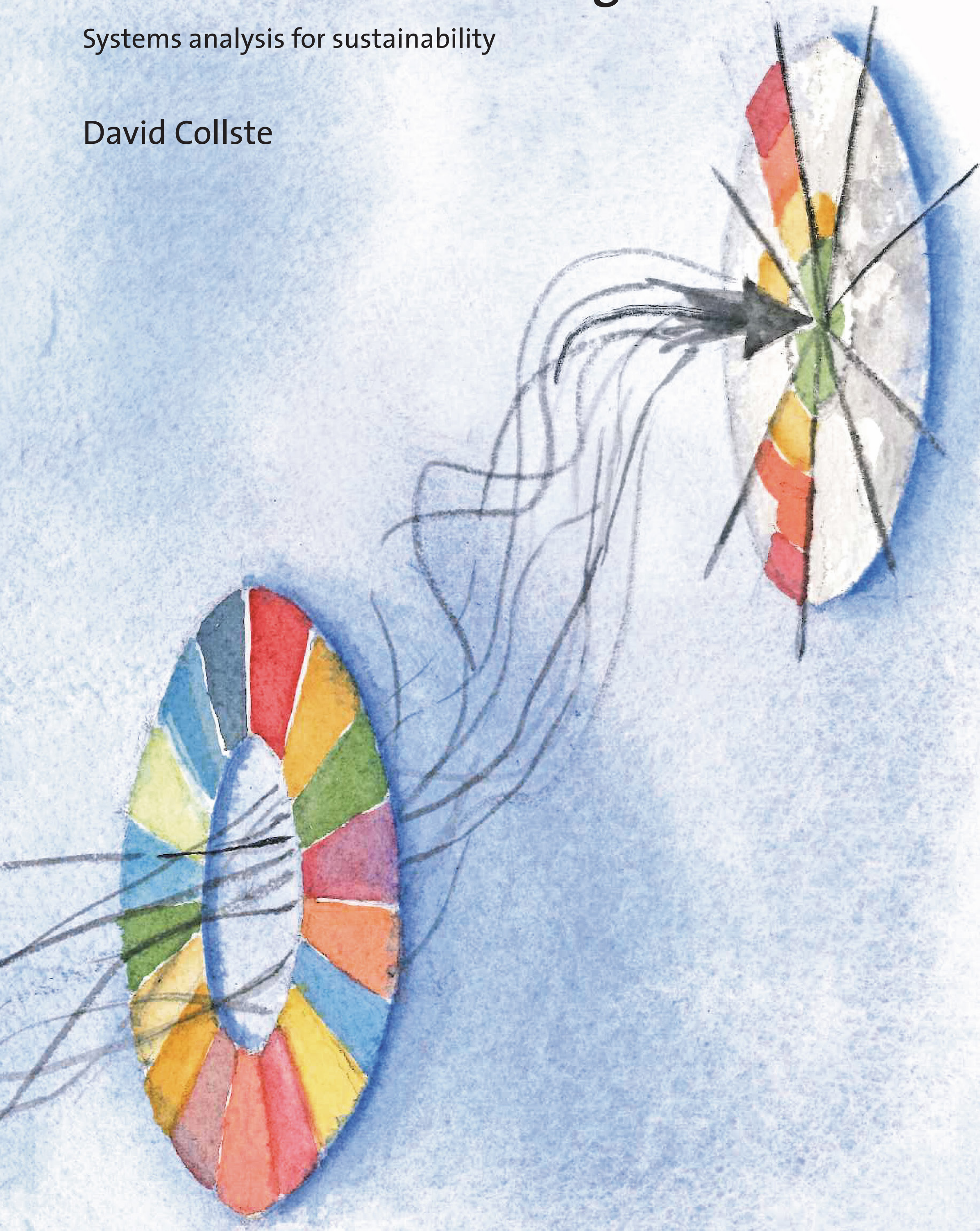
The Indivisible 2030 Agenda

Systems analysis for sustainability

David Collste



Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2021
Doctoral Thesis in Economics at Université Clermont Auvergne, France 2021

The Indivisible 2030 Agenda

Systems analysis for sustainability

David Collste

Academic dissertation for the Degree of Doctor of Philosophy in Sustainability Science at Stockholm University to be publicly defended on Thursday 3 June 2021 at 14.15 in Vivi Täckholmsslen (Q-salen), NPQ-huset and online via Zoom, public link is available at the Stockholm Resilience Centre website.

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.

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

Stockholm 2021
http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-192266

ISBN 978-91-7911-492-3
ISBN 978-91-7911-493-0

Stockholm Resilience Centre

Stockholm University, 106 91 Stockholm

Stockholm University

THE INDIVISIBLE 2030 AGENDA

David Collste

Stockholm University

The Indivisible 2030 Agenda

Systems analysis for sustainability

David Collste

ISBN print 978-91-7911-492-3
ISBN PDF 978-91-7911-493-0

The cover is painted by Christina Nilsson-Collste, from an original illustration by Jerker Lokrantz at Azote.

The photograph on the back of the cover was taken by Kristian Pohl.

Printed in Sweden by Universitetsservice US-AB, Stockholm 2021

Till mina föräldrar
Kicki och Göran.

This dissertation is submitted for a double doctorate degree in Sustainability Science, awarded by Stockholm University, and Economics, awarded by the University of Clermont Auvergne, through a bilateral cotutelle agreement.

Supervisors:

Dr. Sarah E. Cornell, Stockholm Resilience Centre, Stockholm University, Sweden
Dr. Arnaud Diemer, CERDI, Université Clermont Auvergne, France
Dr. Thomas Hahn, Stockholm Resilience Centre, Stockholm University, Sweden
Dr. Ana Paula Aguiar, Stockholm Resilience Centre, Stockholm University, Sweden

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675153

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 wellbeing 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.

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.

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, developpé 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 capabilités 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.

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.*

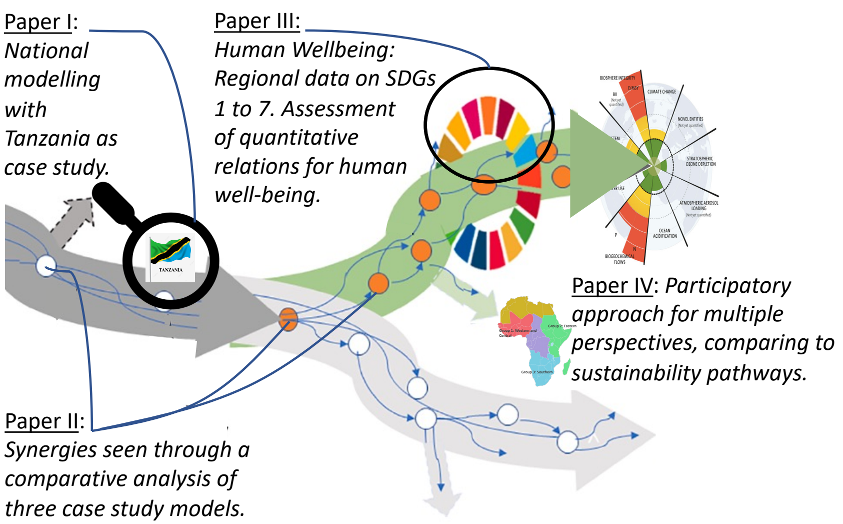
Contribution to included papers

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

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-dialouge_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

Contents

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 21st 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 manner. 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.

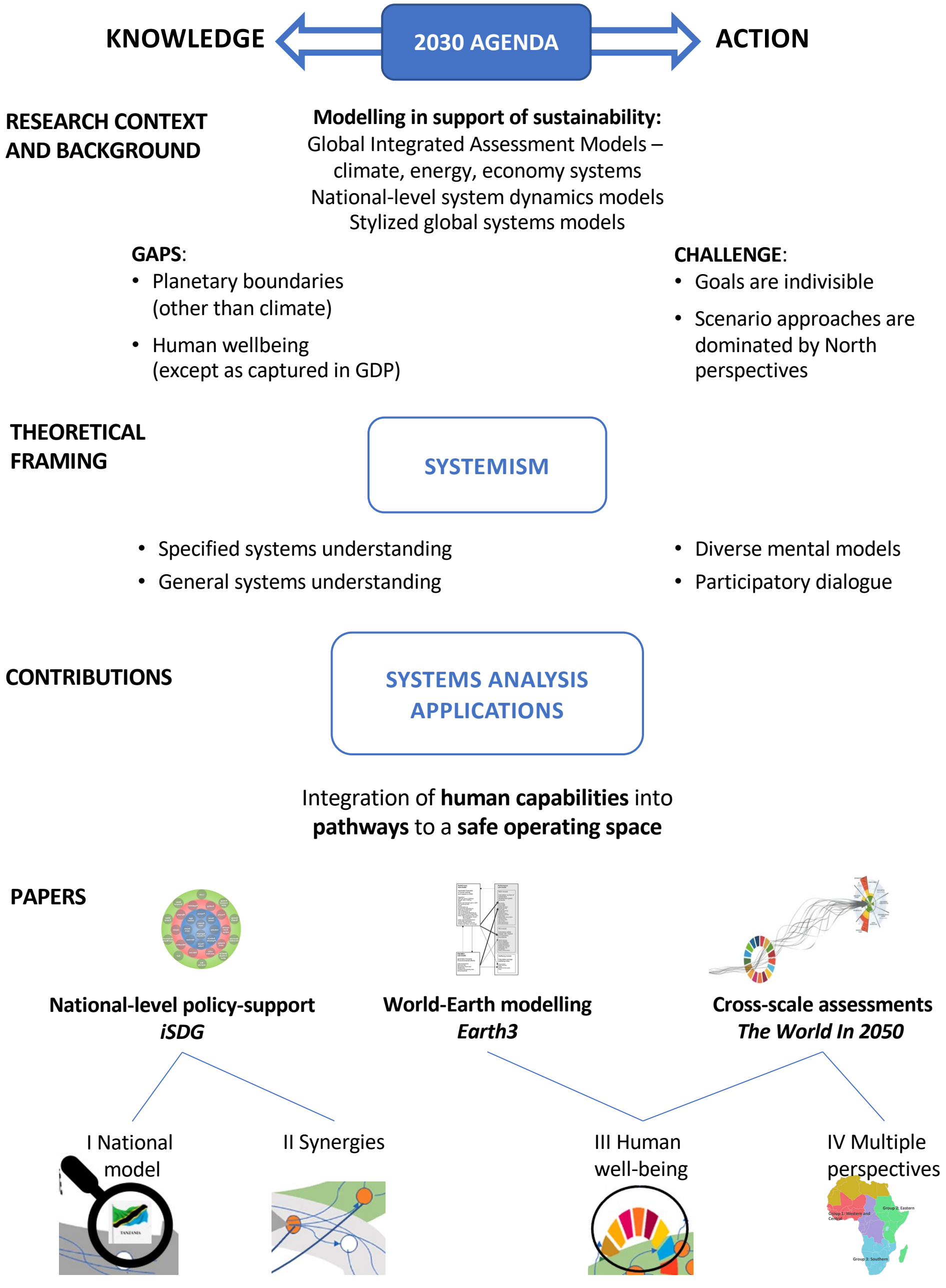


Figure 1: Overview of the thesis contribution and kappa structure.

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 21st 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[1] (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).

[1] 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 interlinked 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_2 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) 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.

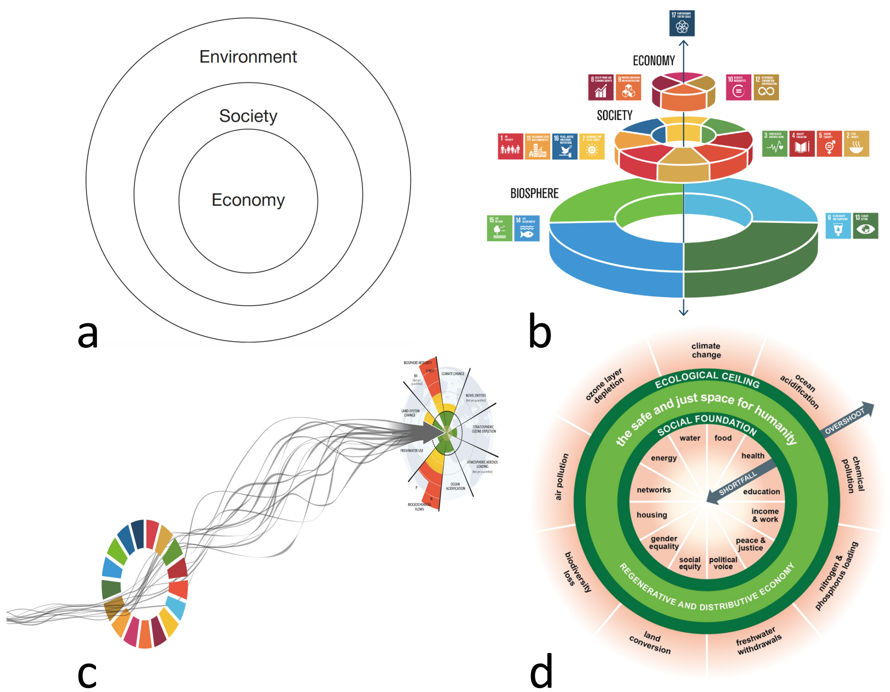


Figure 2 (a, b, c, and d): Four conceptualisations. 2a illustrates the ecological economics notion of the economy and society as embedded in the environment, 2b illustrates the 17 SDGs in a similar framework (Azote for Stockholm Resilience Centre). 2c illustrates a figure from the World in 2050 initiative (Illustration copyright: J. Lokrantz/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 makeup 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 3illustrates 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).

Macrolevel	Electricity coverage	→	Economic activity
	↓		↑
Microlevel	Hours of studying	→	Years in school

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.

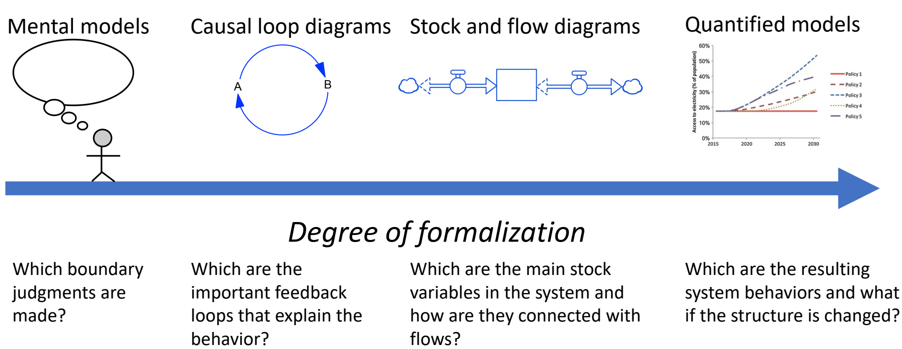


Figure 4: Mental models and formal models: An illustration of the different degrees of model formalisations in system dynamics.

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 beteen 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 modellers 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.

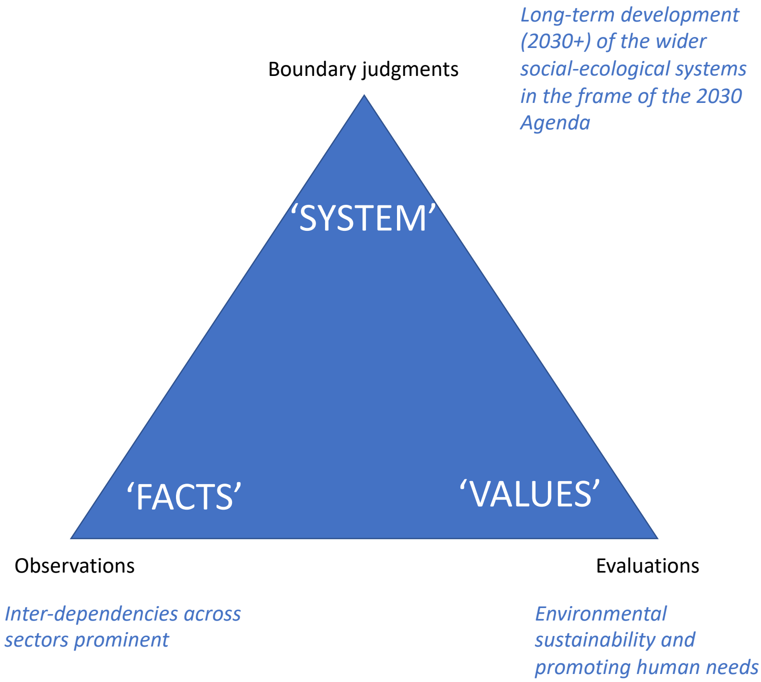


Figure 5: Ulrich's systemic triangulation links the system, facts, and values. The blue italic text indicates the application to the overarching scope of the thesis. Adapted from Ulrich 2003.

Throughout this dissertation, the term 'System' incorporates the long-term development of the wider social-ecological systems in the frame of the 2030 Agenda's goals and its overarching aims. (See *blue and italics* in Figure 5). This wide definition of the system is narrowed within the respective dissertation papers. 'Facts' include the general observations at the outset of the papers, suggesting that there are interdependencies across sectors crucial for operationalising the Agenda. Finally, a general demarcation of the 'Values' corner of the triangle seeks to harmonise environmental sustainability and promote human needs.

The main benefit of systemic triangulation is that it encourages and guides the application of systems methods to be considerate of, and to be explicit about, the judgments present in a particular study. This includes not only what relationships are included and how boundaries are drawn, but also considers values and goals. Considering systemic triangulation, the critique of any systems application - or knowledge claims in general - are either grounded in disagreement on values, facts or boundaries, or a combination of the three. Furthermore, 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_2, 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 50th 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 (Aguiar 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.

