the form of an influence diagram. The ‘+’ signs at the arrowhead indicate that the effect is positively related to the cause (e.g., an increase in production causes the material throughput to rise above what it otherwise would have been). The ‘-’ signs at the arrowhead indicate that the effect is negatively related to the cause (e.g., a social-ecological disruption causes production to fall below what it otherwise would have been). With loops this would be considered a causal loop diagram.*

## 6. Discussion and conclusion: systems approaches for an indivisible 2030 Agenda future

In this section I reflect on how the aim of the dissertation has been fulfilled and what conclusions could be drawn. Three main insights have materialised from this thesis.

### 6.1 Key insights

**Insight 1: System dynamics models can highlight 2030 Agenda links and facilitate a shift to a development discourse grounded in systems thinking.**

Within the knowledge-action interfaces of the 2030 Agenda, there has been much emphasis on the need for systems understanding, and taking a systems approach in general. An in-depth understanding is needed of the cross-sector impacts and synergies of policies designed to meet the SDGs as the 2030 deadline approaches. However, in order to ensure that abstractly expressed systems aspirations can be translated into specified systems understanding, the systems approach should be implemented rigorously and explicitly.

Papers I and II show how the system dynamics tradition provides useful tools for specifying system structures, studying causal relationships, and quantitatively anticipating the consequences of interventions on system behaviour. Combined with insights about representing diverse values and plural perspectives, system dynamics tools can also be used for improving understanding of the implications of seeking multiple social and environmental goals at the same time.

Modelling, even at low degrees of formalisation - as in influence diagrams and results chain analysis, can reveal more coherent approaches to policy planning. The process of calculating SDG synergies presented in Paper II takes specified systems understanding from the case studies and generalises it. The methodological significance of this abstract understanding is that it can shift the focus from mechanistic searches goal by goal, to pursuing synergies through systemic improvements. It also gives new insights for SDG practitioners on how synergies and dyssynergies can be analysed in an integrated and coherent manner, saving precious resources and enhancing progress on the 2030 Agenda as a whole.

## **Insight 2: Human well-being SDGs offer a way to effectively and transparently include more complex measures of wellbeing in models**

Incorporating human well-being has long posed a challenge for global modelers, not only because there may be modelling trade-offs between the need for simplification, e.g., by using GDP instead of more complex notions of well-being. To be more relevant both normatively and for societal discussions, these models also need to reflect key concepts of human well-being. This could be achieved with reference to theories of human needs and capabilities.

Paper III bridges an understanding of human well-being (as tracked in historic data) with the explicit need for simplicity of system representation of world-Earth models. The worldwide political consensus behind the 2030 Agenda resolution provides legitimacy for the ‘values’ aspect of systemic triangulation. By integrating seven societal goals through their historic relationship to GDP, a new generation of models might better comprehend the significant challenges of ensuring human well-being while navigating towards Earth’s safe operating space.

## **Insight 3: When there are multiple possible pathways to meet global goals, multiple voices need to be heard.**

Values influence both the strategies for the 2030 Agenda and the design and communication of global target-seeking scenarios for sustainability planning. Diversities in values need to be brought to light, as they influence what can be considered as desirable futures and how to get there. The comprehensive integrated assessment models that quantify many aspects of these possible futures include implicit value assumptions, as well as the pathways to reach them.

Finding sustainable pathways boils down to a matter of both values and of facts. If the normative side of the endeavour is neglected, there is a risk of, for example, not considering what pathways are inconsistent with human well-being. Participatory methods that examine the output generated by model-based scenario studies can highlight value aspects.

The participatory pathways method presented in Paper IV navigates this landscape by bringing divergent views to the surface, and shows how this can be done with a focus on a crucial sector (food and agriculture systems), across different scales. In Paper IV, it is clear that there are differences between local perspectives and global narratives. There were for example major differences between the actual local perspectives and the assumptions made by the World in 2050-related modellers regarding population futures and the form of agriculture that should be promoted. To be relevant to the overarching discussions on world futures, discussions on SDGs need to both be creatively developed

and owned by the participants, and compared to global scenarios. Thereby, a wider plurality of possible futures can be considered also at the global scale.

## 6.2 Implications for practice and policy

The purpose of this research is to be situated within the knowledge-action interface of the 2030 Agenda. Primarily, I see my results as enhancing the use of systems thinking and approaches when analysing the Agenda's implementation, and how it can be linked to other perspectives. It is difficult to directly trace policy impacts of my work, however, I have observed some footprints of my research in policy-related documents. In particular Paper I has been referenced in several UN publications and texts, including the *2019 Global Sustainable Development Report* (Independent Group of Scientists appointed by the Secretary-General 2019), the *2018 Public Sector report* (United Nations 2018), and the *Global Environmental Outlook – GEO 6* (UN Environment 2019). Furthermore, the Swedish Environmental Protection Agency has used Figure 6 of Paper I in reference to 2030 Agenda interdependencies (Ekener and Katzeff 2018), and the paper is also discussed in a policy study by PBL Netherlands Environmental Assessment Agency (Ruijs et al. 2018). Besides the, also other reports that I have contributed to have been referenced within influential publications. A significant example is the mentioned *Transformation is feasible* (Randers et al. 2018) that was an outcome of the Earth3 project. The report was presented at the 50<sup>th</sup> anniversary of the Club of Rome and in a TED talk by Johan Rockström that so far has had 1.8 million views online (Rockström 2018). Finally, the Stockholm Resilience Centre background report (Galaz, Collste and Moore 2020) to the *2020 Human Development Report* (United Nations Development Programme 2020) is an important contribution to the discussion of what human development entails in the Anthropocene.

## 6.3 Ethical reflections

The scientific enterprise is built on a foundation of trust and it should be the responsibility of every researcher to uphold this foundation. This implies not only following codes of good research practice, but also to actively reflect on ethical issues in relation to the many aspects of the research process, including how the knowledge that is generated can be used in broader society (National Academy of Sciences, National Academy of Engineering (US) and Institute of Medicine (US) Committee on Science, Engineering, and Public Policy 2009). The main ethical questions in relation to my research relate to the modelling process and the use of models (Papers I-III), as well as the treatment of participants and their contributions (Paper IV).