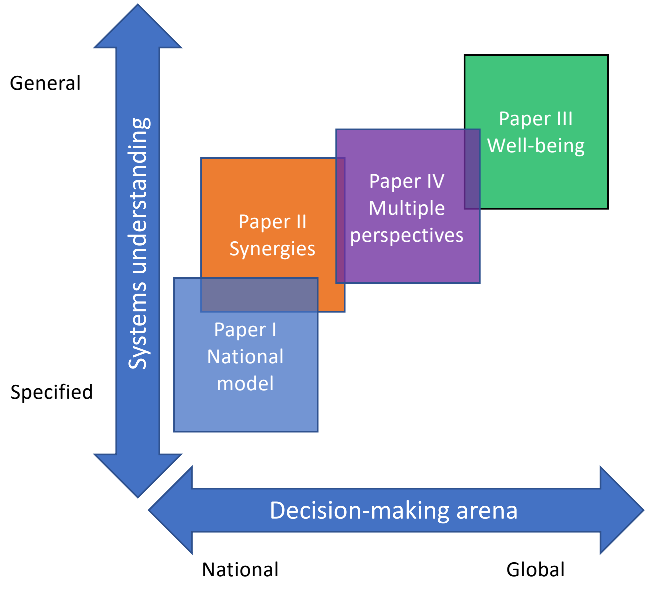


Figure 6: The four papers in the landscape of the knowledge-action interface of the 2030 Agenda. The papers are laid out in respect to the two dimensions, i.e., the type of systems understanding that they contribute to and the decision-making arena that they contribute to.

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.

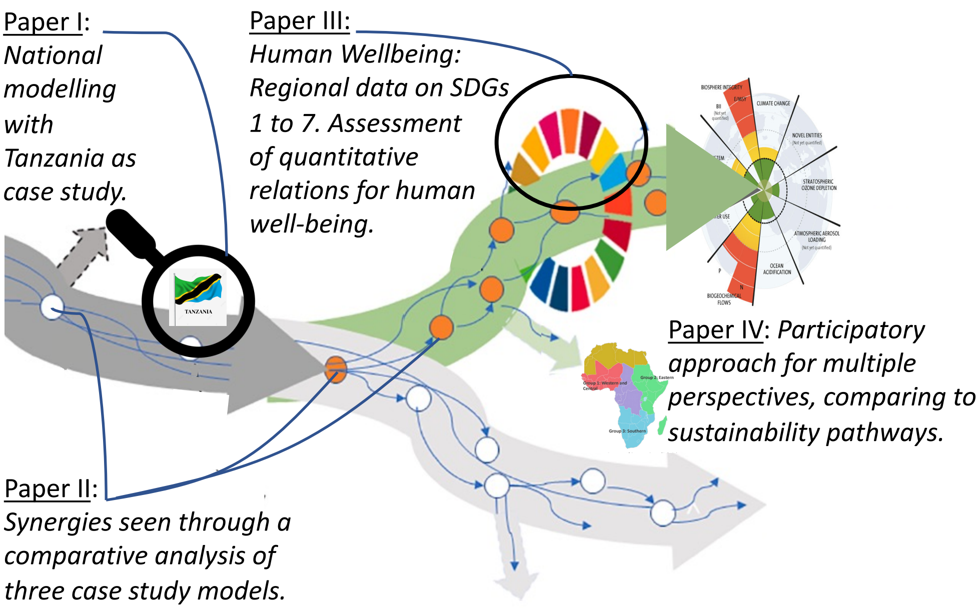


Figure 7: A conceptual figure showing the four thesis papers positioning on different aspects of pathways for global sustainability. Figure adapted from the figure in Aguiar, Collste, Harmáčková, Pereira, Selomane, Galafassi, van Vuuren and van der Leeuw. (2020), that was based on Fazey et al.(2016)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

Publication	Scale of analysis	Data types	Methods for data collection and analyses
Paper I National model	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.
Paper II Synergies	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.
Paper III Well-being	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.
Paper IV Multiple perspectives	Cross-scale: African sub-regions based on African Union classifications, and global sustainability narratives.	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 Earht3 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.

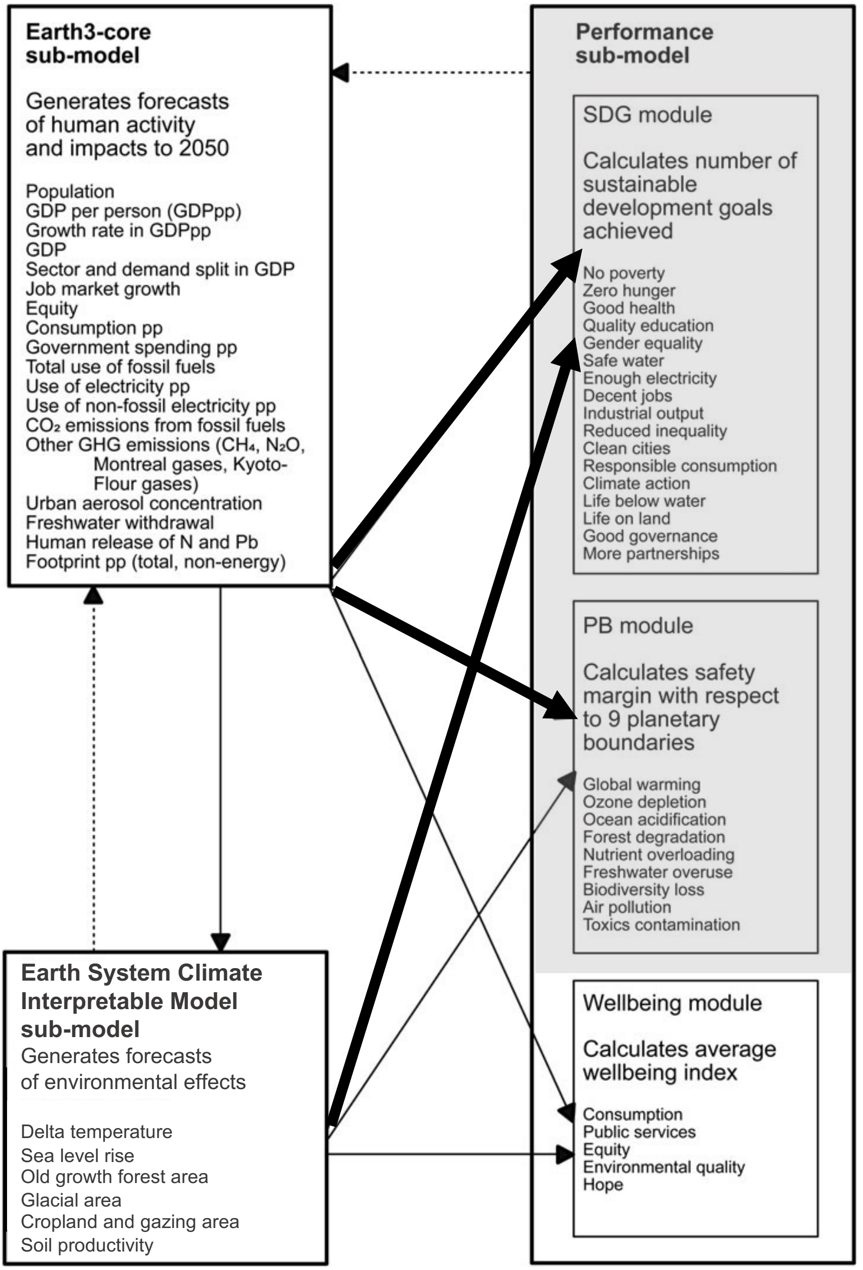


Figure 8: Overview of the Earth3 model system. My contribution is highlighted with the shaded area on the right side of the figure as well as with thick lines. Details in Goluke et al. (2018). Dashed lines indicate where added feedbacks would convert Earth3 into a full system dynamics model. Based on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

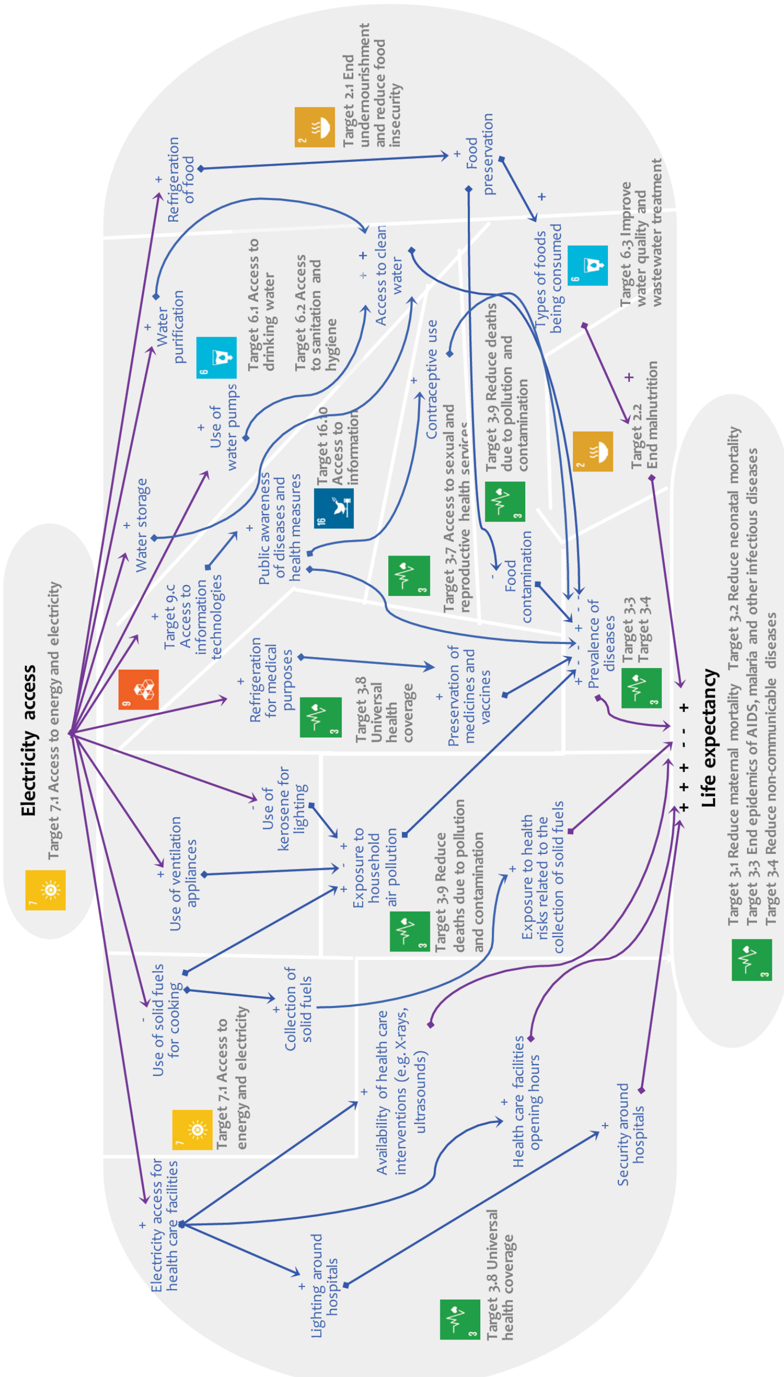


Figure 9: A modified version of Paper I's Figure 5 with SDG targets superimposed. Reprinted from United Nations 2018.

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).

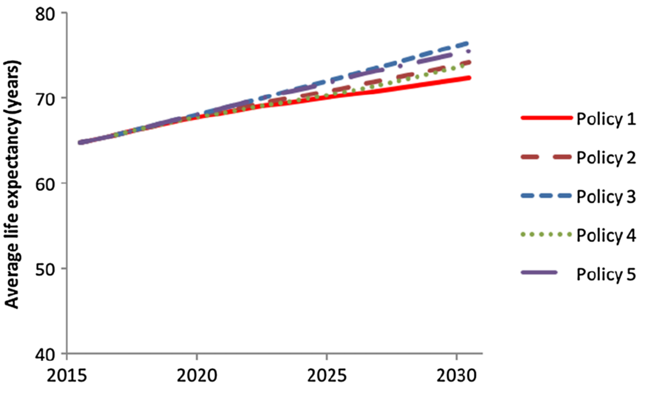


Figure 10: The simulated behaviour of life expectancy using the entire iSDG model, simulating the results of five different policies. Policy 1 incorporate no expenditure for large scale photovoltaic capacity, Policy 2 represents 1 % of GDP investments from 2016 to 2031, Policy 3 represents 3 % investments. 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.

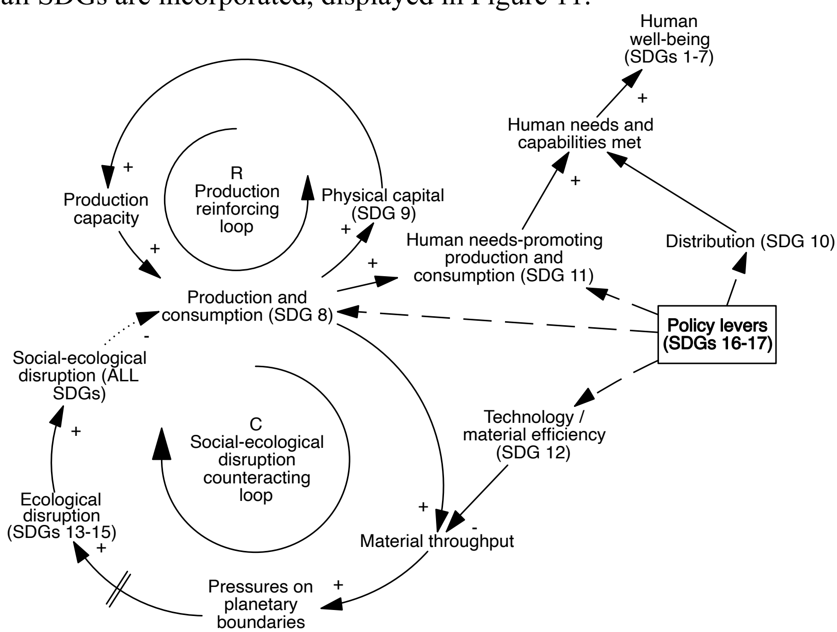


Figure 11: Conceptual sketch of key feedbacks and influences in World-Earth modelling within the Earth3 model. Each arrow represents a causal relationship. The '+' signs at the arrowhead indicate that the effect is positively related to the cause (e.g., an increase in production causes the material throughput 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 in 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.

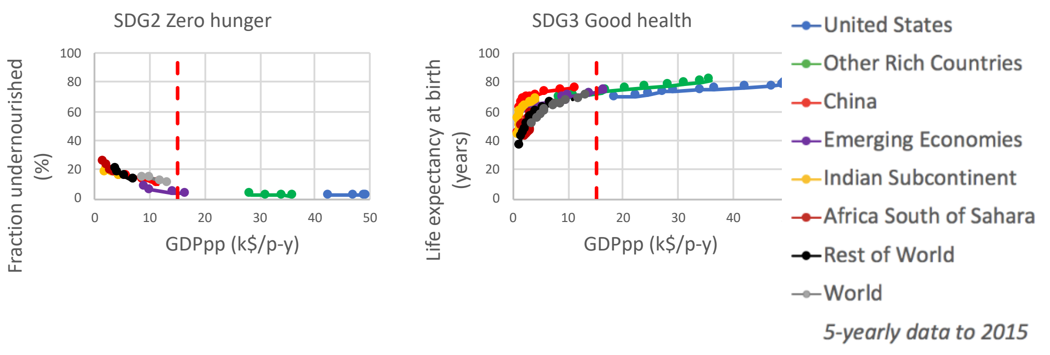


Figure 12: Data sources: All regions develop to increased GDPpp (measured in constant 2011 PPP \$). Vertical line represents GDPpp at 15k. Data sources: adapted from World Development Indicators, The World Bank, World Bank EdStats, UN Population statistics and Penn World Tables.

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.

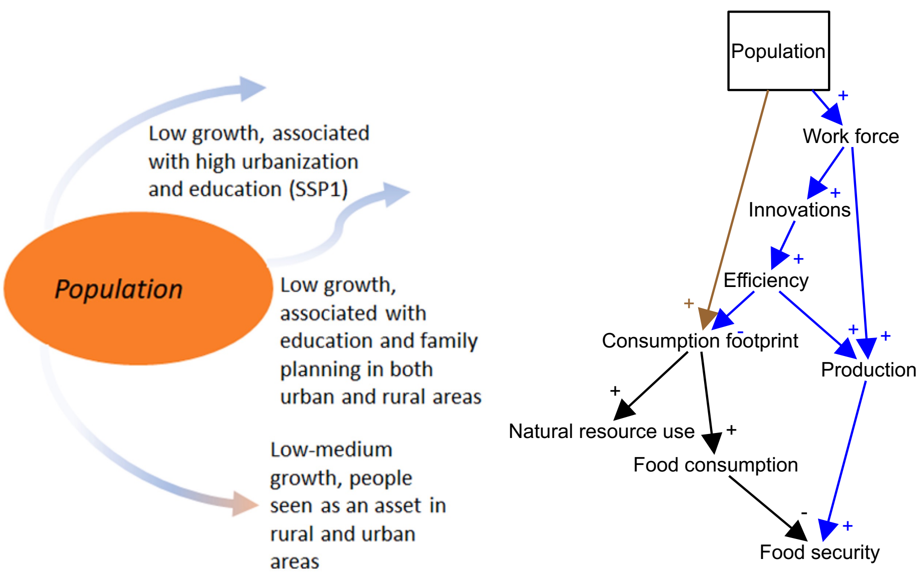
Pathway and unique features	Future visions
Ubuntu (West and Central Africa): Fully organic and cooperatives dominating.	Agriculture and food systems dominated by farmers' associations and cooperatives. Future characterised by diversity, inclusiveness, and agroecology.
Peaceful and Prosperous East Africa: 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.
Urugendo (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.
Rainbow (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 modellers, 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 50th 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 (Bennich, 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.

6.5 Financial support

For my PhD fellowship, I have received funding from the European Union's 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement no. 675153: Adaptation to a new economic reality (AdaptEconII).

Literature cited

Aguiar, A. P., D. Collste, D. Galafassi, Z. Harmáčková, K. Houngbedji, 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. Lebada, 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. *Sutainability 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 multiscale 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. Fuso-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. Zemelman, 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 Publichers, 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. Wenstøp, and S. Wenstøp. 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. Harmsen, 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. Bennett, 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. Liverman, 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 Anthropocene. *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 recognize 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 Sustainable 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. Wagreich, 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

Thank you

First of all, I would like to thank my supervisors. I want thank to Sarah Cornell, for showing me the way, for intellectual as well a personal support along these difficult and beautiful years. At our first supervisory meeting you told me that, in science, we are all equals and what matters is knowledge and ideas, and not who is sharing them. To move science forward we need to listen, talk and learn. I would also like to thank my co-supervisor Arnaud Diemer for welcoming me to Clermont-Ferrand with open arms, with runs in the mountains, and with intellectual guidance and support. Thank you for bringing people together. I would also like to thank my co-supervisor Ana Paula Aguiar for guiding me towards understanding of how much perspectives matters, and for emphasizing that emotions do belong to science. I want to thank my co-supervisor Thomas Hahn for guiding me towards pluralism in economics, for encouraging me to focus on my expertise and my disciplinary background.

I want to thank Vala Ragnarsdottir for starting the AdaptEcon project and enthusiastically showing that we are unstoppable – another world is possible. Thank you to Jenneth Parker for interesting philosophical discussions on critical realism, for welcoming me to Bristol and the Schumacher institute, despite the many lost emails.

I would like to thank Johan Rockström and Sarah Cornell for taking the risk to include me in what to me has been a world modelling dream project, in a vulnerable time of my life. I would like to thank the rest of the Earth3 modelling core team – Jorgen Randers, Per Espen Stoknes and Ulrich Goluke. It has been an honour to work together and I cannot wait to jump on the ongoing continuation of the project. A special thanks to Jorgen Randers for sharing the advice that the goal for a PhD student is to finish the thesis.

Besides Ana Paula Aguiar, I would like to thank the 2018 African Dialogue team, Zuzana Harmáčková for your sharp contributions to science, support and encouragements along the way. I would like to thank Laura Pereira, Odirilwe Selomane, Diego Galafassi and Sander van der Leeuw for great academic advices and good times together.

I would like to thank my internal reviewer Garry Peterson for feedback and encouragement on my thesis draft, thank you to Romina Martin for reviewing my licentiate thesis and providing feedback, and to Birgit Kopainsky, Therese Lindahl and Peter Søgaard Jørgensen for guiding me from the licentiate examination towards finalizing this PhD thesis.

Thank you to Göran Collste for support in proof reading my thesis kappa, and coming with critical questions. Thank you to English language expert Ami Golland for proof reading the thesis kappa and making it more understandable.

I want to thank Victor Galaz and Michele Lee-Moore for inviting me to together work on the SRC contribution to the 2020 Human development report. I want to thank Uno Svedin for the many hours of discussions about systems approaches to sustainability, and for emphasizing: architecture, architecture, architecture.

I would like to thank my academic mentor John M. Richardson for leading me to system dynamics and encouraging me along the way, and for writing the most inspiring book on world system modelling: DH Meadows, JM. Richardson and G Bruckmann (1982): *Groping in the dark: the first decade of global modelling*. Thank you, John, also for reminding of the brilliance of Dana Meadows and her writings. I would like to thank John and Jamila Haider, for bringing me to the fantastic Balaton group. I would like to thank the Balaton group for everything that I have learned from you.

I want to thank the Planetary Boundaries group at SRC, especially Celinda Palm, Avit Bhowmik, Andrea Downing, Tim DuBois, Lan Wang Erlandsson, Ingo Fetzer, Tiina Häyhä, Steven Lade, Patricia Villarubia. I am so glad for all your support over these years – personal and professional. I would like to thank Lisen Schultz for reaching out and being available for life-important shares. I would also like to thank Jenny Ohlsson, Carl Fredrik Wettermark, Maylat Mesfin, Andile Ngwenya Kalusokoma, May Hui and Sebastian Baayel for the invaluable support for me in Kigali.

I would like to thank SwedBio colleagues – including Hanna Wetterstrand, Maria Schultz, Pamela Cordero Fannkvist and Sara Elfstrand, for welcoming me at my first visit to SRC in 2015, and for all your support over these years.

I would like to thank the Millennium Institute team with modelling guru Matteo Pedercini and my idol Hans Herren.

I would like to thank Sturle H. Simonsen for helping me to be less shy in front of Zoom, and the rest of the amazing communication team at SRC for inviting the world to sustainability science.

I would like to thank the administrative support team at SRC for all the help and assistance.

I would like to thank Therese Bennich for sharing this research journey and being a close friend over the past eight years. Thank you, Jennifer Hinton, for being my closest colleague, sharing office, difficulties, happiness, laughter, encouragement and for showing what it means to be a friend.

A special thank you to Nathalie Spittler for being there for me. I want to thank Marie Schellens for friendship and for guiding through the Icelandic volcanoes and glaciers. To the rest of the amazing G12 team for discussions, laughter, cloth switches and great times.

I would like to thank Katja Malmborg for afternoon reflections, my favourite sweater, laughter and enormous support, and for singing Emmylou. I want to thank Victoria Voss Bignet for support, discussions and showing how music should be performed, and the many emotions it entails. I would like to thank Ashley Perl for being a supportive friend and for Vasaloppet, to Johanna Hedlund for mentoring, to Alice Dauriach for all support. I would like to thank the rest of the fantastic team of colleagues at SRC.

I would like to thank Andreas, Filip, Johannes, Torsten and Viktor for sharing life, discussing and for being there whenever I have needed it the most.

The beginning of this PhD, and the following years would not have been the same without the personal support, from the beginning to the end. Pernilla, without your support in the beginning of this journey and in my life, this would have been immensely more difficult. I am eternally grateful for your moment on Earth. Thank you also for bringing Ylva, Marika and all the rest to my life.

During these years of thesis writing and life, I have also been grateful for the support from my family. I am grateful for my mother, cover painter, Christina for artistic help with academic figures, for repeatedly showing me how beautiful this world is and what a blessing it is to live. I am grateful for Göran, for sharing a commitment to science, justice and for celebrating Djurgården victories. I would like to thank my sisters Jenny and Lisa for always, always being there for me, lately while having six children running around your feet. To my whole family, thank you for sharing the hardest time of my personal life and for carrying me when my feet have not been strong enough to walk.

Towards the last years of this journey, I would like to thank Kriszti for all your support on this journey, and for being by my side. For love, scientific discussions, laughter, yoga, encouragement and all the beautiful memories.

…det bästa det har inte hänt än, vad var det ni sa?

- Laleh

I

Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies

Sustain Sci (2017) 12:921–931
DOI 10.1007/s11625-017-0457-x

SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainability Science and Implementing the Sustainable Development Goals

Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies

David Collste[1] · Matteo Pedercini[2] · Sarah E. Cornell[1]

Received: 17 March 2017 / Accepted: 11 July 2017 / Published online: 26 July 2017

Abstract Coherently addressing the 17 Sustainable Development Goals requires planning tools that guide policy makers. Given the integrative nature of the SDGs, we believe that integrative modelling techniques are especially useful for this purpose. In this paper, we present and demonstrate the use of the new System Dynamics based iSDG family of models. We use a national model for Tanzania to analyse impacts of substantial investments in photovoltaic capacity. Our focus is on the impacts on three SDGs: SDG 3 on healthy lives and well-being, SDG 4 on education, and SDG 7 on energy. In our simulations, the investments in photovoltaics positively affect life expectancy, years of schooling and access to electricity. More importantly, the progress on these dimensions synergizes and leads to broader system-wide impacts. While this one national example illustrates the anticipated impact of an intervention in one specific area on several SDGs, the iSDG model can be used to support similar analyses for policies related to all the 17 SDGs, both individually and concurrently. We believe that integrated models such as the iSDG model can bring interlinks to the forefront and facilitate a shift to a discussion on development grounded in systems thinking.

Keywords Sustainable development goals · SDGs · Agenda 2030 · System dynamics · policy coherence · Integration · Trade-offs · Synergies · National development planning

Handled by Shunsuke Managi, Tohoku University, Japan.

✉ David Collste
david.collste@su.se

[1] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

[2] Millennium Institute, Washington, DC, USA

Introduction: the challenge of integration

The Agenda 2030 resolution includes 17 sustainable development goals (SDGs) that are described as *integrated* (United Nations 2015). This implies that the goals, and the effectiveness of the policies addressed to achieve them, depend on each other. Implementation efforts that isolate goals one by one and overlook these systemic interdependencies may hardly be fit for purpose. There are many efforts underway to measure sustainability progress, but to date these have been focused on measures of national and regional asset stocks, or ‘capitals’ (Dasgupta et al. 2015; Managi 2017). Instead, there is a need for integrative approaches that are capable of analysing and elucidating the dynamic effects of interdependencies. This need for approaches grounded in systems thinking has earlier been emphasized in the System Dynamics literature (Barney 2002; Richardson 2005; Kopainsky et al. 2010; and Saeed 2016).

An integrative implementation approach typically begins with identifying causal relationships between goals and policies. Nilsson et al. (2016) propose a simple framework for rating such relationships between SDG targets along a scale of interaction (also in International Council for Science 2016). Their ratings are: −3 cancelling, −2 counteracting, −1 constraining, 0 consistent, +1 enabling, +2 reinforcing, and +3 indivisible. Although useful as a first step in the conceptualization of linkages among the SDGs, the Nilsson et al. framework would benefit from being complemented with more quantitative and integrative simulation tools that support policy analysis. Such tools may complement the framework by enabling connections to be traced across several policies and targets, and identifying probable system-wide impacts of different policy choices.

Designing coherent policies requires acknowledging the corresponding system's feedback structure. A feedback is a chain of causal relationships that leads back to its origin. For example, if a country invests in education, this may over time, cause a more skilled labour force which may increase productivity. With an effective tax system, this increased productivity could lead to higher government revenues which enable new educational investments. This example of a virtuous cycle of education and productivity improvements involves significant delays, which may need to be considered for successfully assessing the long-term effects of policy choices. From a systems perspective, a multitude of such feedback loops act concurrently to shape a country's development (Wolstenholme 1983; Richardson 2005; Dangerfield 2008; Qureshi 2009; Kopainsky et al. 2010).

Integrated simulation tools assist policy makers in system-wide policy planning. Such tools or *models* may be considered as bookkeeping units where feedback structures have been identified and translated to conceptual maps and equations that capture dynamic behaviour. Accompanied by scientific insights about various relationships and enriched by data, models can be seen as policy 'flight simulators' (Richardson 1997; Sterman 2000; Sterman et al. 2013). Global System Dynamics simulation models have been used to assess problems relating to global commons and limits of material and population growth (Forrester 1971; Meadows et al. 1972; Meadows et al. 2004). Such models may, however, be too blunt and general to be used as tools for assessing the consequences of particular policies on national or sub-national levels, as they do not sufficiently match the policy makers' geographical scope and level of direct influence.

As most relevant policy making takes place on regional, national and sub-national levels, models that can bridge scales may be particularly useful (Häyhä et al. 2016).

In this paper, our objective is to demonstrate how integrated simulation models may be used to understand and develop scenarios to study synergies and trade-offs for progress on the SDGs on the national level. We present the newly developed *Threshold 21 iSDG model*. iSDG is a flexibly structured System Dynamics based model designed to explore scenarios for policy integration to achieve the SDGs. It builds on the well-vetted Threshold 21 model that has been applied to over 40 nations and has evolved over the past 30 years through research and application (Barney 2002; OECD 2016). The models are developed by the nonpartisan non-profit organization Millennium Institute (2017). iSDG is designed for regional, national and sub-national policy development, and is typically customized to be applicable to the specific contexts where it is to be used.

In this paper, we present an iSDG model with the focus on three SDGs: 3 (on health), 4 (on education) and 7 (on energy). These goals have clear causal interlinkages and relate to both socioeconomic and environmental aspects of sustainable development. Focusing on three goals assists in identifying potential synergies and bottlenecks related to these particular goals. We use one indicator for each goal: life expectancy for SDG 3, average years of schooling for SDG 4 and access to electricity for SDG 7.

To clearly demonstrate the model, we have chosen to zoom in on one country, Tanzania. In broad strokes, Tanzania is a low-income country in Sub-Saharan Africa, ranked 151 out of 182 countries in the UN's Human Development Index (United Nations Development Programme 2015). According to World Bank data, 43.5% of the population lives on less than $1.25 a day (on a purchasing power parity basis) (World Bank 2015). Electricity access was 15.3% in 2012 and average years of schooling 5.81 years (Barro and Lee 2015; World Bank 2016).

As a policy intervention to study scenarios, we use investments in photovoltaics. Investments in photovoltaics are directly relevant to SDG 7 on energy, are highly relevant to the environmental dimension of sustainable development, and substantial energy investments has been put forward as an enabler for both social and economic development (Modi et al. 2006). Thereby, we expect that impacts on SDG 7 also will affect the progress on SDGs 3 (health) and 4 (education). Furthermore, as a renewable energy source with limited emissions we do not expect clear counteracting effects, such as reduced air quality, which would likely have been the result of coal plant investments. In the subsequent simulations, we identify the expected effects of yearly investments of 1–3% of GDP in photovoltaics, between 2015 and 2031.

Materials and methods: system dynamics and the iSDG model

System dynamics

System Dynamics is a discipline and a systems analysis approach that is used to study behavioural patterns of systems. The behavioural patterns are analysed as the outcomes of complex systems in which variables are causally connected in feedback loops. Models are constructed as simplified representations of real-world systems, and are used to facilitate learning about the hypothesized causal structure and behaviour of the real-world systems. System dynamics typically use both cognitive maps, such as causal loop diagrams, and simulation models. In the simulation models, the mathematical representations are combined with interfaces that make the assumptions about causalities explicit. This typically enables exploring different what-if questions and performing sensitivity tests to explore potential system-level leverage points. In mathematical terms, system dynamics models consist of series of integrals, also referred to as stocks or accumulations; and derivatives, referred to as flows (Axelrod 2003; Ford 2009; Sterman 2000; Meadows 2008; Richardson 2005).

Variables that are related to the iSDG model can be separated into three categories:

- *Endogenous variables* are variables that are derived from (that is, depend on) other variables from within the model.
- *Exogenous variables* are given from outside the model, and
- *Excluded variables* are variables that are not included in the model.

(Following the approach of Sterman 2000; Ford 2009).

Building confidence in a system dynamics model entails ensuring its causal relationships are credible. Qualitative aspects of the model are, therefore, often in focus. Model validity requires having a thorough and well-supported theory of causality in addition to more quantifiable validation criteria (Barlas 1996).

The iSDG model

The iSDG model is designed to assist in development planning by providing a credible representation of real-world development. iSDG, like its forerunner Threshold 21, is based on feedbacks between and within three main sectors that may be referred to as *environment*, *society* and *economy and governance*, Fig. 1.

Each sector consists of 10 subsectors, as displayed in Fig. 2. Within these sectors, the iSDG model includes more than 1000 stock variables. It is, therefore, not possible here to give a detailed presentation of the entire model. Instead, we outline a few simplified examples of model structure when explaining the key components of our demonstration case of the effects of investments in photovoltaics and the feedbacks between SDGs 3, 4 and 7 for Tanzania. Documentation of the iSDG model structure can be found at http://isdgs.org (Millennium Institute 2016), and the full model may be shared upon request.

Variables in focus for development planning are modelled as endogenous. These include for example aggregate production, population, the demand and supply of energy, and their determinants. Modelling these variables as endogenous enables the model to be used to explore a systems perspective of development. The allocation of public resources between different subsectors of government is typically modelled exogenously, to enable the exploration of alternative scenarios for national development planning, by varying the budget allocations.

The adoption of Agenda 2030 and the increased availability of relevant literature and data have supported enriching the iSDG model structure with additional relationships between various SDGs. Strengthening the feedback network across the SDGs makes the model correspond better to reality, and provides a more accurate representation of development processes and their contribution to the system's behaviour. In addition, a better mapping of the relationships between the goals is becoming increasingly relevant both in the academic (Nilsson et al. 2016) and political arenas (United Nations 2015). Strengthening the feedback network may, therefore, also make the model more policy relevant.

In our development of an applied iSDG model, we note prime characteristics of system dynamics model formulations (Forrester 1992; Barlas 1996): the use of diverse data sources and the focus on anticipated causal structure and qualitative aspects of models in model validation.

As the intention is to provide a credible, well-grounded and useful hypothesis of the overall causal structure of a country's development, *data sources* used are not restricted to numerical data, for example, from national account databases, but can also incorporate other sources of information. These include qualitative theories of causal relationships from literature, and data from diverse experiences provided through expert or stakeholder interviews (Forrester 1992). As the first national customization of the iSDG model, the calibration process of applying the model to Tanzania was based on earlier Threshold 21 models (Kopainsky et al. 2015; UNEP 2015; Allen et al. 2016), relationships included in published papers, and publicly available data. The main numerical data sources used were the World Bank and International Energy Agency. Typically, however, the Millennium Institute's calibration process also includes interviewing stakeholders, iterating between different possible model formulations, and investigating their respective consequences for the anticipated model behaviour.

Both the quantitative behaviour of the model (its outputs) and its causal hypotheses need to be supported with evidence. With the aspiration to create credible causal hypotheses of national development, *model validation* of the iSDG model includes both comparing the model's behaviour with data on historical behaviour, and qualitatively and quantitatively studying model formulations in isolation and combined with the rest of the model.