As modelling incorporates boundary setting which is based on value judgments and facts (see Ulrich's systemic triangulation above), a relevant question is what views are represented in the model. Modelling choices may reflect interests, disciplinary orientations and biases of modellers. When models are sensitive to specific parameters and relations that in turn depend on these biases, their outcomes may invite partial or one-sided policy conclusions. In light of the handling of modelling results in relation to the coronavirus pandemic, Saltelli et al. (2020) have suggested principles of good scientific practice for modellers to adhere to. In particular, they highlight the need for transparency. For the two models used in my research, the function of the models was to increase systems understanding rather than to offer precise answers to specific policy questions. Therefore, the focus is not only on model simulations but also on the structure of the models themselves and how they can improve our understanding of systematic relations. To promote transparency and enable the replicability, the two models used in my work are openly available. The iSDG model is explained in a detailed model description available on the Millennium Institute's web page (see <https://www.millennium-institute.org/documentation>). The Earth3 model is also available online (<http://www.2052.info/earth3/>).

However, the iSDG model is highly elaborated with many sectors and several hundred relationships. This makes it time consuming and complicated even for a trained modeller to go through each quantitative relationship. This has been a challenge for me in working with the pre-existing model structure, as I did for Paper I. From a critical standpoint, one could thus argue that there is transparency in theory – but not in practice.

One of the risks that Saltelli et al. (2020) highlight is that modellers are becoming over-confident in their models. This is a risk that comes with the large amount of time invested in model development. The model can thus come to be seen as an “Electronic oracle”, as the partly ironic title of the book on the subject by Meadows and Robinson (1985) points at. To instead work on model development in a more scientifically robust manner, implies critically re-examining model assumptions, communicating the models' inherent uncertainty and being open about its limitations. One may also invite outside perspectives or involve stakeholders in the model development. For instance, national applications of the iSDG model are often developed with input from key stakeholders. The transparent architecture of system dynamics modelling software also invites non-modellers to study and scrutinise its assumptions.

Did the participatory research resulting in Paper IV entail any ethical challenges? We did not process any personal information, participation was voluntary, and the research did not affect research persons in any ethically relevant way. We also shared the report from the Dialogue with the participants

for feedback before publishing it. Thus, the research did not raise any ethical problems. In relation to Paper IV, I also made a self-assessment of ethical considerations using the Ethical Review Tool, an online form provided by Stockholm University (<https://www.su.se/staff/services/research/research-ethics/ethical-review-of-research-involving-humans-1.332303>), which indicated that no formal ethical review was necessary for the project according to Sweden's Ethical Review Act 2003:460. Established social research methods were followed, including making the participants' survey answers anonymous.

Implementing the 2030 Agenda goals is urgently needed as it addresses the worsening impacts of global environmental change. Hopefully, my research will support the realisation of the SDGs. Like many sustainability scientists, I regard this as an issue of research ethics even though it is not covered under regulations and formal recommendations. My research required international traveling, and to avoid negative ecological impacts I have chosen to travel by train instead of by air whenever possible.

## 6.4 Personal reflections on my research journey

Before embarking on this PhD journey, I had been involved in what came to be the 2030 Agenda negotiations at the United Nations. The negotiations were organised in a way that allowed strong involvement of research expertise. Here, I saw how researchers can be constructively involved in the international science-policy arena. This made me interested in pursuing research. I was particularly struck by the messages from Johan Rockström who presented the planetary boundaries in one of the stocktaking sections of the negotiations in New York. I had also, by the end of my European Master degree in system dynamics, been working with two other students on possible adjustments to the World3 model of *Limits to Growth* (Meadows et al. 1972, 2004) in order for it to incorporate different practical policy proposals in relation to the contemporary degrowth debate. Finding it difficult to incorporate societal changes into the World3 model, we concluded that the model was designed for another purpose and that the chosen degrowth proposals could not meaningfully be integrated. We saw the potential of system dynamics as a tool to discuss these kinds of alternative futures and we recognised that such discussions could also incorporate the views of different stakeholder groups (Benich, Bongers and Collste 2015). We presented our work at the 2015 International System Dynamics Conference and received the Barry Richmond Scholarship Award.

Working on this PhD has enabled me to combine my interest in the science-policy interface with my knowledge in system dynamics thinking and modelling. It has let me to explore how different stakeholders' views relate to what

is shown in global models. It has also enabled me to work directly with the development of models with the aim to find sustainability pathways in a systemic possibility space that environmental scientists argue is shifting rapidly in undesirable ways.

The journey has however not been straightforward. My initial plan for the PhD was to dive deeper into a philosophical discussion of world models and the system dynamics field. After a while, I realised that I needed to gain experience in working with a variety of modelling-related projects in order for me to be able to more convincingly contribute to such theoretical discussions. I have been fortunate to learn from many inspiring modellers. Due to my earlier engagements with Matteo Pedercini and Hans Herren at the Millennium Institute who introduced me to the Threshold 21 model, my work with Hanna Wetterstrand and Maria Schultz at SwedBio (at Stockholm Resilience Centre) who initiated me to work on stakeholder input to *the World in 2050*, and to my supervisor Sarah Cornell and Johan Rockström, Jorgen Randers, Ulrich Goluke and Per Espen Stoknes who were involved in the Earth3 project, I have been able to gain a better understanding of different models and their science-policy interfaces. I am now more prepared for a wider discussion of the philosophical underpinnings of models. Together with Uno Svedin, I have compared different systems-oriented approaches on sustainability.

Through my position at Stockholm Resilience Centre, I have come across various systems approaches, predominantly social-ecological systems as complex adaptive systems, but also aspects of Earth system analysis. This has given me a more reflective perspective of the system dynamics approach, and made me further emphasise uncertainty and emergent features in sustainability-oriented systems. This is in line with the understanding of systems from a social-ecological systems perspective. Both Papers I and II therefore emphasise the role of models as devices to learn more about the systems incorporated into national development planning, rather than as crystal balls to predict the future. In both papers, this implied making explicit the often-implicit intermediates, not just the causal link between policy options and outcomes. If models are to be learning tools that link systems, facts and values, this attention to a wide range of possibilities is essential.