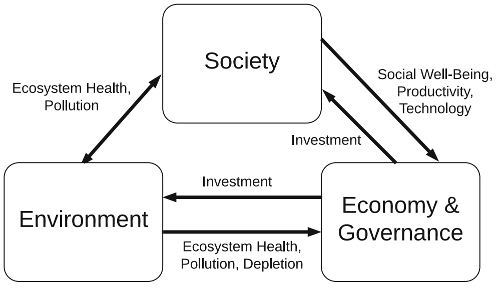


Fig. 1 Main sectors of the iSDG model. Based on Barney (2002)

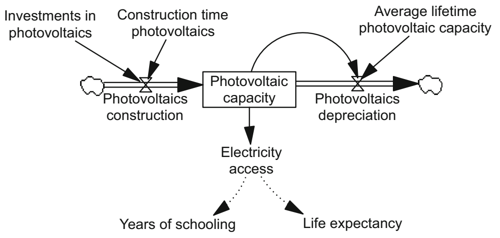


Fig. 3 A simplified system dynamics representation of the photovoltaic electricity capacity part of the model

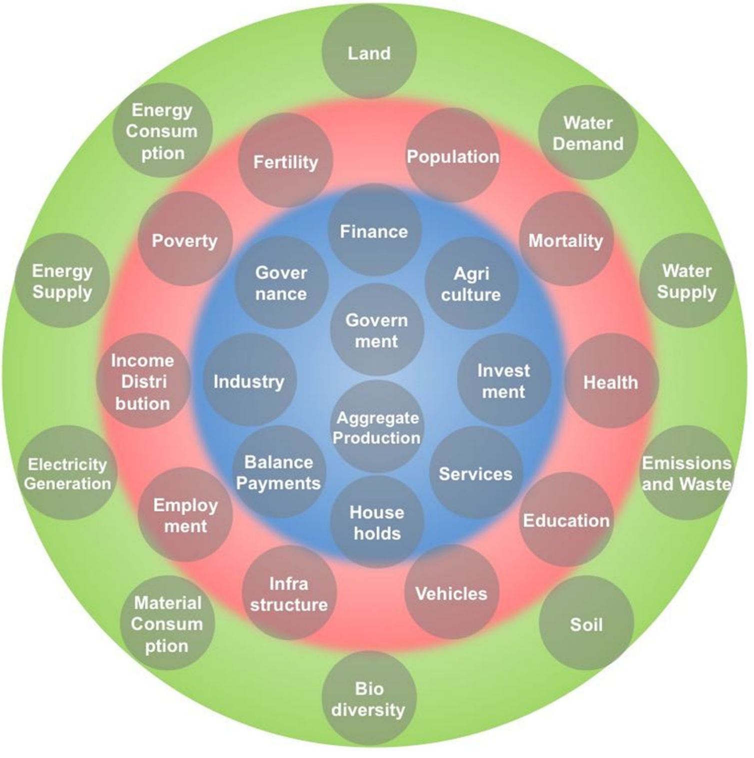


Fig. 2 Overview of the iSDG subsectors. The *outer green* field includes the environment subsectors, the *middle red* field the society subsectors and the *inner green* field the economy and governance subsectors. Source: Millennium Institute (2016)

An example of iSDG model structure: the construction of photovoltaic capacity

One piece of the new iSDG model structure relates to the construction of photovoltaic electricity capacity, of which a simplified representation is portrayed in Fig. 3.

The arrows in Fig. 3 represent causal relationships. All variables are presented as labels in the Figure. *Photovoltaics construction* is portrayed as a function of the variables *Investments in photovoltaics* and *Construction time photovoltaics*. The more *Investments in photovoltaics*, the more capacity is constructed. The longer the *Construction time photovoltaics*, the slower the construction process. The box in the middle represents *Photovoltaic capacity* as a stock variable, which accumulates over time. The constructed photovoltaics have an average lifetime before they depreciate, represented by the outflow to the right of *Photovoltaics capacity*. Parameter values for all these variables were derived from the International Energy Agency's estimates. The *Photovoltaics depreciation* flow is a function of *Photovoltaic capacity* and the *Average lifetime photovoltaic capacity.*[1] *Photovoltaic capacity* affects *Electricity access,* which in turn affects *Years of schooling* and *Life expectancy*. These links are discussed below.

The output obtained from running the entire iSDG model was compared with historical data for 1990–2015 for selected variables, including GDP, life expectancy, electricity access and years of schooling. The model output matched the historical behaviour well, which increased our confidence in using the model to explore plausible future scenarios incorporating policies that include significant investments in photovoltaics.

Mapping causalities

In this section, we explore causal relationships between SDGs 3, 4 and 7, identify model modifications to enable an investigation of an energy system intervention (investment in photovoltaics), and outline how these are incorporated into the iSDG model structure.

Relationships between SDGs 3, 4 and 7

Causal links between access to electricity, life expectancy and years of schooling may be presented as causal pathways including chains of causal connections where the final outcomes depend on interaction between various factors. By focusing on three of the SDGs we have six such potential causal chains (Fig. 4). The causal chain from education to health has already been included in the earlier version of the Threshold 21 model, so it will not be further discussed here.

Each causal chain may be either positive or negative. For example, *life expectancy* may affect *years of schooling* either positively (that is, *higher life expectancy* causes an increase in *years of schooling*) or negatively (i.e. *higher life expectancy* causes a decrease in *years of schooling*), and *years of schooling* may, in turn, affect *life expectancy* either positively or negatively. Moreover, significant delays between the parts of the chains may exist, e.g. it may take time for improvements in early childhood nutritional status to affect educational outcomes. Below, we go through each causal chain separately.

[1] Note that the depreciation function averages the lifetime of the constructed photovoltaics. In a more detailed study on the constructed capacity, *photovoltaic capacity* may be separated into different age cohorts based on when the capacity was constructed. The iSDG model allows for such modifications, to reflect technical innovation.

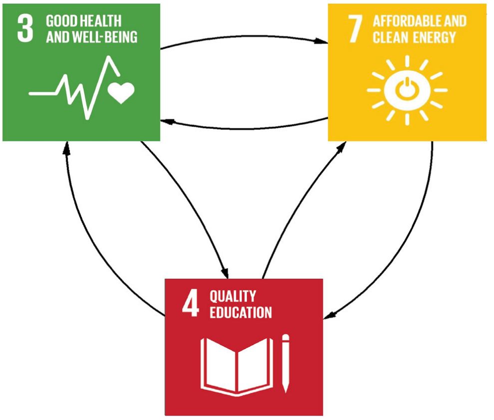


Fig. 4 Potential causal chains between electricity access, life expectancy and years of schooling. Note that the many intermediates through which the effects are channelled are not included in the Figure

The effect of electricity access on life expectancy

Incorporating a positive causal relationship from electricity access to life expectancy may be justified based on the following reasoning (Abdelkarim et al. 2014; Ezzati et al. 2004; Khandker et al. 2013; Lim et al. 2012; Modi et al. 2006; The World Bank 2008):

- Access to electricity reduces the use of solid fuels and kerosene for cooking and lighting. The use of solid fuels and kerosene for cooking is common practice in many countries. The consequential indoor air pollution causes many diseases and has severe health effects. Electricity access enables the use of alternative sources for heating and lighting, such as electric kettles and light bulbs, and also enables the use of ventilation appliances. There are also health risks related to fuel collection that can be decreased through the provision of electricity.
- Electric appliances may improve food preservation, which both reduces contamination and enables an increase in the variety of foods that are being consumed. Electricity may also enable the use of electric water pumps and water purification techniques. All this is beneficial for health.
- Electricity access enables refrigeration for medical purposes and improves health care infrastructure. For example, refrigerated medicines and vaccines may be stored for longer; health care facilities with electric lighting can be open after dark, and electricity enables the use of many health services and interventions such as x-rays and ultra-sounds.

- With electricity access, information technology can be used to spread public awareness and knowledge related to for example diseases and health practices.

The causal pathways between electricity access and life expectancy are summarized in the diamond diagram in Fig. 5. Together, these points clearly indicate a positive causal relationship between electricity access and life expectancy. This is incorporated into the national level application of the iSDG model by a single positive link from *electricity access* to *life expectancy*.

The effect of electricity access on average years of schooling

Several arguments point to causal relationships from electricity access to average years of schooling:

- Electricity access enables students to spend more time studying through better light quality, longer duration of lighting, and decreased time spent on collecting water and fuel. A study in Vietnam indicated that electricity access attributed to an increase school attendance by 0.13 years for boys and almost one year for girls (Khandker et al. 2013).
- Learning conditions are improved by access to information communication technologies. Access to electricity in rural areas may also increase the areas' attractiveness for good quality teachers.

Although the major effects of electrification on years of schooling appear to be positive, the literature also suggests potential negative effects. Abdelkarim et al. (2014) and Modi et al. (2006) suggest that entertainment activities enabled by electricity, such as TV watching, may outcompete studying. Electricity access may also increase the job opportunities in the productive sector, which could affect educational attainment negatively. Provided that these potential negative effects do not dominate, the points together indicate a positive causal relationship from electricity access to average years of schooling. This was incorporated into the iSDG model structure.

The effect of life expectancy on years of schooling

The existence of a positive causal relationship from life expectancy (or more specifically, life expectancy as an indicator for health) to average years of schooling may be justified based on the following:

- Healthy students are more present in school, are physically better prepared for studying, and are likely to stay in school for more years. In a study using household survey data from rural areas in China, Zhao

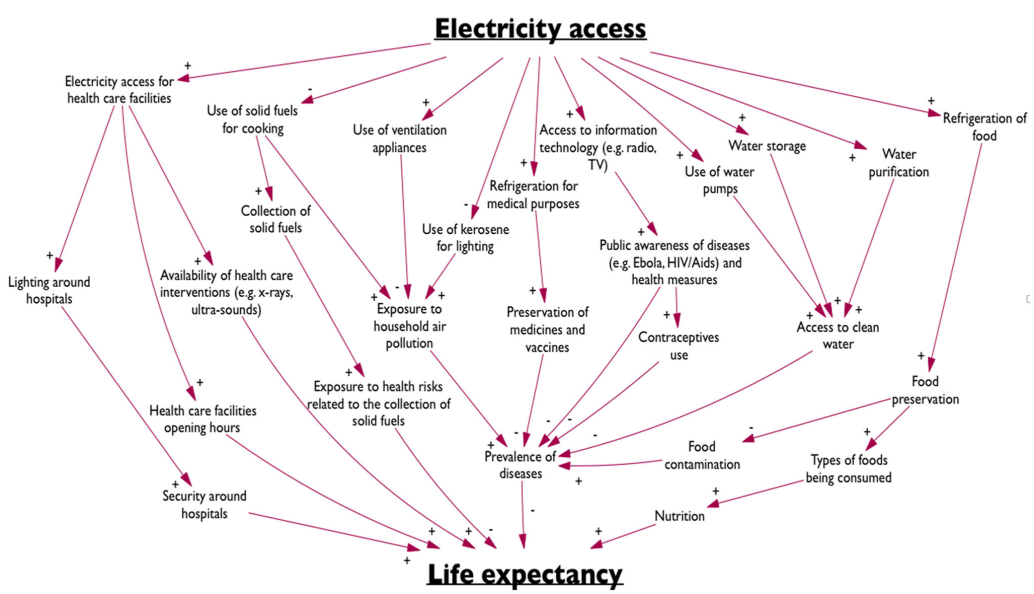


Fig. 5 A causal map displaying the relationships between electricity access and life expectancy (referred to as a 'diamond diagram'). A '+'-sign represents a ceteris paribus positive causal relationships (an increase in A causes B to increase, all things equal) and a '-'-sign represents a ceteris paribus negative causal relationship (an increase in A causes B to decrease, all things equal)

and Glewwe (2010) found evidence indicating that children's nutritional status early in life had a significant effect on completed years of schooling. (Cutler and Lleras-Muney 2006)

This supports adding a causal link from life expectancy to years of schooling in the iSDG model.

The effect of life expectancy on electricity access and the effect of years of schooling on electricity access

There seem to be less evidence of causal chains from life expectancy to electricity access, and from years of schooling to electricity access, beside via the productivity effects of health and education. However, we can surmise that a healthy and educated population may take better care of, and upgrade, electrical infrastructure and equipment. Also, education may enable the use of more advanced electrical equipment, which could increase the demand for electricity access.

Resulting links

The literature has provided a basis for positive causal chains between electricity access and years of schooling and electricity access and life expectancy. Furthermore, there seem to be bidirectional causality between years of schooling and life expectancy. We did not find strong support for causal chains that go from life expectancy and years of schooling to electricity access, except for via productivity.

When incorporating the new links into the existing model structure, new reinforcing feedback loops are initiated, displayed in Fig. 6. These three reinforcing feedback loops are labelled R1, R2 and R3. R1 may be referred to as the *Electricity access—years of schooling reinforcing loop* and displays that an increase in electricity access causes an increase in years of schooling which, in turn, leads to productivity improvements. Increases in productivity means an increase in GDP which, through increased both government and private funding, enable further investments in electricity which improves its access. R2 could be labelled the *Electricity access—life expectancy* reinforcing loop. It displays the assumptions that electricity access improves life expectancy which increases productivity. As is assumed in the R1 loop, improved productivity, over time, causes an increase in electricity access. Finally, the R3 loop that we may label the *Years of schooling-life expectancy* reinforcing loop portrays the assumption that improvements in years of schooling are beneficial for health and causes improved life expectancy which, in turn, causes an increase in school attendance. There are significant delays inherent in the feedbacks, e.g. it takes many years for improvements in education to affect a country's productivity. These delays have been incorporated into the model structure.

The added links make the iSDG model incorporate synergizing impacts between the SDGs 3, 4 and 7. Based on the existing literature we have identified reasonable ranges for parameter values related to these links. We have further indirectly calibrated the relationships by fitting them to historical data for the period 1990–2015 using partial model testing (Homer 2012).

Incorporating an intervention: investments in photovoltaic capacity

In addition to the causal links added between SDGs 3, 4 and 7, model structure associated with the construction of photovoltaic capacity was incorporated into iSDG. This enables simulating plausible future scenarios that include investments in photovoltaic capacity. Investments in photovoltaics are represented by the dashed line in Fig. 6.

Five different investment policies were considered, ranging from no investments to yearly investments of 3% of GDP (Table 1). All investments are modelled as additional government expenditure, financed through additional financing from financial markets. Accordingly, the policies also imply increased costs for government loans which are endogenous in the iSDG model formulation.

Simulation results

The simulated behaviour of electricity access, years of schooling and life expectancy with the photovoltaics investment policies are presented in Figs. 7, 8 and 9.

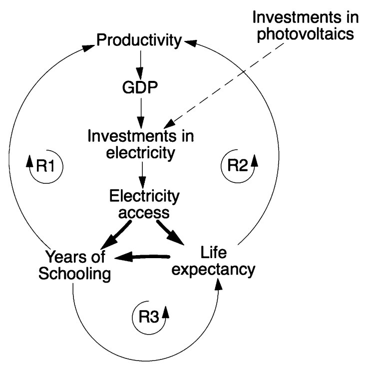


Fig. 6 A simplified causal loop diagram displaying the discussed relationships. Each *arrow* represents a positive causal relationship. The *three bold arrows* represent the links that were added to the model. R1, R2 and R3 represents reinforcing loops initiated by the added links

Table 1 Policy options explored using the iSDG Tanzania model

Name	Explanation
Policy 1	No expenditure for large scale photovoltaic capacity
Policy 2	1% of GDP expenditures for large scale photovoltaics 2016–2031
Policy 3	3% of GDP expenditures for large scale photovoltaics 2016–2031
Policy 4	0% of GDP expenditures for large scale photovoltaics 2016–2020
	1% of GDP expenditures for large scale photovoltaics 2020–2025
	2% of GDP expenditures for large scale photovoltaics 2025–2030
	3% of GDP expenditures for large scale photovoltaics 2030–2031
Policy 5	3% of GDP expenditures for large scale photovoltaics 2016–2020
	2% of GDP expenditures for large scale photovoltaics 2020–2025
	1% of GDP expenditures for large scale photovoltaics 2030–2031

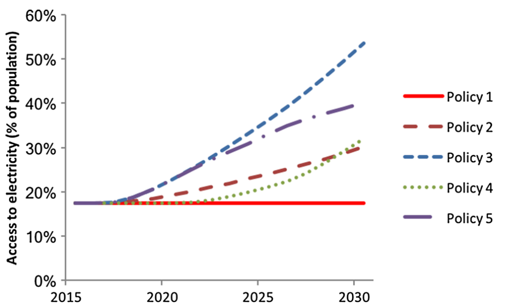


Fig. 7 Simulated behaviour of electricity access for the five policy options with the entire iSDG model simulated

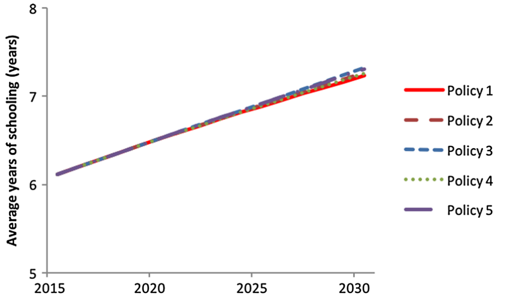


Fig. 8 Simulated behaviour of average years of schooling for the five policy options with the entire iSDG model simulated

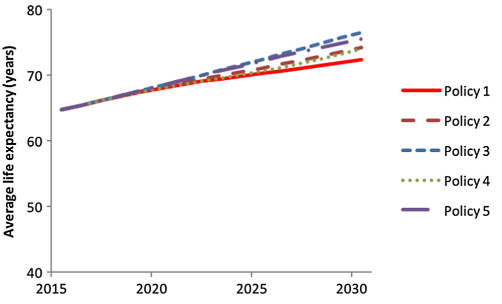


Fig. 9 Simulated behaviour of life expectancy for the five policy options with the entire iSDG model simulated

The shape of the behaviour of electricity access displayed in Fig. 7 comes as no surprise, as it relates directly to the added investments in photovoltaics in the policy. However, the change is not merely a direct result of these investments. By going back and forth between the model's causal structure and the simulations, we are able to trace the causalities that affect the model's overall behaviour. We observe that the effects of the investments are reinforced through their effects on productivity which enables increased future photovoltaic investments (note that investments are added as shares of GDP). Also, the causal chains incorporated in the model that goes via health and education (R1, R2 and R3 in Fig. 6) amplify this reinforcement—the loops synergize. All this contributes to the exponential trend of electricity access for policies 2, 3 and 4.

For average years of schooling (Fig. 8), the simulated differences between the policy options are fairly small. This is because of the long delays incorporated in the model structure related to average years of schooling. Average years of schooling represent the average for the entire population, not just the children currently in school. This means that there is a large adjustment time in response to policy interventions, and changes in average years of schooling play out very slowly. When we consider the effects on lower age cohorts it is greater. Also, there is a saturation effect incorporated in the model's relationships related to years of schooling, because the number of years of schooling does not continue to rise forever in any country.

With regard to life expectancy, Fig. 9, the differences between the policy scenarios are larger. Life expectancy changes faster than average years of schooling, as the delays in the model structure are shorter. The reasoning behind this is that, while education typically only involves younger age cohorts, a large share of the population is directly affected by health improvements (not least the elderly). A comparison between policies 4 and 5 also indicates that early investments are better than later ones. This is because the earlier investments allow the reinforcing loops to play out for a longer time than investments made later.

Discussion: the use of integrated planning tools for policy coherence on the SDGs

The research highlights benefits from considering interactions between SDGs in a structured way with the use of integrated simulation tools. Working with the iSDG model brings the multitudes of possible feedback loops that shape a country's development to the forefront. The model not only maps interlinkages, but also says something plausible about the resulting behaviour of different policy options. The synergies that we have found between SDGs 3, 4 and 7 in Tanzania seem to give rise to system-wide improvements beneficial for goals attainment. The model may also be used to study other causal pathways in which investments in photovoltaics affect development. For example, investments in photovoltaics could also be evaluated with a focus on hypothesized effects on infrastructure. Furthermore, discovering more synergies related to human development might strengthen the case for investments in photovoltaics. However, bottlenecks may also be found, where increased investment does not have the intended effect. The model also allows for studying other policy options and technological investments such as investments to increase agricultural productivity. By comparing plausible results from different interventions, synergies and bottlenecks can be assessed systematically rather than piecemeal.

Our approach illuminates the SDGs interaction framework suggested by Nilsson et al. (2016; also in International Council for Science 2016, and expanded in Nilsson 2017). Using their ratings, our analysis indicates that the improvements in electricity access *enable* progress in educational attainment and life expectancy (+1, "*Creates conditions that further another goal*"[2]). Electricity access also causes improvements in life expectancy and years of schooling via productivity increases (higher GDP). We did not find evidence for causal relationships in the opposite direction, from life expectancy and years of schooling to electricity access. These may thereby be rated as *consistent* (0, *"No significant positive or negative interactions"*). Furthermore, the causal relationships between life expectancy and years of schooling are *reinforcing* (+2, *"Aids the achievement of another goal"*), as there is bidirectional causality between the two that does not go via productivity improvements.

[2] International Council for Science (2016) in fact uses the relationship between electricity and education as an example of an enabling relationship.

The conclusions from the exploration of the iSDG model may also be used in policy planning and to inform public debates. Actual iSDG models may either be used directly in the policy formulation phase, or outsourced to a revision unit that evaluates plausible long-time effects of actual anticipated policies. In both contexts, the model can be used to explore anticipated consequences of different policy options. The iSDG model has been used in a country study on Cote D'Ivoire (Pedercini et al. 2016).

To carefully exploit the many benefits of using integrated models for assessing SDG goals attainment one also has to be cautious of their limitations. There may be unanticipated and unintended consequences of policies that are not included in the scope of the model. Such consequences may affect goal attainment, and the reality will always be more complex than the model and thus incorporate more uncertainties and unforeseen effects. Models can assist us in structuring our thoughts and put light on unintended consequences of different policies, but they do not immunize us against uncertainties and unpredictable real-world behaviours. Also, evidence for many relationships and potential formulations is disputed so alternative model designs always need to be considered. This has been emphasized in an updated version of the Nilsson et al. framework (Nilsson 2017) in which such relationships are discussed.

Conclusions

We have identified positive causal pathways between educational attainment, life expectancy and electricity access. Integrating these links into the iSDG model initiates reinforcing feedback loops that affect the model's behaviour. In the simulations, investments in photovoltaics affect both education and health positively, with an enhanced effect caused by synergies in the corresponding feedback structure.

This analysis shows how integrated models can be used to explore systemic relationships between SDGs. It thus demonstrates a flexible, adaptable and suitably transparent approach to generate actionable information that complements the SDG interaction scorings of the Nilsson et al. framework (Nilsson et al. 2016, International Council for Science 2016, and expanded in Nilsson 2017). For models to correspond better to reality and to reflect the ongoing academic and policy debates on integration of SDGs, the behaviour of relevant development indicators needs to be modelled endogenously. Without this, it is difficult to enable broad, cross-sector and long-term analyses of the impact of alternative policies.

Yet integrative modelling is just one part of a shift towards an informed systemic discussion of sustainable development and how best to attain it. An effective analysis process goes beyond the desk study of the published literature and data on causal links to include the exploration of policy options with decision-takers and stakeholders. They bring knowledge of their own contexts that informs the model development and may improve the model's correspondence to reality.

Research on the attainment of multiple SDGs is growing, but without structured systems understanding there is a risk of repeating the silo approach seen in the implementation of the millennium development goals (Rippin 2014). Integrated tools such as the iSDG model can bring interlinks to the forefront and facilitate a shift to a development discussion based on systems thinking.

Acknowledgements We thank Pål Davidsen and Andreas Größler for useful discussions and input in the early stages of the study. This Project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No 675153 (ITN JD AdaptEconII).

References

Abdelkarim OB, Ben Youssef A, M'Henni H, Rault C (2014) Testing the causality between electricity consumption, energy use and education in Africa (Working Paper No. 1084). William Davidson Institute at the University of Michigan

Allen C, Metternicht G, Wiedmann T (2016) National pathways to the sustainable development goals (SDGs): a comparative review of scenario modelling tools. Environ Sci Policy 66:199–207. doi:10.1016/j.envsci.2016.09.008

Axelrod R (2003) Advancing the Art of Simulation in the Social Sciences. Jpn J Manag Inf Syst 12:1–19

Barlas Y (1996) Formal aspects of model validity and validation in system dynamics. Syst Dyn Rev 12:183–210

Barney GO (2002) The global 2000 report to the president and the threshold 21 model: influences of dana meadows and system dynamics. Syst Dyn Rev 18:123–136. doi:10.1002/sdr.233

Barro RJ, Lee J-W (2013) Barro-Lee: Educational Attainment Dataset. In: Barro-Lee.com. http://www.barrolee.com/. Accessed 28 Dec 2016

Cutler DM, Lleras-Muney A (2006) Education and health: evaluating theories and evidence (Working Paper No. 12352). National Bureau of Economic Research, Cambridge, MA, US

Dangerfield B (2008) System dynamics advances strategic economic transition planning in a developing nation. In: Qudrat-Ullah H, Spector JM, Davidsen PI (eds) Complex decision making: theory and practice. Springer, Berlin, Heidelberg, pp 185–209

Dasgupta P, Duraiappah A, Managi S, Barbier E, Collins R, Fraumeni B, Gundimeda H, Liu G, Mumford KJ (2015) How to measure sustainability progress. Science 350:748. doi:10.1126/science.350.6262.748

Ezzati M, Bailis R, Kammen DM, Holloway T, Price L, Cifuentes LA, Barnes B, Chaurey A, Dhanapala KN (2004) Energy management and global health. Ann Rev Environ Res 29:383–419

Ford A (2009) Modeling the environment: an introduction to system dynamics modeling of environmental systems, 2nd edn. Island Press, Washington, D.C.

Forrester JW (1971) World dynamics, 2nd edn. Wright-Allen Press, Massachusetts

Forrester JW (1992) Policies, decisions and information sources for modeling. Eur J Oper Res 59:42–63

Homer JB (2012) Partial-model testing as a validation tool for system dynamics (1983). Syst Dyn Rev 28:281–294. doi:10.1002/sdr.1478

Häyhä T, Lucas PL, van Vuuren DP, Cornell SE, Hoff H (2016) From planetary boundaries to national fair shares of the global safe operating space—how can the scales be bridged? Global Environ Change 40:60–72. doi:10.1016/j.gloenvcha.2016.06.008

International Council for Science (2016) Working paper "A draft framework for understanding SDG interactions.". Paris: International Council for Science (ICSU)

Khandker SR, Barnes DF, Samad HA (2013) Welfare impacts of rural electrification: a panel data analysis from Vietnam. Econ Dev Cult Change 61(3):659–692

Kopainsky B, Pedercini M, Davidsen PI, Alessi SM (2010) A blend of planning and learning: simplifying a simulation model of national development. Simul Gaming 41(5):641–662

Kopainsky B, Huber R, Pedercini M (2015) Food provision and environmental goals in the Swiss agri-food system: system dynamics and the social-ecological systems framework. Syst Res 32:414–432. doi:10.1002/sres.2334

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M, Anderson HR, Andrews KG, Aryee M, Atkinson C, Bacchus LJ, Bahalim AN, Balakrishnan K, Balmes J, Barker-Collo S, Baxter A, Bell ML, Blore JD, Blyth F, Bonner C, Borges G, Bourne R, Boussinesq M, Brauer M, Brooks P, Bruce NG, Brunekreef B, Bryan-Hancock C, Bucello C, Buchbinder R, Bull F, Burnett RT, Byers TE, Calabria B, Carapetis J, Carnahan E, Chafe Z, Charlson F, Chen H, Chen JS, Cheng AT-A, Child JC, Cohen A, Colson KE, Cowie BC, Darby S, Darling S, Davis A, Degenhardt L, Dentener F, Jarlais DCD, Devries K, Dherani M, Ding EL, Dorsey ER, Driscoll T, Edmond K, Ali SE, Engell RE, Erwin PJ, Fahimi S, Falder G, Farzadfar F, Ferrari A, Finucane MM, Flaxman S, Fowkes FGR, Freedman G, Freeman MK, Gakidou E, Ghosh S, Giovannucci E, Gmel G, Graham K, Grainger R, Grant B, Gunnell D, Gutierrez HR, Hall W, Hoek HW, Hogan A, Hosgood HD, Hoy D, Hu H, Hubbell BJ, Hutchings SJ, Ibeanusi SE, Jacklyn GL, Jasrasaria R, Jonas JB, Kan H, Kanis JA, Kassebaum N, Kawakami N, Khang Y-H, Khatibzadeh S, Khoo J-P, Kok C, Laden F, Lalloo R, Lan Q, Lathlean T, Leasher JL, Leigh J, Li Y, Lin JK, Lipshultz SE, London S, Lozano R, Lu Y, Mak J, Malekzadeh R, Mallinger L, Marcenes W, March L, Marks R, Martin R, McGale P, McGrath J, Mehta S, Memish ZA, Mensah GA, Merriman TR, Micha R, Michaud C, Mishra V, Hanafiah KM, Mokdad AA, Morawska L, Mozaffarian D, Murphy T, Naghavi M, Neal B, Nelson PK, Nolla JM, Norman R, Olives C, Omer SB, Orchard J, Osborne R, Ostro B, Page A, Pandey KD, Parry CD, Passmore E, Patra J, Pearce N, Pelizzari PM, Petzold M, Phillips MR, Pope D, Pope CA, Powles J, Rao M, Razavi H, Rehfuess EA, Rehm JT, Ritz B, Rivara FP, Roberts T, Robinson C, Rodriguez-Portales JA, Romieu I, Room R, Rosenfeld LC, Roy A, Rushton L, Salomon JA, Sampson U, Sanchez-Riera L, Sanman E, Sapkota A, Seedat S, Shi P, Shield K, Shivakoti R, Singh GM, Sleet DA, Smith E, Smith KR, Stapelberg NJ, Steenland K, Stöckl H, Stovner LJ, Straif K, Straney L, Thurston GD, Tran JH, Dingenen RV, van Donkelaar A, Veerman JL, Vijayakumar L, Weintraub R, Weissman MM, White RA, Whiteford H, Wiersma ST, Wilkinson JD, Williams HC, Williams W, Wilson N, Woolf AD, Yip P, Zielinski JM, Lopez

AD, Murray CJ, Ezzati M (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380:2224–2260. doi:10.1016/S0140-6736(12)61766-8

Managi S (2017) The wealth of nations and regions. Routledge, Abingdon, Oxon

Meadows DH (2008) Thinking in systems: a primer. Chelsea Green, White River Junction, Vermont

Meadows D, Meadows D, Randers J, Behrens WW 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 DH, Randers J, Meadows DL (2004) Limits to growth: the 30-year update, 3rd edn. Chelsea Green Publishing, Vermont

Millennium Institute (2016) isdgs-model | Documentation. http://www.isdgs.org/documentation. Accessed 28 Dec 2016

Millennium Institute (2017) Millennium Institute. http://millennium-institute.org/. Accessed 1 July 2017

Modi VS, McDade S, Lallement D, Saghir J (2006) Energy services for the millennium development goals. Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millenium Project, World Bank, New York

Nilsson M (2017) Important interactions among the sustainable development goals under review at the high-level political forum 2017. Stockholm Environment Institute, Working Paper 2017-06

Nilsson M, Griggs D, Visbeck M (2016) Policy: map the interactions between sustainable development goals. Nature 534:320–322. doi:10.1038/534320a

OECD (2016) Better Policies for Sustainable Development 2016: A New Framework for Policy Coherence. OECD Publishing, Paris. doi:10.1787/9789264256996-en

Pedercini M, Zuellich G, Arquitt S (2016) Cote D'Ivoire 2016 iSDG Report. Millennium Institute, Washington, D.C.

Qureshi MA (2009) Human development, public expenditure and economic growth: a system dynamics approach. Int J Soc Econ 36:93–104. doi:10.1108/03068290910921217

Richardson GP (1997) Modeling for management: simulation in support of systems thinking. Ashgate Publishing Company, Brookfield

Richardson J (2005) Paradise poisoned: Learning about conflict, terrorism and development from Sri Lanka's civil wars. International Centre for Ethnic Studies, Kandy, Sri Lanka

Rippin N (2014) How to avoid the silo structure of the millennium development goals (MDGs). In: Ye J, Fues T (eds) The United Nations Post-2015 agenda for global development: perspectives from China and Europe. German Development Institute, Bonn, pp 253–266

Saeed K (2016) Development planning and policy design: a system dynamics approach, 2nd edn. Khalid Saeed, Worcester, MA

Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Boston

Sterman JD, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L (2013) Management flight simulators to support climate negotiations. Environ Model Softw 44:122–135. doi:10.1016/j.envsoft.2012.06.004

The World Bank (2008) The welfare impact of rural electrification: a reassessment of the costs and benefits. The World Bank, Washington

UNEP (2015) UNEP—Green economy assessment report for Ghana. UNEP, Ghana

United Nations (2015) Transforming our world: the 2030 Agenda for sustainable development A/RES/70/1. United Nations General Assembly, New York

United Nations Development Programme (2015) 2015 Human Development Report. http://report.hdr.undp.org/. Accessed 22 Dec 2016

Wolstenholme EF (1983) Modelling national development programmes—an exercise in system description and qualitative analysis using system dynamics. J Oper Res Society 34:1133. doi:10.2307/2581837

World Bank (2015) Poverty & equity data - Tanzania. In: The World Bank. http://povertydata.worldbank.org/poverty/country/TZA

World Bank (2016) Access to electricity (% of population) - Data. http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=TZ. Accessed 27 Dec 2016

Zhao M, Glewwe P (2010) What determines basic school attainment in developing countries? Evidence from rural China. Econ Educ Rev 29:451–460. doi:10.1016/j.econedurev.2009.10.008

II

Harvesting synergy from sustainable development goal interactions

Harvesting synergy from sustainable development goal interactions

Matteo Pedercini[a], Steve Arquitt[a], David Collste[a,b,c], and Hans Herren[a,1]

[a]The Millennium Institute, Washington, DC 20037; [b]Stockholm Resilience Centre, Stockholm University, SE-10691 Stockholm, Sweden; and [c]Centre d'Etudes et de Recherches sur le Développement International (CNRS), Université Clermont-Auvergne, 63000 Clermont-Ferrand, France

Contributed by Hans Herren, October 1, 2019 (sent for review October 8, 2018; reviewed by Wayne M. Getz and Graciela Metternicht)

As countries pursue sustainable development across sectors as diverse as health, agriculture, and infrastructure, sectoral policies interact, generating synergies that alter their effectiveness. Identifying those synergies ex ante facilitates the harmonization of policies and provides an important lever to achieve the sustainable development goals (SDGs) of the United Nations 2030 Agenda. However, identifying and quantifying these synergetic interactions are infeasible with traditional approaches to policy analysis. In this paper, we present a method for identifying synergies and assessing them quantitatively. We also introduce a typology of 5 classes of synergies that enables an understanding of their causal structures. We operationalize the typology in pilot studies of SDG strategies undertaken in Senegal, Côte d'Ivoire, and Malawi. In the pilots, the integrated SDG (iSDG) model was used to simulate the effects of policies over the SDG time horizon and to assess the contributions of synergies. Synergy contributions to overall SDG performance were 7% for Côte d'Ivoire, 0.7% for Malawi, and 2% for Senegal. We estimate the value of these contributions to be 3% of gross domestic product (GDP) for Côte d'Ivoire, 0.4% for Malawi, and 0.7% for Senegal. We conclude that enhanced understanding of synergies in sustainable development planning can contribute to progress on the SDGs—and free substantial amounts of resources.

sustainable development goals | SDGs | synergy | integrated policy

The 2030 Agenda for Sustainable Development launched by the United Nations in 2015 provides a framework to guide global progress toward 17 sustainable development goals (SDGs) and 169 targets (1). These cover a broad spectrum of development issues relevant to all countries. The Agenda is innovative in that it recognizes the integrated nature of the SDGs and explicitly calls for policy integration.

Policy integration, often used interchangeably with policy coherence, refers to "policy making processes that take into account interdependences between dimensions and sectors" (2), in contrast to "silo planning" (3). In the context of the 2030 Agenda, policy integration entails the analysis and management of cross-sector impacts and synergies between policies directed to achieve the SDGs (4). Such analysis is valuable for designing suitable policies to reach the SDGs, estimating their costs, and valuing their global impact.*

Synergies arising from the interaction of policies, in which the aggregate impact is different from the sum of the individual impacts, may offer unique opportunities for cost-effective SDG strategies. In this paper, we present a framework with which to identify and quantify synergetic policy mixes for improving national SDG performance.

The synergies are generated by the dynamic interactions among system elements, which cannot be captured using a siloed, reductionist approach. To effectively analyze synergies, it is useful to adopt a quantitative representation of major development processes across the SDG spectrum. With such a quantitative model, multiple policies in different sectors can be simulated individually as well as simultaneously to assess potential individual and combined effects.