Working with the team in the process of developing the Earth3 model was an intense learning experience. My work incorporated data mining and translating data from different data bases, but also connecting across different modelling sectors. One part of the work consisted of proposing indicators for the respective SDGs, significantly SDGs 1 to 7 – which is presented in Paper III. The selection of indicators exposes different biases and assumptions about the world. For me, it was important that we chose indicators that reflected key

human well-being frameworks such as needs and capabilities rather than relying on arbitrary selection simply because datasets were available. The project was also clearly set within the knowledge-action interface as there was a clear time-bound task to finish a particular model and deliver an accompanying report while maintaining strict scientific standards (including those on modelling as discussed in my ethical reflections).

During the writing of the thesis, I have been involved in other policy-related projects including *the World in 2050* with the stated purpose to support the implementation of the 2030 Agenda (TWI2050 - The World in 2050 2018, 2019, 2020). Since August 2020, I have also been working part-time for *Sweden's National Coordinator of the 2030 Agenda*. These experiences have provided me with different perspectives on 2030 Agenda policies and practices. Not in the least, the work of the National 2030 Agenda coordinator has shown me the difficulty in bridging knowledge and action.

Two weeks before sending this thesis for print, I caught Covid-19, getting a fever and having difficulties in concentrating. This was very ironic timing given that I had wanted to be sharp and alert when going through my thesis for final review. Ideally, however, this has taught me to not leave work until the end of a project and to expect the unexpected. After all, we live in the Anthropocene, where the unexpected is now the norm.

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## Literature cited

- Aguiar, A. P., D. Collste, D. Galafassi, Z. Harmáčková, K. Hounghbedji, M. Mesfin, D. Ndahiro, L. Pereira, O. Selomane, and S. van der Leeuw. 2019. *The Second African Dialogue on the World In 2050 - How to attain the SDGs within planetary boundaries: Agriculture and food systems. Report on a Multi-Actor Dialogue for TWI2050, 30 - 31 October 2018, Kigali, Rwanda*. Sustainable Development Goals Center for Africa and SwedBio/Stockholm Resilience Centre at Stockholm University.
- Aguiar, A. P. D., D. Collste, Z. V. Harmáčková, L. Pereira, O. Selomane, D. Galafassi, D. Van Vuuren, and S. Van Der Leeuw. 2020. Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. *Global Environmental Change* 65:102198.
- Allen, C., G. Metternicht, and T. Wiedmann. 2016. National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. *Environmental Science & Policy* 66:199–207.
- Allen, C., G. Metternicht, and T. Wiedmann. 2018. Initial progress in implementing the Sustainable Development Goals (SDGs): a review of evidence from countries. *Sustainability Science* 13(5):1453–1467.
- Allen, C., G. Metternicht, and T. Wiedmann. 2021a. Priorities for science to support national implementation of the sustainable development goals: A review of progress and gaps. *Sustainable Development*:1–18.
- Allen, C., G. Metternicht, T. Wiedmann, and M. Pedercini. 2019. Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging. *Nature Sustainability* 2(11):1041–1050.
- Allen, C., G. Metternicht, T. Wiedmann, and M. Pedercini. 2021b. Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing States. *Global Sustainability*:1–25.
- Antunes, P., R. Santos, and N. Videira. 2006. Participatory decision making for sustainable development—the use of mediated modelling techniques. *Land Use Policy* 23(1):44–52.
- Armitage, D. R., F. Berkes, and N. Doubleday, editors. 2007. *Adaptive co-management: collaboration, learning, and multi-level governance*. UBC Press, Vancouver.
- Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review* 12(3):183–210.
- Barlas, Y., and S. Carpenter. 1990. Philosophical roots of model validation: Two paradigms. *System Dynamics Review* 6(2):148–166.
- Barney, G. O. 2002. The Global 2000 Report to the President and the Threshold 21 model: influences of Dana Meadows and system dynamics. *System Dynamics Review* 18(2):123–136.

- van den Belt, M. 2004. *Mediated Modeling: A System Dynamics Approach to Environmental Consensus Building*. Island Press, Washington.
- Bennich, T., T. Bongers, and D. Collste. 2015. Exploring Degrowth Pathways Using System Dynamics. Pages 372–399 *33rd International Conference of the System Dynamics Society 2015*. System Dynamics Society, Cambridge, MA, US.
- Bennich, T., N. Weitz, and H. Carlsen. 2020. Deciphering the scientific literature on SDG interactions: A review and reading guide. *Science of The Total Environment* 728.
- Berkes, F., and C. Folke, editors. 1998. *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press, Cambridge, U.K.
- Biermann, F., N. Kanie, and R. E. Kim. 2017. Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. *Current Opinion in Environmental Sustainability* 26–27:26–31.
- Biggs, R., C. Raudsepp-Hearne, C. Atkinson-Palombo, E. Bohensky, E. Boyd, G. Cundill, H. Fox, S. Ingram, K. Kok, S. Spehar, M. Tengö, D. Timmer, and M. Zurek. 2007. Linking Futures across Scales: a Dialog on Multiscale Scenarios. *Ecology and Society* 12(1):art17.
- Boulding, K. E. 1966. The economics of the coming spaceship Earth. Pages 3–14 in H. E. Jarrett, editor. *Environmental quality in a growing economy*. John Hopkins University Press, Baltimore.
- Briant Carant, J. 2017. Unheard voices: a critical discourse analysis of the Millennium Development Goals' evolution into the Sustainable Development Goals. *Third World Quarterly* 38(1):16–41.
- Bunge, M. 2000. Systemism: the alternative to individualism and holism. *The Journal of Socio-Economics* 29(2):147–157.
- Carson, R. 1962. *Silent spring*. Houghton Mifflin, Boston.
- Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. H. Guston, J. Jäger, and R. B. Mitchell. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences* 100(14):8086–8091.
- Castro, R., and P. Jacovkis. 2015. Computer-Based Global Models: From Early Experiences to Complex Systems. *Journal of Artificial Societies and Social Simulation* 18(1):13.
- Chasek, P. S., L. M. Wagner, F. Leone, A.-M. Lebeda, and N. Risse. 2016. Getting to 2030: Negotiating the Post-2015 Sustainable Development Agenda. *Review of European, Comparative & International Environmental Law* 25(1):5–14.
- Collste, D., and T. Bennich. in prep. A Modelling Framework for Transformational Change.
- Collste, D., J. Randers, U. Goluke, P. E. Stoknes, S. Cornell, and J. Rockström. 2018. *The Empirical Bases for the Earth3 Model: Technical*