Method

A few frameworks have been developed to assist with conceptualizing the interconnectivity that characterizes the SDGs. The best known of these include the framework for understanding SDG interactions developed by the International Science Council (ICSU) (5, 6); the SDG network diagrams developed at United Nations Department of Economic and Social Affairs (UN-DESA) (4); and the SDG interlinkages tool developed at the Institute for Global Environmental Strategies (IGES) (7). These frameworks are useful for developing an initial understanding of the interconnections among the goals. The UN-DESA SDG conceptual network maps connections between SDGs and targets, showing how some targets connect to more than one SDG. This may help in identifying targets that are central in the network of SDGs, but the framework is purely qualitative and does not provide the means to quantify synergies. The ICSU framework attempts to provide some measure of the intensity of the relationships between SDGs on a −3/+3 scale. The scale can be thought of as a set of influence coefficients. For example, a +3 relationship indicates that progress on a dependent target or goal is strongly positively influenced by progress on another specific target or goal. Scores of +2 or +1 indicate that progress on a dependent target or goal is less influenced. A −3 score indicates that progress on the dependent target or goal is halted by progress on another target or goal; scores of −2 or −1 indicate more moderate negative influence. This semiquantitative scale can be useful to develop an understanding of the centrality of some of the goals

Significance

The sustainable development goals (SDGs) offer the global community a compelling vision and universally agreed-upon framework to achieve a sustainable and equitable future—but present a costly undertaking in the short term. Our research suggests that synergetic effects arising from appropriately designed policy mixes can bring significant cost savings and improve SDG attainment. Identifying and quantifying synergies requires innovative and unorthodox approaches to policy analysis such as those operationalized in our 3 pilots. The synergy assessment method and typology introduced in this paper are widely applicable, even though the patterns of synergies vary considerably between countries. Our pilot studies focus on national policy for the SDGs. Our approach is nevertheless generalizable to integrated planning at other scales and time horizons.

Author contributions: M.P. and S.A. designed research; M.P. and S.A. performed research; M.P. and S.A. analyzed data; and M.P., S.A., D.C., and H.H. wrote the paper.

Reviewers: W.M.G., University of California, Berkeley; and G.M., University of New South Wales, Sydney.

The authors declare no competing interest.

[1]To whom correspondence may be addressed. Email: hh@millennium-institute.org.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1817276116/-/DCSupplemental.

First published October 30, 2019.

*Analysis of cross-sector impacts and policy synergies should be reflected in countries' national development plans and reported in their Voluntary National Reviews (VNRs). An examination of the VNRs of the last 2 y reveals that, while the majority of reporting countries have established institutional arrangements to facilitate integrated planning (e.g., the creation of SDG coordination units), little progress is reported on comprehensive and integrated analysis of SDG strategies, and cross-sector policy coherence remains a challenge (38–40). The lack of quantitative approaches and tools for integrated analysis of SDG strategies makes this endeavor especially difficult.

SUSTAINABILITY SCIENCE

for broader development. However, its significance for quantitative analysis is debatable—e.g., it is unclear whether 2 +1 interactions are equivalent to a +2 interaction: or whether a +1 and a −1 interaction would have a null effect. Also, such an approach may neglect synergies that take place at different stages of the intervention. The IGES SDG interlinkages tool is quantitative in nature, and maps and assigns strengths to complicated linkages between SDGs and targets for 9 different Asia Pacific countries. However, the IGES tool does not simulate specific policies over the SDG time horizon, and therefore cannot be used to assess synergies associated with policy mixes.

The Millennium Institute has developed the integrated sustainable development goal (iSDG) model for national-scale SDG planning. The iSDG model is a system dynamics-based model. As such, the behavioral patterns (i.e., how different system variables changes over time) are analyzed as the outcomes of complex systems in which variables are causally connected in feedback loops. The mathematical representations in the model, in the form of differential equations, are combined with interfaces that make the assumptions about causalities explicit (8–13). This transparent approach to modeling invites discussion about the actual underlying causal structure of national development planning—and enables simulation of various "what-if" scenarios. The iSDG model is accordingly designed to assist development planning by providing a credible representation of real-world development. iSDG, like its forerunner Threshold 21, is based on feedback loops between and within 3 main sectors that may be referred to as environment, society, and economy and governance. Documentation of the iSDG model structure is available on the Millennium Institute website (11). Also, a detailed description of the iSDG structure is provided by Pedercini et al. (14). Copies of mathematical models and accompanying data can be obtained from the corresponding author. For model validation, see the technical note on iSDG model validation in *SI Appendix*.

The iSDG model can simulate multiple policies individually and in aggregate, thus enabling the quantitative assessment of anticipated synergies among SDG policies (13, 14). Other development planning tools adopting a similarly integrated simulation approach include the Threshold 21, a system dynamics-based model, and the International Futures system, a hybrid systems–macroeconomic model (15, 16); however, to our knowledge, no other tool has the comprehensive coverage of the SDGs as does the iSDG model. These characteristics make the iSDG specifically useful in studying the anticipated effects of SDG policies across sectors in an integrated way. We have applied the iSDG model in 3 countries in sub-Saharan Africa (SSA) to analyze the potential nature and extent of synergies between policies for SDG progress. Based on these 3 cases, we describe in this paper a framework to guide and systematize synergy analysis in the context of SDG policies.

The structure of the paper is as follows. *Synergy—A Definition for SDG Analysis* describes the definition of synergy that we adopt, and the calculation method we use to estimate synergies, including relevant details on the iSDG model. *A Framework for Analysis of SDG Synergies* lays out our framework for synergy analysis. *Estimates from Pilot Studies* presents our results from the 3 pilot studies. Here, we demonstrate that SDG policies that harvest synergies have the potential to substantially reduce implementation costs. *Discussion* presents our conclusions and identifies promising directions for future research.

Synergy—A Definition for SDG Analysis

The term synergy, from the Greek word for "working together," is used in different fields such as biology, pharmacology, information science, and systems science. It has distinct connotations in different fields and travels under names such as emergence, cooperativity, symbiosis, coevolution, symmetry, order, interactions, interdependencies, systemic effects, even complexity and dynamical attractors (17). In most cases, it is used to convey the same fundamental concept: that a combination of different actions or elements strengthen each other, leading to a result that is greater than the sum of their individual impacts.

We have developed the following definition for synergy in the context of SDG implementation/intervention analysis: 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. Dissynergy occurs when the combined interventions lead to smaller progress than the sum of their individual impacts. When multiple interventions are implemented, instances of synergy and dissynergy compensate each other to yield a net value. For ease of expression, we will use the plural form "synergies" to refer collectively to instances of synergy and dissynergy.

Synergies arising from the interactions of interventions implemented in diverse policy sectors indicate that the SDGs are part of a highly interconnected social–ecological system. Therefore, their existence may also represent an indirect measure of the interconnectedness of the policy system. An appropriate analytical approach that can identify the type and assess the strength of synergies would help to identify investment strategies that maximize the occurrence of synergy while minimizing dissynergy.

In economics, the analysis and quantification of synergies have been developed in the context of mergers and acquisitions from a financial and management perspective (18, 19). Also, the concept of synergies has been used to analyze the interaction of economic players and institutions in a network, as in "synergetics" (20, 21). In the case of development policy, analysis of synergies has been carried out, focusing on specific thematic areas (22) or on interactions between organizations (23). Differential-equation–based systems models, such as the International Futures system (16), the Threshold 21 modeling framework (24), and the World3 model of the Limits to Growth study (25, 26) are suitable frameworks with which to conduct dynamic analysis of synergies as they account for delays and allow for circular causality. However, to our knowledge, no broad, quantitative analytical framework is available to support analysis of potential synergies in the context of SDG policies at the time of this study. This may relate to the difficulty of measuring the actual synergies related to, in this case, different policies for development. Carrying out experiments is hardly possible on a scale that is relevant to the analysis, and is ethically debatable. Ex post, comparative studies of the performance of different countries' SDG strategies can be carried out to assess the contributions of synergies. Even then, as in much social science research, it would be difficult to avoid exogenous disturbances and meaningfully isolate the effects of individual policies to be able to measure their synergies. Also, many SDG interventions will only demonstrate their full impacts many years after they are implemented. However, findings that can guide SDG policies have practical relevance primarily a priori, when these strategies are being developed. We therefore use a model-based method to identify synergies—carrying out thought experiments by simulating different policies using an integrated simulation model. In this way, we can anticipate the effects of the policies. The models we use serve as "policy flight simulators" (27). With these, the simulated effects of different policies can be compared and "what-if" scenarios simulated (10, 12, 27).

Tools to calculate the anticipated contribution of synergies to progress on a given SDG target should respond to a series of criteria. First, the tool must be multisectoral, i.e., it must be able to represent policy implementation in different sectors within the same model structure—a necessary precondition to jointly analyze interventions in different areas. Second, the model sectors must be dynamically integrated, and share key structural components (such as the fundamental demographic, economic, and resource-related structures) to properly capture the combined impacts of alternative policies. Third, the tool must explicitly represent the mechanisms of policy implementation, to support the analysis of the dynamics through which synergies may arise. Fourth, the tool must encompass a broad range of SDG indicators, ideally covering all SDGs, to provide a comprehensive picture of where synergies may occur. The iSDG model complies with these 4 criteria, and we adopt it for our study.

We adopt a simple method for the calculation of synergies. First, we simulate a business-as-usual (BAU) scenario, in which no additional policy is introduced beyond those currently in place. We then simulate all relevant SDG policies (e.g., those included in a national development plan) individually and record the impacts on the SDG indicators used in the model, measuring the differences between the values generated by the policy simulations and the BAU simulation. Subsequently, we simulate all policies simultaneously and record their collective impact on the

SDG indicators. Finally, we calculate the differences between the impacts on SDG indicators recorded in the simulation of all policies combined and the sum of the impacts of the individual policies. Formulated as a mathematical expression, we calculate anticipated synergies as shown in the following equation; where Impact_c is the impact generated when jointly implementing all interventions, and Impact_i is the impact generated by the single intervention:

$$\mathrm{Synergy} = \mathrm{Impact}_c - \sum_{i=1}^{n} \mathrm{Impact}_i .$$

The resulting value can be positive (synergy), null, or negative (dissynergy). Synergy indicates faster progress toward the SDGs than the sum of individual interventions would suggest; a dissynergy indicates slower progress.

Besides understanding the value of synergies, to maximize the potential impact of combinations of interventions it is necessary to understand the source mechanisms of both synergy and dissynergy. The following section provides a framework to classify synergies based on the types of mechanisms from which they arise.

A Framework for Analysis of SDG Synergies

The quantitative assessment of anticipated synergies is fundamental to identifying combinations of interventions that are estimated to be especially effective versus others that may lead to slower than expected progress. However, harvesting synergetic potential through the design of effective SDG strategies also requires an in-depth understanding of the sources of synergies, which can be assisted by a model that captures these.

Identifying the stage in the intervention process during which synergies have the potential to arise is important for both synergy and dissynergy. For synergy, such knowledge is important to ensure that the necessary conditions are in place to harvest synergy when interventions are implemented. For dissynergy, a good understanding of the specific mechanisms at their root is important for design interventions to limit their occurrence. This implies intervening in the right place at the right stage of the implementation process.

To depict how synergies can arise from different causes during the implementation of an intervention, we use a simple results chain for a single intervention. This is a well-known tool for results-based management broadly adopted to assess the impact of development interventions (28–30). We identify 5 fundamental mechanisms at different stages in the results chain that potentially give rise to synergies (Fig. 1): type I, inputs; type II, enabling conditions; type III, target group, area, and institution; type IV, marginal returns; and type V, overshooting objectives (a special case of type IV).

Type I synergies arise from the change in the inputs, e.g., financial resources, available for the implementation of a given intervention caused by the implementation of another intervention. For instance, a microcredit intervention might lead to faster economic growth and thus to higher revenue for the government. That higher revenue can then be used to improve the coverage and/or quality of an intervention in another sector, such as health or education. In that case, we would observe a synergy for health and education-related indicators.

Type II synergies arise when the implementation of a policy intervention changes the immediate outcomes of another intervention by affecting its enabling conditions. For instance, a policy directed to build a more extensive road network may improve the enabling conditions for a food distribution intervention, facilitating the transportation of food aid by road. In such a case, we would observe synergy for food security-related indicators.

Type III synergies take place when an intervention in a given sector affects the target group of another intervention. For instance, an intervention directed to improve access to contraceptive methods could extend the proportional coverage of a vaccination intervention, as there would be fewer children to vaccinate. In that case, we may observe synergy for health-related indicators.

Type IV synergies appear when the cost-effectiveness of progressing on a target indicator changes as the level of the indicator improves, i.e., when related interventions are characterized by increasing or decreasing marginal returns. In the case of rural

SUSTAINABILITY SCIENCE

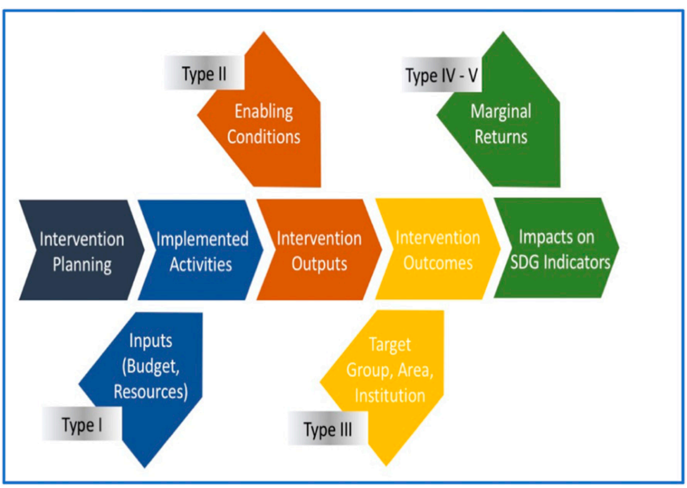


Fig. 1. Results chain for a single development intervention. There are 5 types of mechanisms at different stages of the chain that give rise to synergy. Type I synergies arise from interventions (e.g., financial investment) that increase the resources available for other interventions; type II synergies arise when an intervention creates enabling conditions for a second intervention; type III synergies arise when an intervention affects the target group of another intervention; type IV synergies arise when the cost-effectiveness of progressing on a target indicator changes as the level of the indicator improves; type V synergy occurs when progress on an indicator cannot, or should not, exceed a given target value.

access, for example, the marginal cost of reaching a person in a rural area would normally increase as people in less densely populated areas acquire access. Improving rail and road infrastructure might have both a positive impact on rural access in a given area, and good marginal returns if implemented in isolation to reach out to more densely populated rural areas. However, if rail infrastructure is first improved in the more densely populated areas, then to further increase rural access, road infrastructure would have to be developed in less densely populated areas. Since the marginal cost increases, the combined cost-effectiveness of the interventions would be reduced, generating a dissynergy. The dissynergy arises from the fact that the 2 policies have the same 'target audiences'—people in rural areas.

Type V synergies are a special case of type IV synergies; they arise when progress on an indicator cannot, or should not, exceed a given target value. That is the case, for instance, when an intervention designed to achieve universal (net) school enrolment (e.g., expanding the coverage of the school system) is combined with another intervention that could further increase school enrolment (e.g., improving public transport). Together, the 2 combined interventions could be more than enough to reach a level of school enrolment of 100%. In this case, all investments above the level at which 100% of enrolment is reached would have no effect on attaining the specific target. The marginal return would be equal to zero as school enrolment cannot exceed 100%. That mechanism can thus generate only dissynergies. In this instance, simulations with an appropriate model could help planners avoid overinvestment in the policies, preventing the potential dissynergy.

When simulating a large number of anticipated policy interventions, the generated net synergies can be determined by the combination of synergies of different types or polarities. In those cases, our analytical approach should be simulated incrementally: first including only pairs of interventions, and then gradually including more interventions until the full strategy is jointly simulated. By way of this process, not only the total net synergies can be appreciated, but a better understanding of the sources of those synergies can be developed.

A failure to understand possible synergies among policy interventions can easily lead to undesired results and suboptimal allocation of resources (24). The identification of the type of synergies that arise from the interactions of interventions is thus an important aspect to fine-tune policies and coordinate implementation, or in essence, to effectively harvest the synergetic potential of multisector strategies.

Estimates from Pilot Studies

In a first attempt to measure the contribution of potential synergies to progress toward the SDGs, we conducted pilot studies in 3 countries: Côte d'Ivoire, Malawi, and Senegal. We focused our pilot studies on SSA, a region where achieving the SDGs is especially challenging. In SSA, poverty levels are high, human development low, and resources for development interventions scarce. Côte d'Ivoire, Malawi, and Senegal are similar in their human development indices (0.474, 0.476, and 0.494, respectively) (31) and income levels: Malawi and Senegal are classified as low-income economies according to the World Bank Atlas method classification (32), and Côte d'Ivoire as a lower-middle income economy.

To perform a quantitative analysis of synergies, we use results from the iSDG simulation model (33), which was implemented and calibrated for the 3 countries. In all 3 cases, the model was developed using data from international databases (e.g., refs. 32, 34, and 35) and information sourced from experts within governmental planning institutions. The models underwent standard structural and behavioral validation tests for system dynamics models (36), including replication of historical data for key indicators over the period 1990 to 2015. A detailed description of iSDG model validation and testing is provided in *SI Appendix*.

For each country, we analyze performance for about 80 SDG targets under 2 different scenarios: a BAU scenario reflecting the current policies and budget allocation shares; and an SDG policy scenario, in which ambitious interventions to achieve the SDGs are simulated. In all 3 countries, the SDG policy scenarios have been designed in collaboration with the governmental planning institutions, to include as broad a range of policies to achieve the SDGs as possible. Nevertheless, these scenarios are not to be considered as reflecting an established development plan, but rather as a step in a reiterative and adaptive policy design process toward a gradual refinement of a development strategy.

We use the results from the 2 scenarios to assess anticipated synergies as described in the previous sections, based on the measured impact of each policy in the SDG scenario with respect to a BAU scenario. The performance of each SDG indicator is normalized with respect to a given target value that either is derived from the definition of the goal and target in the 2030 Agenda, or is estimated by experts from the local planning institutions. The performance on each indicator was then averaged to obtain the performance at the SDG target level; and performances at the target level were then averaged to calculate performance at the goal level. For further explanation of the calculation of SDG performance, refer to *SI Appendix*. The simulation results highlight important differences across the 3 countries but also significant similarities, as discussed in the following paragraphs.

Cross-Country Comparison of Results. The challenges to realizing the SDGs in the 3 countries are major, and the analysis of our BAU scenarios indicates that continuation on the current development path would lead to very low levels of achievement by 2030. In the case of Côte d'Ivoire, the simulated level of achievement is only 21% at year 2030 (Table 1). For Senegal and Malawi, levels of simulated SDG achievement under BAU assumptions are very low. In the case of Malawi, the BAU simulation indicates only 30% average attainment of SDGs by year 2030; in the case of Senegal, average attainment reaches only 29% by 2030.

Fig. 2 provides an overview of the contribution of each individual policy included in the SDG scenario on the progress toward achieving the 17 SDGs and of the synergies generated (highlighted in lavender color) for Malawi.

Fig. 2 highlights that, when simulated separately, many policies relevant to the SDGs have substantial cross-sector impacts. When jointly simulated, synergies generated from the interaction of those interventions are substantial. For cross-sector impacts and synergies for Côte d'Ivoire and Senegal, see *SI Appendix*, Figs. S3 and S4.

Fig. 3 shows and compares the contributions of BAU, SDG policies, and synergies. For simplification, all of the SDG policies are lumped together. The SDG policy mix varies between the 3 countries. Note that SDG policies can have both positive and negative influence on SDG performance. The black line with dots indicates SDG performance at year 2030.

In the case of the Côte d'Ivoire model, synergy is observed for 9 of the 17 goals, for an average contribution of the progress on each of those goals of about 13% and an overall average contribution across the 17 SDGs of about 7%. For the Malawi model, synergy is observed for 3 of the goals, with an average contribution of about 3% to each of those goals and an overall average contribution across the 17 SDGs of about 0.7%. For the Senegal model, we observe synergy for 6 of the goals, for an average contribution of about 6% to each and an overall average contribution across the 17 SDGs of about 2%.

Because synergy arises from combinations of interventions with different unit costs and effectiveness, the economic value of synergy is difficult to estimate. As a first approximation, we consider the percentage contribution of synergy to the overall improvement in performance across the 17 goals over the BAU simulations and relate it to the total cost of the simulated SDG

Table 1. Summary of SDG performance and synergies for the 3 pilot countries

	Côte d'Ivoire, %	Malawi, %	Senegal, %
Goals achievement—BAU scenario	21	30	29
Goals achievement—SDG scenario	67	59	61
Cost of simulated SDG strategy (% GDP per year)	19	18	11
Synergy—contribution to performance	7	0.7	2
Synergy—economic value (% GDP per year)	3	0.4	0.7
Dissynergy	10	8	4
Type V dissynergy	5	0.0	0.0
Other dissynergy	4	8	4
Economic value of type V dissynergy (% GDP per year)	2	0.0	0.0
Economic value of other dissynergy (% GDP per year)	2	3	1
Total saving from synergy and type V dissynergy (% GDP per year)	5	0.4	0.7

Goal achievement is the average achievement of the targets underlying the goal. The method for calculating goal and target achievement is explained in *SI Appendix*. Economic values are given in percent of GDP.

strategy. For the Côte d'Ivoire model, the total cost of the simulated SDG strategy is about 19% of gross domestic product (GDP) per year over 15 y, so that the economic value of synergy is in the order of 3% of GDP as shown in Table 1. For the Malawi model, the total cost for the SDG strategy is about 18% of GDP per year; the economic value of synergy is ∼0.4% of GDP per year. For the Senegal model, the cost of implementing the planned SDG strategy is about 11% of GDP per year, and the economic value of synergy is thus 0.7% of GDP per year.

We also observe dissynergy for 7 goals in the Côte d'Ivoire model, for 11 goals in the Malawi model, and for 10 goals in the Senegal model. The dissynergy implies a simulated drag on performance of 10% on the overall SDG performance for the Côte d'Ivoire model, of 8% in the Malawi model, and of 4% in the Senegal model. Although the degree of dissynergy is alarming, the policy implications depend strongly on the type. While observed synergy is mostly of type I, II, and III, dissynergy is mostly of types IV and V, as discussed below.

Type I synergy is mostly evident through the simulated increase in domestic revenue observed in the SDG scenario, which is due to the acceleration in economic growth and the formalization of the informal sector. The increase in domestic revenue over BAU is as large as 3-fold for the Côte d'Ivoire model, about 1.7 times higher for the Malawi model, and 1.8 times larger for the Senegal model. The acceleration in the mobilization of financial resources from domestic sources facilitates a substantial

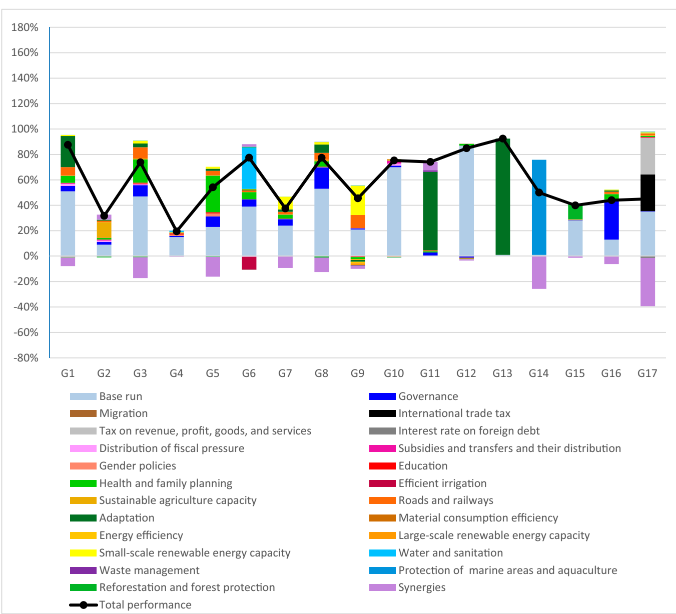


Fig. 2. Cross-sector policy impacts and synergies and summary chart for Malawi. The figure shows the influences of policies on all 17 SDGs at year 2030 Malawi, 1 of the 3 case studies. Business-as-usual (BAU) SDG performance is indicated in light blue. The performances of policies over or below the BAU when simulated individually are color-coded. The level of attainment for each SDG when the policies are simulated together is indicated by the black dots connected by the black line. Synergies (synergy and dissynergy) are indicated in light purple. The synergies represent the difference between SDG performances when all policies are simulated together and the sum of the policies simulated in isolation for each SDG.

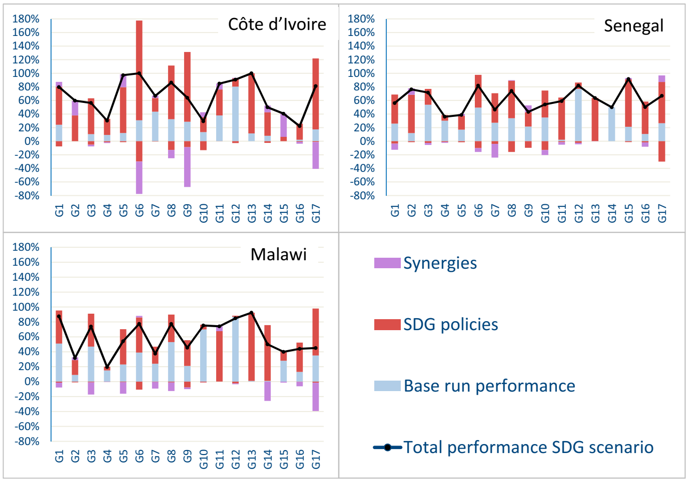


Fig. 3. Contributions to SDG attainment of BAU (base run performance), SDG policies, and synergies arising from policy interactions for Côte d'Ivoire, Senegal, and Malawi. The black line indicates the level of attainment of each SDG at year 2030. For simplification, the effects of the SDG policies are shown in aggregate. The SDG policy mix varies between the 3 countries. Note that SDG policies can sometimes exert a negative influence on some SDGs, e.g., expansion of irrigation for improvement of SDG2 could negatively impact water availability for human consumption (SDG6). The chart for Côte d'Ivoire exhibits instances of goal overshoot for SDGs 6, 8, 9, and 17, where the charts for Senegal and Malawi show all SDGs under 100% attainment. This is because the Senegal and Malawi cases have undergone several rounds of iterations to eliminate goal overshoot and redistribute resources to other SDG policies.

increase in public expenditure for the SDGs, while keeping the deficit under control and limiting the need for external support.

Synergy from enabling conditions (type II) appears to be strong in the 3 countries analyzed. Their current status of transportation and energy infrastructure, as well as education and governance indicators, suggest an unfavorable environment for implementation of SDG interventions. In the SDG scenarios, transportation infrastructure grows substantially faster in the 3 countries, leading to a paved-roads network 37% larger by 2030 for the Côte d'Ivoire model, more than doubling in the Malawi model, and 24% larger in the Senegal model. Similarly, energy infrastructure is more rapidly expanded in the SDG scenario, leading by 2030 to universal access to electricity (vs. 74% in the BAU) in Côte d'Ivoire, in Malawi increasing to 26% (over 6% in the BAU case), and in Senegal reaching 100% (vs. 93% in the BAU case). Education indicators also perform better in the SDG scenario than in the BAU scenario for all countries, leading to 12% higher average years of schooling by 2030 in the Côte d'Ivoire model, and 5% higher in the Malawi and Senegal models. Finally, governance indicators are assumed to increase substantially for the 3 countries, resulting in an overall improvement of 35% in the Côte d'Ivoire model, 76% in the Malawi model, and 40% in the Senegal model. Progress on those indicators, and especially on governance, generates strong improvements in enabling conditions in all of the 3 pilot countries, leading to synergy across SDGs. In the model environment, acting rapidly on enabling conditions achieves major savings in the implementation of SDG interventions.

Type III synergy in the 3 countries mostly derives from the overall slower growth in population observed when simulating the SDG interventions: Total population is about 16% smaller by 2030 than in the base run in Côte d'Ivoire, 8% smaller in Malawi, and 2% smaller in Senegal. The overall slower growth is the result of a simulated rapid decrease in births—due to both increases in income and education. The decrease in births is only partially compensated by a decrease in mortality, which leads to a slightly larger elderly population than would otherwise have been the case. Those results are in line with the findings from Abel et al. (37).

Dissynergy is observed for various goals in all of the 3 country models, mostly of types IV and V. Type IV dissynergy arises in many cases from the decreasing marginal returns that characterize interventions on infrastructure in the simulations. This is the case, for instance, for the dissynergy observed for Côte d'Ivoire and Senegal on goal 6 (on clean water and sanitation), and for Côte d'Ivoire on goal 9 (on industry, innovation, and infrastructure). In those cases, the marginal cost of extending the infrastructure gradually increases as the most cost-effective options are exhausted. Type IV dissynergy also arises for the 3 countries for goal 3 (on health and well-being). In that case, life expectancy increases to 68 y by year 2030 (vs. 60 in the BAU case) in the Côte d'Ivoire model, to 68 in the Malawi model (vs. 58 in the BAU case), and to 69 in the Senegal model (vs. 65 in the BAU case). As life expectancy increases because the leading causes of early death are eliminated, marginal return can approach zero as the cost of treating more complex diseases is higher. That type of dynamic calls for complementary interventions specifically designed to reach out to the most marginal areas or groups, who are especially difficult and expensive to serve.

For the Côte d'Ivoire model, the largest dissynergy is of type V. This dissynergy is especially ample for goals 6 (on clean water and sanitation), 8 (on decent work and economic growth), 9 (on industry, innovation, and infrastructure), and 17 (on partnerships for the goals). In all those cases, the sum of contributions of individual policies exceeds the 100% achievement limit, so that the excess performance represents a type V dissynergy. The simulated overshoot of objectives is due to the cross-sector impacts of interventions that, when properly accounted for, lead to far faster progress on SDG indicators than expected. Such phenomenon implies that excess resources can be reallocated to interventions directed to support other goals, bringing about a more homogenous SDG performance. In the cases of the Senegal and Malawi models, the SDG strategy has gone through several rounds of refinement and analysis through simulation; hence dissynergy of type V has been largely eliminated in the model environment.

If we account for type V dissynergy as a potential source of resources to be reallocated to interventions in other sectors, then a linear evaluation of the savings from synergy and type V dissynergy can account for as much as 5% of GDP per year in the Côte d'Ivoire model, and the remaining dissynergy to about 2% of GDP. For the Malawi model, synergy accounts for about 0.4% of GDP per year; the remaining dissynergy comes to about 3%. For the Senegal model, synergy accounts for about 0.7% of GDP, and other dissynergy for about 1%. Although these values are only a first approximation in the various simulations, they call for the importance of proper quantitative analysis of synergies in the context of the elaboration of integrated strategies to achieve the SDGs.

Overall, the simulations suggest significant variations in the impact of synergies on performance across the 3 countries. Globally, larger synergies are observed in the model for Côte d'Ivoire, and smaller synergies for Malawi and Senegal. The underlying reasons have to do with the different types of interventions simulated in the 3 countries, with the size of the interventions' budget, and with differences in the countries' socioeconomic structure as represented in the models.

Despite those differences, the possibilities in the 3 pilot countries for economic development, their lack of financial resources for implementing SDG policies, their initially poor enabling conditions, and their rapid population growth set the stage for strong synergetic potential. That may not be the case for mid- and high-income countries, whose economic and demographic development might respond less elastically to policy interventions and could thus exhibit weaker synergetic impacts. To develop a broader understanding of the potential importance of synergies in achieving the SDGs at the global scale, it would therefore be important to extend our analysis to countries from other income groups. In addition, our analysis is performed on individual country models, and therefore we do not account for synergies that can emerge from the interaction of policies that are implemented in different countries. We think that such synergies are becoming more and more important in the increasingly interconnected social–ecological system of our planet and should be further investigated.

Discussion

Our analysis based on simulations of combined SDG policies suggests that synergy can account for a relevant share of the progress toward achieving the SDGs (Fig. 3). We estimate the economic value of synergy in the simulated models to be 3% of GDP for Côte d'Ivoire, 0.4% for Malawi, and 0.7% for Senegal. Effectively harvesting synergy could free a substantial amount of resources for further SDG investment.

Dissynergy also impacts performance in the 3 country models. Some types of dissynergy are inherent to the nature of the interventions implemented in the models, while others can be more easily reduced. More specifically, type V dissynergy resulting from exceeding SDG targets is indicative of resources that could be more productively allocated to other sector policies through effective planning. By eliminating type V dissynergy, the total savings account for about 5% of GDP per year in our Côte d'Ivoire model. In the Senegal and Malawi models, type V dissynergy has been addressed in the development of SDG intervention scenarios, contributing to the development of more effective SDG strategies.

The identification and quantification of synergies could yield important opportunities to enhance SDG performance. Synergies arise because of fundamentally different phenomena, as described in the typology of synergies outlined in *A Framework for Analysis of SDG Synergies*. A correct understanding of the underlying sources of synergies is essential for effective leveraging of synergies in policy design. To this end, an integrated model that explicitly maps causal relationships within and across sectors, and that is capable of simulating the effects of multiple SDG policies both in aggregate and in isolation, is necessary. This is not to say that qualitative and semiquantitative methods, or other quantitative methods not using simulation, do not make important contributions to the understanding of SDG synergies; rather, insights from such research can inform and improve integrated simulation models and vice versa—the approaches complement one other.

Our analysis of policy synergies is based on results from models developed in pilot studies undertaken in 3 countries of SSA. From these studies, we expect that the synergies typology and assessment method introduced in this paper will be broadly applicable, while the results of synergies analyses will vary significantly for individual countries or regions. The extent of synergies depends on the strengths of the relationships between the social–ecological system elements, which can significantly differ across countries. In particular, we would expect different results between high-income countries and lower-income countries, due to, among other factors, the less dynamic economic and demographic conditions of the former. For effective policy analysis and planning, it is therefore important that all countries have access to appropriate tools for assessing policy options and their potential synergies.

A limitation to this research is that our study focuses on individual country models and does not account for synergies arising from the interaction of interventions between countries. This is appropriate for the SDGs as the 2030 Agenda mandates the SDGs at national scale. Regional and global synergy assessments are nevertheless promising areas of research and will be essential to building a more complete understanding of the relevance of synergies in the global effort to achieve the SDGs.

ACKNOWLEDGMENTS. We thank the Editor and our 2 referees for their valuable comments on earlier drafts of this article. We also give special thanks to our partners in the governments of Côte d'Ivoire, Senegal, and Malawi and the United Nations Development Programme.

1. United Nations, "Transforming our world: The 2030 Agenda for Sustainable Development" (A/RES/70/1, United Nations General Assembly, New York, 2015).
2. E. Meijers, D. Stead, "Policy integration: What does it mean and how can it be achieved? A multi-disciplinary review" in *2004 Berlin Conference on the Human Dimensions of Global Environmental Change: Greening of Policies—Interlinkages and Policy Integration* (Freie Universität Berlin, 2004), pp. 1–15.
3. OECD, *Better Policies for Sustainable Development 2016: A New Framework for Policy Coherence* (OECD Publishing, Paris, 2016), p. 65.
4. D. Le Blanc, Towards integration at last? The sustainable development goals as a network of targets. *Sustain. Dev.* **23**, 176–187 (2015).
5. N. Weitz, H. Carlsen, M. Nilsson, K. Skånberg, Towards systemic and contextual priority setting for implementing the 2030 Agenda. *Sustain. Sci.* **13**, 531–548 (2018).
6. M. Nilsson, D. Griggs, M. Visbeck, Policy: Map the interactions between sustainable development goals. *Nature* **534**, 320–322 (2016).
7. X. Zhou, M. Moinuddin, Z. Xu, Sustainable Development Goals Interlinkages and Network Analysis: A *Practical Tool* for SDG *Integration* and *Policy Coherence* (Institute for Global Environmental Studies, 2017). file:///Users/sparquitt/Downloads/IGES_Research%20Report_SDG%20Interlinkages_Publication.pdf. Accessed 19 October 2019.
8. R. Axelrod, Advancing the art of simulation in the social sciences. *Jpn. J. Manag. Inf. Syst.* **12**, 1–19 (2003).
9. A. Ford, *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems* (Island Press, ed. 2, 2009).
10. J. D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Irwin/McGraw-Hill, 2000).
11. D. H. Meadows, D. Wright, *Thinking in Systems: A Primer* (Chelsea Green Publishers, 2008).
12. G. P. Richardson, *Modeling for Management: Simulation in Support of Systems Thinking* (Ashgate Publishing Company, 1997).
13. D. Collste, M. Pedercini, S. E. Cornell, Policy coherence to achieve the SDGs: Using integrated simulation models to assess effective policies. *Sustain. Sci.* **12**, 921–931 (2017).
14. M. Pedercini, G. Zuellich, K. Dianati, S. Arquitt, Toward achieving sustainable development goals in Ivory Coast: Simulating pathways to sustainable development. *Sustain. Dev.* **26**, 588–595 (2018).
15. C. Allen, G. Metternicht, T. Wiedmann, National pathways to the sustainable development goals (SDGs): A comparative review of scenario modelling tools. *Environ. Sci. Policy* **66**, 199–207 (2016).