- Notes on the Sustainable Development Goals and Planetary Boundaries*. preprint, EarthArXiv.
- Cornell, S., F. Berkhout, W. Tuinstra, I. Chabay, B. de Wit, R. Langlais, D. Mills, P. Moll, I. M. Otto, A. Petersen, C. Pohl, and L. van Kerkhoff. 2013. Opening up knowledge systems for better responses to global environmental change. *environmental science*:11.
- Cornell, S., I. C. Prentice, J. House, and C. Downy, editors. 2012. *Understanding the earth system: global change science for application*. Cambridge University Press, Cambridge.
- Costanza, R., R. Leemans, R. M. J. Boumans, and E. Gaddis. 2007. Integrated Global Models. Pages 417–446 in R. Costanza, L. J. Graumlich, and W. Steffen, editors. *Sustainability or Collapse? An Integrated History and Future of People on Earth*. MIT Press.
- Daly, H. E. 1991. *Steady-state economics*. Island, Washington, D.C.
- Danermark, B., and M. Ekström. 2019. *Explaining society: critical realism in the social sciences*. Second edition. Routledge, Taylor & Francis Group, London ; New York.
- Doyal, L., and I. Gough. 1984. A theory of human needs. *Critical Social Policy* 4(10):6–38.
- Doyal, L., and I. Gough. 1991. *A theory of human need*. Macmillan, Basingstoke, Hampshire.
- Dutra Aguiar, A. P. 2015. Transition to sustainability: are participatory multi-scale scenarios a useful tool? *GLP news*(11).
- Easterlin, R. A. 1974. Does Economic Growth Improve the Human Lot? Some Empirical Evidence. Pages 89–125 in P. A. David and M. W. Reder, editors. *Nations and Households in Economic Growth: Essays in Honor of Moses Abramovitz*. Academic Press.
- Easterlin, R. A. 2003. Explaining happiness. *Proceedings of the National Academy of Sciences* 100(19):11176–11183.
- Easterlin, R. A., L. A. McVey, M. Switek, O. Sawangfa, and J. S. Zweig. 2010. The happiness-income paradox revisited. *Proceedings of the National Academy of Sciences* 107(52):22463–22468.
- Easterly, W. 2015. The SDGs Should Stand for Senseless, Dreamy, Garbled. <https://foreignpolicy.com/2015/09/28/the-sdgs-are-utopian-and-worthless-mdgs-development-rise-of-the-rest/>.
- Ehrlich, P. R. 1971. *The population bomb*. Buccaneer Books, Cutchogue, N.Y.
- Ekener, E., and C. Katzeff. 2018. *Ömsesidiga beroende mellan hållbarhetsdimensionerna. En kunskapsöversikt, Rapport 6805*. Naturvårdsverket.
- Engström, R. E., D. Collste, S. E. Cornell, F. X. Johnson, H. Carlsen, F. Jaramillo, G. Finnveden, G. Destouni, M. Howells, N. Weitz, V. Palm, and F. Fusco-Nerini. 2020. Succeeding at home and abroad -- Accounting for the international spillovers of cities' SDG actions. *arXiv:2012.14153 [physics, q-fin]*.

- Engström, R. E., D. Collste, S. E. Cornell, F. X. Johnson, H. Carlsen, F. Jaramillo, G. Finnveden, G. Destouni, M. Howells, N. Weitz, V. Palm, and F. Fuso-Nerini. 2021. Succeeding at home and abroad: accounting for the international spillovers of cities' SDG actions. *npj Urban Sustainability* 1(1):18.
- Fazey, I., R. M. Wise, C. Lyon, C. Câmpeanu, P. Moug, and T. E. Davies. 2016. Past and future adaptation pathways. *Climate and Development* 8(1):26–44.
- Folhes, R. T., A. P. D. de Aguiar, E. Stoll, E. L. Dalla-Nora, R. Araújo, A. Coelho, and O. do Canto. 2015. Multi-scale participatory scenario methods and territorial planning in the Brazilian Amazon. *Futures* 73:86–99.
- Folke, C., R. Biggs, A. V. Norström, B. Reyers, and J. Rockström. 2016. Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society* 21(3).
- Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and society* 15(4).
- Folke, C., L. Pritchard Jr, F. Berkes, J. Colding, and U. Svedin. 1998. *IHDP Working Paper No 2: The Problem of Fit between Ecosystems and Institutions*. A Report for the IHDP, International Human Dimensions Programme on Global Environmental Change (IHDP).
- Ford, A. 2010. *Modeling the Environment*. 2nd edition. Island Press, Washington, DC.
- Forrester, J. W. 1971. *World Dynamics*. Wright-Allen Press.
- Forrester, J. W. 1987. Lessons from system dynamics modeling. *System Dynamics Review* 3(2):136–149.
- Forrester, J. W. 1994. System dynamics, systems thinking, and soft OR. *System Dynamics Review* 10(2–3):245–256.
- Forrester, J. W. 2007. System dynamics—a personal view of the first fifty years. *System Dynamics Review* 23(2–3):345–358.
- Galaz, V., D. Collste, and M.-L. Moore. 2020. Planetary Change and Human Development. Unpublished manuscript, Stockholm Resilience Centre, Stockholm University. Background paper to the 2020 Human Development Report: The next frontier: Human Development and the Anthropocene.
- Galaz, V., P. Olsson, T. Hahn, C. Folke, and U. Svedin. 2008. The problem of fit among biophysical systems, environmental and resource regimes, and broader governance systems: insights and emerging challenges. Pages 147–186 in O. R. Young, L. A. King, and H. Schroeder, editors. *Institutions and Environmental Change: Principal Findings, Applications, and Research Frontiers*. The MIT Press, Cambridge, USA.
- Global Footprint Network. 2016, July 20. Sustainable development: two indices, two different views - Global Footprint Network.

- <https://www.footprintnetwork.org/2016/07/20/measure-sustainable-development-two-new-indeces-two-different-views/>.
- Goluke, U., J. Randers, D. Collste, and P. E. Stoknes. 2018. The Earth3 model system. <https://osf.io/a8mvf/>.
- Griggs, D., M. Stafford-Smith, O. Gaffney, J. Rockström, M. C. Öhman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble. 2013. Policy: Sustainable development goals for people and planet. *Nature*:305–307.
- de Haan, J. (Hans), and J. Rotmans. 2011. Patterns in transitions: Understanding complex chains of change. *Technol. Forecast. Soc. Change* 78(1):90–102.
- Hamilton, C. 2017. *Defiant earth: the fate of humans in the anthropocene*. Polity, Cambridge, UK ; Malden, MA.
- Hickel, J. 2019. The contradiction of the sustainable development goals: Growth versus ecology on a finite planet. *Sustainable Development* 27(5):873–884.
- Holling, C. S., editor. 1978. *Adaptive environmental assessment and management*. International Institute for Applied Systems Analysis ; Wiley, [Laxenburg, Austria] : Chichester ; New York.
- Holling, C. S. 1986. The resilience of terrestrial ecosystems: Local surprise and global change. Pages 292–320 in W. C. Clark and R. E. Munn, editors. *Sustainable development of the biosphere*. Cambridge University Press, Cambridge.
- Holling, C. S. 1998. Two Cultures of Ecology. *Ecology & Society* 2(2):4.
- Homer, J. B. 1996. Why we iterate: scientific modeling in theory and practice. *System Dynamics Review* 12(1):1–19.
- Hughes, B. B. 1999. The International Futures (IFs) Modeling Project. *Simulation & Gaming* 30(3):304–326.
- Hughes, B. B. 2019. *International futures: building and using global models*. Academic Press (Elsevier Ltd), London.
- Independent Group of Scientists appointed by the Secretary-General. 2019. *Global sustainable development report 2019: the future is now - science for achieving sustainable development*. United Nations, New York.
- IPBES. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES secretariat, Bonn, Germany.
- IPCC. 1992. *Climate change: the IPCC 1990 and 1992 assessments*. IPCC, Geneva.
- IPCC. 1996. *Climate change 1995: the science of climate change*. Cambridge University Press, Cambridge ; New York.
- IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

- IPCC. 2019. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.*
- Lade, S. J., B. H. Walker, and L. J. Haider. 2020. Resilience as pathway diversity: linking systems, individual, and temporal perspectives on resilience. *Ecology and Society* 25(3)(19).
- Lawton, J. 2001. Editorial: Earth System Science. *Science* 292(5524):1965.
- Le Blanc, D. 2015. Towards Integration at Last? The Sustainable Development Goals as a Network of Targets: The sustainable development goals as a network of targets. *Sustainable Development* 23(3):176–187.
- Leach, M., I. Scoones, and A. Stirling. 2010. *Dynamic sustainabilities: technology, environment, social justice.* Earthscan, London ; Washington, DC.
- van der Leeuw, S. E. 2020a. *Social sustainability, past and future: undoing unintended consequences for the earth's survival.* Cambridge University Press, Cambridge, United Kingdom ; New York, NY.
- van der Leeuw, S. 2020b. The role of narratives in human-environmental relations: an essay on elaborating win-win solutions to climate change and sustainability. *Climatic Change* 160:509–519.
- Levin, S. A. 1998. Ecosystems and the Biosphere as Complex Adaptive Systems. *Ecosystems* 1(5):431–436.
- Lindberg, C. 2016. Tracking progress in policy coherence for development. Page *Better Policies for Sustainable Development 2016: A New Framework for Policy Coherence.* OECD Publishing, Paris.
- Linnér, B.-O., and V. Wibeck. 2019. *Sustainability Transformations Across Societies: Agents and Drivers across Societies.* Cambridge University Press.
- Lovelock, J. E. 1972. Gaia as seen through the atmosphere. *Atmospheric Environment (1967)* 6(8):579–580.
- Lovelock, J. E., and L. Margulis. 1974. Atmospheric homeostasis by and for the biosphere: the gaia hypothesis. *Tellus* 16(1–2):2–10.
- Max-Neef, M. A. 1991. *Human scale development: conception, application and further reflections.* The Apex Press, New York.
- Max-Neef, M., A. Elizalde, M. Hopenhayn, F. Herrera, H. Zelman, J. Jataba, and L. Weinstein. 1989. Human Scale Development: An Option for the Future. *Development dialogue* 1:5–55.
- Meadows, D. 2008. *Thinking in Systems: A Primer.* Chelsea Green.
- Meadows, D. H. 1976. The Unavoidable A priori. Pages 161–240 *Proceedings of the 1976 International Conference on System Dynamics.* System Dynamics Society, Geilo, Norway.

- Meadows, D. H., D. L. Meadows, and J. Randers. 1992. *Beyond the limits, confronting global collapse*. Chelsea Green, White River Junction, VT.
- Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens III. 1972. *The Limits to Growth: A Report for THE CLUB OF ROME'S Project on the Predicament of Mankind*. Universe Books, New York.
- Meadows, D. H., J. Randers, and D. L. Meadows. 2004. *Limits to Growth: The 30-Year Update*. 3 edition. Chelsea Green Publishing, White River Junction, Vt.
- Meadows, D. H., J. M. Richardson, and G. Bruckmann. 1982. *Groping in the dark: the first decade of global modelling*. Wiley, Chichester [West Sussex]; New York.
- Meadows, D. H., and J. M. Robinson. 1985. *The Electronic Oracle: Computer Models and Social Decisions*. John Wiley & Sons, Suffolk.
- Meadows, D. L., W. W. Behrens III, R. F. Naill, J. Randers, and E. K. O. Zahn. 1974. *Dynamics of Growth in a Finite World*. Productivity Press Inc, Cambridge, Mass.
- Midgley, G. 2000. *Systemic Intervention: Philosophy, Methodology, and Practice*. Kluwer Academic / Plenum Publishers, New York.
- Midgley, G., I. Munlo, and M. Brown. 1998. The theory and practice of boundary critique: developing housing services for older people. *Journal of the Operational Research Society* 49(5):467–478.
- Millennium Institute. 2017. Official documentation of the iSDG model. <https://www.millennium-institute.org/documentation>.
- Mohammed, A. J. 2015. Sustainable Development: A Universal, Integrated, and Transformative Agenda. <https://www.diplomaticourier.com/posts/sustainable-development-a-universal-integrated-and-transformative-agenda>.
- NASA. 1988. *Earth System Science: A Closer View (The Bretherton Report)*. National Academies Press, Washington, D.C.
- National Academy of Sciences, National Academy of Engineering (US) and Institute of Medicine (US) Committee on Science, Engineering, and Public Policy. 2009. *On Being a Scientist: A Guide to Responsible Conduct in Research: Third Edition*. National Academies Press (US), Washington (DC).
- Nilsson, M., D. Griggs, and M. Visbeck. 2016. Policy: Map the interactions between Sustainable Development Goals. *Nature* 534(7607):320–322.
- Nussbaum, M. C. 2011. *Creating Capabilities: The Human Development Approach*. Harvard University Press, Boston.
- Nussbaum, M. C., and A. Sen, editors. 1993. *The Quality of life*. Clarendon Press; Oxford University Press, Oxford [England]; New York.
- OECD. 2015. *Better Policies for Development 2015: Policy Coherence and Green Growth*. OECD Publishing, Paris.

- O'Neill, B. C., T. Carter, K. Ebi, J. Edmonds, S. Hallegatte, E. Kemp-Benedict, E. Kriegler, L. Mearns, R. Moss, K. Riahi, B. van Ruijven, and D. van Vuuren. 2012. *Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research, Boulder, CO, November 2-4, 2011*. CIRED Working Papers, HAL.
- O'Neill, B. C., E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok, M. Levy, and W. Solecki. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* 42:169–180.
- O'Neill, D. W., A. L. Fanning, W. F. Lamb, and J. K. Steinberger. 2018. A good life for all within planetary boundaries. *Nature Sustainability* 1(2):88–95.
- Patterson, J., K. Schulz, J. Vervoort, S. van der Hel, O. Widerberg, C. Adler, M. Hurlbert, K. Anderton, M. Sethi, and A. Barau. 2017. Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions* 24:1–16.
- Pedercini, M. 2007. *Technical Documentation for the Threshold21 Starting Framework model*. Millennium Institute, Washington.
- Pedercini, M., S. Arquitt, and D. Chan. 2020. Integrated simulation for the 2030 agenda†. *System Dynamics Review* 36(3):333–357.
- Pedercini, M., S. Arquitt, D. Collste, and H. Herren. 2019. Harvesting synergy from sustainable development goal interactions. *Proceedings of the National Academy of Sciences* 116(46):23021–23028.
- Pedercini, M., G. Zuellich, K. Dianati, and S. Arquitt. 2018. Toward achieving Sustainable Development Goals in Ivory Coast: Simulating pathways to sustainable development. *Sustainable Development* 26:588–595.
- Pereira, L., N. Frantzeskaki, A. Hebinck, L. Charli-Joseph, S. Drimie, M. Dyer, H. Eakin, D. Galafassi, T. Karpouzoglou, F. Marshall, M.-L. Moore, P. Olsson, J. M. Siqueiros-García, P. van Zwanenberg, and J. M. Vervoort. 2020. Transformative spaces in the making: key lessons from nine cases in the Global South. *Sustainability Science* 15(1):161–178.
- Pereira, L., J. J. Kuiper, O. Selomane, A. P. D. Aguiar, G. R. Asrar, E. M. Bennett, R. Biggs, K. Calvin, S. Hedden, A. Hsu, J. Jabbour, N. King, A. C. Köberle, P. Lucas, J. Nel, A. V. Norström, G. Peterson, N. Sitas, C. Trisos, D. P. van Vuuren, J. Vervoort, and J. Ward. 2021. Advancing a toolkit of diverse futures approaches for global environmental assessments. *Ecosystems and People* 17(1):191–204.
- Pereira, L. M., T. Hichert, M. Hamann, R. Preiser, and R. Biggs. 2018. Using futures methods to create transformative spaces: visions of a good Anthropocene in southern Africa. *Ecology and Society* 23(1).

- Peterson, G. D., G. S. Cumming, and S. R. Carpenter. 2003. Scenario Planning: a Tool for Conservation in an Uncertain World. *Conservation Biology* 17(2):358–366.
- Pindyck, R. 2015. *The Use and Misuse of Models for Climate Policy*. Working Paper, National Bureau of Economic Research, Cambridge, MA.
- Ramage, M., and K. Shipp. 2020. *Systems Thinkers*. Springer London, London.
- Randers, J. 2013. *2052 – A Global Forecast for the Next Forty Years using a mix of models*.
- Randers, J., and U. Goluke. 2020. An earth system model shows self-sustained melting of permafrost even if all man-made GHG emissions stop in 2020. *Scientific Reports* 10(1):18456.
- Randers, J., U. Golüke, F. Wenstöp, and S. Wenstöp. 2016. A user-friendly earth system model of low complexity: the ESCIMO system dynamics model of global warming towards 2100. *Earth System Dynamics* 7(4):831–850.
- Randers, J., J. Rockström, P. E. Stoknes, U. Golüke, D. Collste, and S. E. Cornell. 2018. *Transformation is feasible: How to achieve the Sustainable Development Goals within Planetary Boundaries. A report to the Club of Rome, for its 50 years anniversary 17 October 2018*. Stockholm Resilience Centre.
- Randers, J., J. Rockström, P.-E. Stoknes, U. Goluke, D. Collste, S. E. Cornell, and J. Donges. 2019. Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability* Vol 2(e24):1–11.
- Raworth, K. 2012. A safe and just space for humanity: can we live within the doughnut. *Oxfam Policy and Practice: Climate Change and Resilience* 8(1):1–26.
- Raworth, K. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Random House Business, London.
- Reyers, B., C. Folke, M.-L. Moore, R. Biggs, and V. Galaz. 2018. Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene. *Annual Review of Environment and Resources* 43:267–289.
- Reyers, B., and E. R. Selig. 2020. Global targets that reveal the social–ecological interdependencies of sustainable development. *Nature Ecology & Evolution* 4(8):1011–1019.
- Rippin, N. 2014. How to avoid the silo structure of the Millennium Development Goals (MDGs). Pages 253–266 in J. Ye and T. Fues, editors. *The United Nations Post-2015 Agenda for Global Development: Perspectives from China and Europe*. German Development Institute, Bonn.
- Rockström, J. 2018. *5 transformational policies for a prosperous and sustainable world*. New York City.

- Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. I. Chapin, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. 2009a. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* 14(2):Art. 32.
- Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley. 2009b. A safe operating space for humanity. *Nature* 461(7263):472–475.
- Roy, J., P. Tscharket, H. Waisman, S. Abdul Halim, P. Antwi-Agyei, P. Dasgupta, B. Hayward, M. Kanninen, D. Liverman, C. Okereke, P. F. Pinho, K. Riahi, and A. G. Suarez Rodriguez. 2018. Sustainable development, poverty eradication and reducing inequalities. Page in V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, R. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, editors. *Global Warming of 1.5°C: An IPCC Special Report*. Cambridge University Press.
- Ruijs, A., M. van der Heide, and J. van den Berg. 2018. *Natural Capital Accounting for the Sustainable Development Goals. Current and potential uses and steps forward*. PBL Netherlands Environmental Assessment Agency, The Hague.
- Sachs, J. D. 2012. From Millennium Development Goals to Sustainable Development Goals. *The Lancet* 379(9832):2206–2211.
- Sachs, J., G. Schmidt-Traub, C. Kroll, D. Durand-Delacre, and K. Teksoz. 2016. *SDG Index & Dashboards - Global Report*. Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York.
- Saltelli, A., G. Bammer, I. Bruno, E. Charters, M. Di Fiore, E. Didier, W. Nelson Espeland, J. Kay, S. Lo Piano, D. Mayo, R. Pielke Jr, T. Portaluri, T. M. Porter, A. Puy, I. Rafols, J. R. Ravetz, E. Reinert, D. Sarewitz, P. B. Stark, A. Stirling, J. van der Sluijs, and P. Vineis. 2020. Five ways to ensure that models serve society: a manifesto. *Nature* 582(7813):482–484.
- Schmidt-Traub, G., C. Kroll, K. Teksoz, D. Durand-Delacre, and J. D. Sachs. 2017. National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. *Nat. Geosci.* 10(8):547–555.

- SDGC|A and SwedBio. 2018. *The African Dialogue on The World In 2050: How can agriculture contribute to meeting the SDGs? Report on a Multi-Actor Dialogue for TWI2050, 28–29 August 2017, Kigali, Rwanda*. Sustainable Development Goals Center for Africa and SwedBio/Stockholm Resilience Centre at Stockholm University.
- Sen, A. 1985. *Commodities and capabilities*. North-Holland, Amsterdam.
- Sen, A. 2001. *Development as Freedom*. Oxford University Press, Oxford.
- Sharpe, B. 2020. *THREE HORIZONS: the patterning of hope*. Triarchy Press, Chicago.
- Sharpe, B., A. Hodgson, G. Leicester, A. Lyon, and I. Fazey. 2016. Three horizons: a pathways practice for transformation. *Ecology and Society* 21(2).
- van Soest, H. L., D. P. van Vuuren, J. Hilaire, J. C. Minx, M. J. H. M. Harm- sen, V. Krey, A. Popp, K. Riahi, and G. Luderer. 2019. Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. *Global Transitions* 1:210–225.
- Steffen, W., P. J. Crutzen, and J. R. McNeill. 2007. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature? *Ambio* 36(8):614–621.
- Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Ben- nett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223):1259855–1259855.
- Steffen, W., J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liver- man, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann, and H. J. Schellnhuber. 2018. Trajectories of the Earth System in the An- thropocene. *Proceedings of the National Academy of Sciences* 115(33):8252–8259.
- Steffen, W., A. Sanderson, P. Tyson, J. Jäger, P. Matson, B. Moore III, F. Oldfield, K. Richardson, H. J. Schellnhuber, B. L. I. Turner, and R. J. Wasson, editors. 2004. *Global change and the earth system: a planet under pressure*. Springer, Berlin ; New York.
- Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill Higher Education, Boston.
- Subramanian, M. 2019. Anthropocene now: influential panel votes to recog- nize Earth’s new epoch. *Nature*.
- The Club of Rome. 1970. *The Predicament of Mankind: Quest for Structured Responses to Growing World-wide Complexities and Uncertainties. A Proposal*.
- TWI2050 - The World in 2050. 2018. *Transformations to Achieve the Sus- tainable Development Goals. Report prepared by The World in 2050 initiative*. IIASA, Laxenburg, Austria.

- TWI2050 - The World in 2050. 2019. *The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report prepared by the World in 2050 initiative*. IIASA, Laxenburg, Austria.
- TWI2050 - The World in 2050. 2020. *Innovations for Sustainability: Pathways to an efficient and sufficient post-pandemic future*. IIASA, Laxenburg, Austria.
- Ulrich, W. 1996. Critical Systems Thinking for Citizens. Pages 165–178 in R. L. Flood and N. R. A. Romm, editors. *Critical Systems Thinking: Current Research and Practice*. Springer US, Boston, MA.
- Ulrich, W. 2003. Beyond methodology choice: critical systems thinking as critically systemic discourse. *Journal of the Operational Research Society* 2003(54):325–342.
- Ulrich, W. 2005. A Brief Introduction to Critical Systems Heuristics (CSH). *ECOSENSUS Publications, Knowledge Media Institute (KMI), The Open University*.
- UN Environment. 2019. *Global Environment Outlook - GEO-6: Healthy Planet, Healthy People*.
- United Nations, editor. 1990. *Human development report 1990. Published for the United Nations (New York) Development Programme*. Oxford Univ. Pr, New York.
- United Nations. 2012. *The future we want, United Nations General Assembly resolution 66/288*. United Nations.
- United Nations. 2013. *A New Global Partnership: Eradicate Poverty And Transform Economies Through Sustainable Development-The Report of the High Level Panel of Eminent Persons on The Post-2015 Development Agenda*. United Nations, New York.
- United Nations. 2015. *Transforming our world: the 2030 Agenda for Sustainable Development, General Assembly resolution 70/1*. Resolution.
- United Nations. 2017. *Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development. General Assembly resolution 71/313*.
- United Nations, editor. 2018. *Working together: integration, institutions and the Sustainable Development Goals*. United Nations, New York.
- United Nations Development Programme. 2020. *Human development report 2020: The next frontier: Human Development and the Anthropocene*. United Nations Development Programme, New York.
- Vennix, J. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. John Wiley and Sons, Chichester.
- Victor, P. A. 2019. *Managing without growth: slower by design, not disaster*. Second edition. Edward Elgar Publishing, Cheltenham, UK.
- de Vries, B. J. M. 2013. *Sustainability science*. 1st ed. Cambridge University Press, New York, NY.
- Walker, B. H., and D. Salt. 2006. *Resilience thinking: sustaining ecosystems and people in a changing world*. Island Press, Washington, DC.

- Walker, B. H., and D. Salt. 2012. *Resilience practice: building capacity to absorb disturbance and maintain function*. Island Press, Washington.
- Waters, C. N., J. Zalasiewicz, C. Summerhayes, A. D. Barnosky, C. Poirier, A. Ga uszka, A. Cearreta, M. Edgeworth, E. C. Ellis, M. Ellis, C. Jeandel, R. Leinfelder, J. R. McNeill, D. d. Richter, W. Steffen, J. Syvitski, D. Vidas, M. Wagemich, M. Williams, A. Zhisheng, J. Grinevald, E. Odada, N. Oreskes, and A. P. Wolfe. 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* 351(6269):aad2622–aad2622.
- Weber, H. 2017. Politics of ‘Leaving No One Behind’: Contesting the 2030 Sustainable Development Goals Agenda. *Globalizations* 14(3):399–414.
- Weber, H., and M. Weber. 2020. When means of implementation meet Ecological Modernization Theory: A critical frame for thinking about the Sustainable Development Goals initiative. *World Development* 136:105129.
- Weitz, N., H. Carlsen, M. Nilsson, and K. Skånberg. 2018. Towards systemic and contextual priority setting for implementing the 2030 Agenda. *Sustainability Science* 13(2):531–548.
- Westley, F., S. R. Carpenter, W. A. Brock, C. S. Holling, and L. H. Gunderson. 2002. Why systems of people and nature are not just social and ecological systems. Pages 103–120 in L. H. Gunderson and C. S. Holling, editors. *Panarchy: understanding transformations in human and natural systems*. Washington, DC: Island Press.
- Wiek, A., and D. Iwaniec. 2014. Quality criteria for visions and visioning in sustainability science. *Sustainability Science* 9(4):497–512.
- World Commission on Environment and Development, editor. 1987. *Our common future*. Oxford University Press, Oxford ; New York.
- Zeng, Y., S. Maxwell, R. K. Runting, O. Venter, J. E. M. Watson, and L. R. Carrasco. 2020. Environmental destruction not avoided with the Sustainable Development Goals. *Nature Sustainability* 3(10):795–798.
- Zhou, X., and M. Moinuddin. 2017. *Sustainable development goals interlinkages and network analysis: a practical tool for SDG integration and policy coherence*. Institute for Global Environmental Strategies.
- Zimm, C., F. Sperling, and S. Busch. 2018. Identifying Sustainability and Knowledge Gaps in Socio-Economic Pathways Vis-à-Vis the Sustainable Development Goals. *Economies* 6(2):20.

# Index

- AdaptEconII, 44
- Aguiar, 48, 53, 62
- Allen, 15
- Anthropocene, 14, 21
- Barlas, 38
- Barney, 32, 50
- Bennich, 15, 25
- Biermann, 13, 23
- biosphere, 13
- boundary critique, 41
- Brundtland, 22, 28
- Bunge, 34, 35
- capabilities, 27, 61
- Cash, 15, 45
- Club of Rome, 20, 67
- Cornell, 15, 21, 45
- Criticisms of the 2030 Agenda, 25
- de Vries, 36
- doughnut economics, 29
- Doyal, 27
- Earth3, 44, 51, 52, 60
- Easterlin paradox, 61
- Easterly, 26
- Ecological economics, 28
- embedded view of sustainability, 28
- ethics, 67
- Folke, 13, 21, 39, 47
- Forrester, 20, 36
- Gaia hypothesis, 21
- general systems understanding, 15, 45
- Gough, 27
- Griggs, 13, 28
- Hickel, 25
- holism, 34
- Holling, 14, 21, 35
- Hughes, 14, 32
- Human Development Report, 28, 40
- human needs, 27, 61
- human well-being, 27, 60, 66
- individualism, 34
- indivisible, 25
- insights, 65
- Integrated Assessment Models, 31, 50
- Intergovernmental Panel on Climate Change, 21
- International Council for Science, 31
- International Geosphere-Biosphere Programme, 21
- iSDG, 50, 55, 68
- knowledge-action interface, 15, 45
- Leach, 24, 53
- Limits to Growth*, 20
- Lovelock, 21
- Margulis, 21
- Max-Neef, 27
- Meadows, 13, 20, 32, 36, 38, 40, 53, 68
- mental models, 36
- Millennium Development Goals, 23, 24
- Millennium Institute, 44, 50, 68
- Nussbaum, 27
- Paper I, 16, 55
- Paper II, 16, 58
- Paper III, 17, 60
- Paper IV, 17, 62
- pathways approach, 53
- Pedercini, 21, 31, 50, 58
- policy coherence, 13
- predicament of mankind, 20
- progress, 26
- Randers, 51, 53

Raworth, 29  
resilience, 21, 39  
Rio conference, 22, 29  
Rockström, 22  
Sachs, 23, 24  
SDG wedding cake, 29  
Sen, 27  
Shared Socioeconomic Pathways,  
53, 64  
Social-ecological systems, 21  
specified systems understanding,  
16, 45  
spillovers, 24  
Steffen, 14, 21, 22, 28  
Sterman, 36  
Stockholm conference, 22  
synergies, 58  
system dynamics, 36, 65  
systemic triangulation, 40  
systemism, 34  
systems thinking, 35  
the 2018 African Dialogue on the  
World in 2050, 62, 63, 64  
*The future we want*, 23  
the World in 2050, 29, 31, 45, 53,  
62  
Three Horizons, 62  
Threshold 21, 50, 55  
transdisciplinarity, 44  
transformation, 24  
UNDP, 28, 40  
United Nations, 22, 24  
universal, 24  
van der Leeuw, 24, 26  
Victor, 26  
Weber, 26  
world-Earth models, 22

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...det bästa det har inte hänt än, vad var det ni sa?  
- Laleh