16. B. B. Hughes, *International Futures: Building and Using Global Models* (Academic Press, 2019).
17. P. Corning, Synergy and the Systems Sciences, ISSS Primer Project. http://www.isss.org/primer/corning.htm. Accessed 13 July 2018.
18. M. Bradley, Synergistic gains from corporate acquisitions and their division between the stockholders of target and acquiring firms. *J. Financ. Econ.* **21**, 3–40 (1988).
19. D. Gupta, G. Yigal Gerchak, Quantifying operational synergies in a merger/acquisition. *Manage. Sci.* **48**, 517–533 (2002).
20. N. A. Coulter, Jr, *Synergetics: An Adventure in Human Development, Wichita Human Study Group* (Prentice-Hall, 1976).
21. L. Stan, *The Necessity to Exploit the Economic Network's Synergistic Potential* (LAP LAMBERT Academic Publishing, 2011), pp. 33 and 37.
22. L. A. Duguma, S. W. Wambugu, P. A. Minang, M. van Noordwijk, A systematic analysis of enabling conditions for synergy between climate change mitigation and adaptation measures in developing countries. *Environ. Sci. Policy* **42**, 138–148 (2014).
23. P. Evans, Government action, social capital and development: Reviewing the evidence on synergy. *World Dev.* **24**, 1119–1132 (1996).
24. M. Pedercini, G. Barney, Dynamic analysis of interventions designed to achieve millennium development goals (MDG): The case of Ghana. *Socioecon. Plann. Sci.* **44**, 89–99 (2010).
25. D. H. Meadows, D. L. Meadows, J. Randers, W. W. Behrens, III, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (Universe Books, 1972).
26. D. H. Meadows, J. Randers, D. L. Meadow, *Limits to Growth: The 30-Year Update* (Chelsea Green Publishing, ed. 3, 2004).
27. J. D. Sterman *et al*., Management flight simulators to support climate negotiations. *Environ. Model. Softw.* **44**, 122–135 (2013).
28. UNDP, *Handbook on Planning, Monitoring, and Evaluating for Development Results* (United Nations Development Programme, New York, 2009). http://web.undp.org/evaluation/handbook/documents/english/pme-handbook.pdf. Accessed 19 October 2019.
29. P. J. Gertler, S. Martinez, P. Premand, L. B. Rawlings, C. M. J. Vermeersch; World Bank, *Impact Evaluation in Practice* (The World Bank, Washington, DC, 2011). https://siteresources.worldbank.org/EXTHDOFFICE/Resources/5485726-1295455628620/Impact_Evaluation_in_Practice.pdf. Accessed 19 October 2019.
30. OECD, *Strengthening the Results Chain: Synthesis of Case Studies of Results-Based Management by Providers* (Organisation for Economic Co-operation and Development, Paris, 2017).
31. UNDP, *Human Development Report 2016—Human Development for Everyone* (United Nations Development Programme, New York, 2016). http://hdr.undp.org/sites/default/files/2016_human_development_report.pdf. Accessed 19 October 2019.
32. World Bank, World Development Indicators database, World Bank. https://datacatalog.worldbank.org/dataset/world-development-indicators. Accessed 15 December 2017.
33. Millennium Institute, Official documentation of the iSDG model (Millennium Institute, 2017). https://www.millennium-institute.org/documentation. Accessed 19 October 2019.
34. FAO, Food and Agriculture Organization of the United Nations, FAOSTAT database, Rome, Italy. http://www.fao.org/faostat/en/#home. Accessed 15 December 2017.
35. International Energy Agency, IEA database, Paris, France. https://www.iea.org/statistics/. Accessed 15 December 2017.
36. Y. Barlas, Formal aspects of model validity and validation in system dynamics. *Syst. Dyn. Rev.* **12**, 183–210 (1996).
37. G. J. Abel, B. Barakat, S. Kc, W. Lutz, Meeting the sustainable development goals leads to lower world population growth. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14294–14299 (2016).
38. L. Brimont, D. Demailly, J. Vaillé, "SDG implementation: What are the countries doing?—An assessment of the voluntary reviews submitted to the High-level Political Forum" (Issue Brief, No. 17/16, IDDRI, 2016).
39. UNDESA, Synthesis of Voluntary National Reviews 2016 (Division for Sustainable Development, Department of Economic and Social Affairs, United Nations, New York, 2016).
40. UNDESA, Synthesis of Voluntary National Reviews 2017 (Division for Sustainable Development, Department of Economic and Social Affairs, United Nations, New York, 2017).

PNAS
www.pnas.org

Supplementary Information for

Harvesting synergy from Sustainable Development Goal interactions

Matteo Pedercini; Steve Arquitt; David Collste; Hans Herren

Hans Herren
Email: hh@millennium-institute.org

This PDF file includes:

Supplementary text
Figs. S1 to S4
Table S1
References for SI citations

www.pnas.org/cgi/doi/10.1073/pnas.1817276116

Background on the model structure used for the synergy analysis

The model used for the SDG synergy analysis is called the Integrated Sustainable Development Goal (iSDG) model. The model uses System Dynamics as its core methodology. System Dynamics, originated by Jay Forrester at MIT in the late 1950s, emphasizes the interactions of positive and negative feedback loops, stocks and flows, information delays, and non-linear relationships in the generation of dynamic behaviors (1).

The iSDG model focuses specifically on simulating the impacts of policies designed to promote the SDGs. The iSDG model builds on the Threshold-21 (T21) model for sustainable development planning, which was developed by the Millennium Institute and which has been applied in more than 40 countries worldwide (2).

The iSDG model is organized into three dimensions: economic, social, and environmental. Embedded within these dimensions are 30 sub-sectors. Feedback loops interconnect the sub-sectors within and between the three dimensions creating a holistic and extensively integrated model. The iSDG model is better thought of as a modeling framework that is customized for a particular country or region. The iSDG models used for Côte d'Ivoire, Senegal, and Malawi were informed by stakeholder workshops held in-country and make use of country-specific data. The models feature user-friendly interfaces to promote interactive learning. The models can be made available to interested parties upon request.

When simulated, the effects of interventions in any sub-sector will propagate throughout the model structure revealing impacts on key performance indicators across the time horizon of the simulation. The simulation runs from year 1990 through 2030, the last year of the SDGs; however, the model can be set up to run for longer or shorter time horizons as the user chooses.

Fig. S1. The three dimensions of the Integrated Sustainable Development Goal (iSDG) model. Thirty model sub-sectors are organized within economic (blue), social (red), and ecological (green) dimensions (3). Feedback loops interconnected sub-sectors within and across dimensions create a highly integrated and holistic model. Impacts of interventions will propagate throughout the integrated system demonstrating the cross-sector impacts of policies. Figure from Pedercini et al. (3).

The iSDG addresses all 17 SDGs and makes use of 78 indicators specified by the UN Agenda 2030. For the three case studies, Côte d'Ivoire, Senegal, and Malawi the indicators used are the same. Table S1 shows the indicators used in the iSDG for each SDG. Each of the indicators used has an accompanying target (desired indicator value). Some of these are explicit in the Agenda 2030 mandate, e.g., elimination of deep poverty for all. Other targets are not explicit and are for in-country policy-makers to specify, e.g., the targeted percentage of land area covered in forest. For these non-explicit targets stakeholder workshops were held to establish appropriate values.

Table S1. Indicators used in the iSDG model for each country of the study. The indicators are organized by SDG (left column). The targets for each indicator are given for each country. Some targets are absolute amounts; others are multiples of 2015 values. Units are provided in right column with explanations where meaning is not obvious.

SDG	Indicator	Target (Côte d'Ivoire)	Target (Senegal)	Target (Malawi)	Units
1	Proportion of population below poverty line	0	0	0	Dimensionless, fraction of total population
1	Access to basic health care	1	1	1	Dimensionless, fraction of total population
1	Mortality due to disasters	0	0	0	1/year, fraction of population dying per year
1	Proportion of population affected by natural disasters	0	0	0	Dimensionless, fraction of total population
1	Economic damage due to natural disasters	0	0	0	Dimensionless, fraction of GDP damaged
2	Prevalence of undernourishment	0	0	0	Dimensionless, fraction of population
2	Prevalence of malnutrition	0	0	0	Dimensionless, fraction of population
2	Prevalence of stunting	0	0	0	Dimensionless, fraction of population by age
2	Agricultural production in metric tons per unit labor	Value of 2015*2	Value of 2015 * 2	Value of 2015*2	Metric Tons/(person*year)
2	Proportion of harvested area sustainably managed	1	1	1	Dimensionless, fraction of harvested area
3	Maternal mortality ratio	70	65	70	deaths/100,000 women giving birth
3	Access to basic health care	1	1	1	Dimensionless, fraction of population with access
3	Under 5 mortality	25	25	25	Deaths/1000 live births

3	Neonatal mortality	12	12	12	Deaths/1000 live births
3	Cardiovascular, neoplasm, diabetes, and respiratory mortality	2015 value * 0.667	2015 value * 0.667	2015 value * 0.667	Death/1000 persons
3	Contraceptive prevalence	1	1	1	Dimensionless, fraction of sexually active population using contraception
3	Adolescent birthrate	0	0	0	Births/1000 adolescent women
4	Proportion of population age 20 to 24 that has completed secondary school	1	0.75	1	Dimensionless, fraction of age 20-24 population
4	Proportion of population age 20 to 29 that has enrolled in tertiary education	1	1	Not used	Dimensionless, fraction of age 20-29 population
4	Adult literacy gender gap ratio	0	0	0	Dimensionless, ratio of absolute value of difference in female and male literacy divided by maximum of female or male literacy
4	Average adult literacy rate	1	0.95	1	Dimensionless, fraction of population that is literate
5	Proportion of female legislators senior officials and managers	0.5	0.5	0.5	Dimensionless, fraction of legislators and senior official and managers
5	Contraceptive prevalence rate	1	1	1	Dimensionless, fraction of sexually active population
6	Average Access to improved water source	1	1	1	Dimensionless, fraction of population with access
6	Average Access to improved sanitation facility	1	1	1	Dimensionless, fraction of population with access
6	Total water withdrawal per unit of GDP	2015 value * 0.75	2015 value * 0.75	2015 * 0.75	Cubic meter/currency (cubic meters per year divided by GDP)
6	Water resources vulnerability index	2015 value * 0.5	2015 value*0.5 0.1027	2015 value * 0.5	Dimensionless, total water withdrawal/water supply

7	Percentage of population with access to electricity	100	100	100	Dimensionless, fraction of population with access
7	Renewable share in total final energy consumption	1	0.5	1	Dimensionless, fraction of total final energy consumption that is renewable
7	Energy intensity level of primary energy	2015 value /* 0.667	2015 value * 0.667	2015 value * 0.33	Mega joule/US$ at 2011 value (energy per unit GDP)
8	Real per capita GDP growth rate	0.07	0.07	0.07	1/year (fractional change of per capita GDP per year)
8	GDP per employed person growth rate	0.03	0.03	0.05	1/year (fractional change of GDP per employed person per year)
8	Material footprint	2015 value * 3.33	2015 value *2	2015 value * 2	Metric ton/year
8	Per capita material footprint	5	5	5	Metric ton/(person*year)
8	Material footprint per unit of output	2015 value *0.5	2015 value * 0.5	2015 value * 0.5	Kilogram/$US at 2011 value (Kilograms per year/GDP at $US 2011 purchasing power parity)
8	Domestic material consumption	2015 value *1.67	2015 value *2	2015 value * 2	Metric ton/year
8	Per capita domestic material consumption	5	5	5	Metric ton/year
8	Domestic material consumption per unit of output	2015 *0.5	2015 value * 0.5	2015 value *0.5	Kilogram/$US at 2011 value (Kilograms per year/GDP at $US 2011 purchasing power parity
8	Unemployment rate	0.05	0.06	0.05	Dimensionless, fraction of population unemployed
8	Share of youth not in education, employment or training	2015 value / 2	2015 value /2	2015 value / 2	Dimensionless, fraction of youth
9	Rural access index	1	0.8	1	Dimensionless (proportion of rural population living with 2 kilometers of an all season road)
9	Industry production as share of GDP	2015 value *2	2015 value *	2015 value *2	Dimensionless, Industry share of

			1.5		GDP
9	Per capita industry production	2015 value * 2	2015 value * 2	2015 value *2	Real currency units/(person*year)
9	Industry employment as share of total employment	0.15	0.25	0.25	Dimensionless, fraction of total employment in industry
9	CO_2 emissions per unit of value added	2015 value * 0.8	2015 value * 0.8	2015 value * 0.75	Kilogram/$US at 2011 value (Kilograms per year/GDP at $US 2011 purchasing power parity
10	Bottom 40 percent income growth to average income growth gap	-0.01	-0.01	-0.01	1/year (total real income growth rate minus real income growth rate of poorest 40 percent)
10	Proportion of population below half median income	0	0	0	dimensionless
10	Average labor share	0.6	0.6	0.6	Dimensionless (average share of labor to production shares)
11	Mortality due to disasters	0	0	0	1/year, fraction of population dying per year
11	Proportion of population affected by natural disasters	0	0	0	1/year, fraction of population affected
11	Economic damage due to natural disasters as share of GDP five year average	0	0	0	Dimensionless, fraction of GDP damaged
11	Proportion of urban waste collected and disposed	1	1	1	Dimensionless
11	PM 25 mean annual exposure	0	0	0	Micrograms/(cubic meter*year) (PM 25 = particulate matter 2.5 microns or less)
12	Per capita material footprint	5	5	5	Metric ton/year
12	Material footprint per unit of output	2015 value * 0.5	2015 value * 0.5	2015 value *2	
12	Domestic material consumption	2015 value * 1.67	2015 value *2	2015 value * 2	Metric ton/year
12	Per capita domestic material consumption	5	5	5	Metric ton/(person*year)
12	Domestic material consumption per unit of output	2015 value * 0.5	2015 value * 0.5	2015 value *0.5	Kilogram/$US at 2011 value (Kilograms per year/GDP at $US 2011 purchasing power parity)

13	Mortality due to disasters	0	0	0	1/year, fraction of population dying per year
13	Proportion of population affected by natural disasters	0	0	0	1/year
14	Proportion of fish stocks sustainably exploited	1	1	1	Dimensionless
14	Proportion of territorial waters protected	0.1	0.1	0.1	Dimensionless
15	Forest cover	0.2	0.5	0.5	Dimensionless
15	Proportion of terrestrial area protected	0.2	0.4	0.4	Dimensionless
15	Global Environment Facility (GEF) benefits index for biodiversity*	0.06	0.013	0.18	Dimensionless
16	Total mortality rate by violence	2015 value * 0.2	2015 value * 0.5	2015 value * 0.2	1/year, fraction of population dying due violence per year
16	Bribery incidence**	0	0	0	dimensionless
16	Normalized governance index***	1	1	1	dimensionless
17	Domestic revenue as share of GDP	0.3	0.3	0.3	dimensionless
17	Direct taxes as share of GDP	0.08	0.1	0.12	dimensionless
17	Indirect taxes as share of GDP	0.2	0.2	0.15	dimensionless
17	Tax burden	0.9	0.9	0.9	Dimensionless (taxes on goods and services+taxes on income and profits+taxes on international trade divided by domestic revenue)
17	Grants as share of domestic revenue	0.01	0.1	0.15	dimensionless
17	Interest on public debt as share of export	0.02	0.03	0.04	dimensionless

* "The Global Environment Facility (GEF) Benefits Index (GBI) is a measure of the potential of each country to generate global environmental benefits in a particular focal area." (4)

** "% of firms experiencing at least one bribe request" (5)

*** The normalized governance index includes indicators for: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, control of corruption (6, 7). The indicator ranges from zero to 1 with higher values indicating a better state of governance.

Calculation of SDG performance

The attainment status of each SDG is calculated as the average of the attainment levels of each target falling under the SDG. The structure tracking SDG attainment in the model is shown in Figure S2. The same structure applies to the other SDGs included in the model.

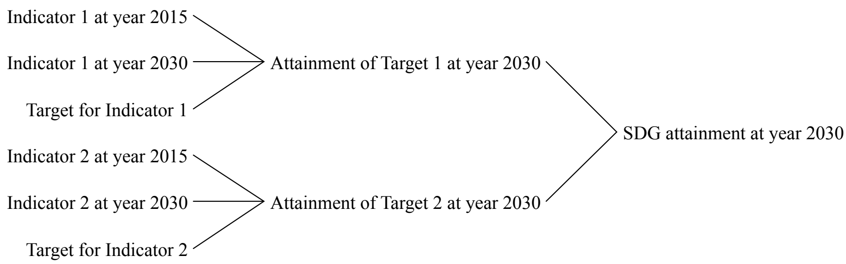


Fig. S2. Diagram of SDG attainment determination. The SDG attainment at years 2030 is the average of the attainments of Targets 1 and 2 at year 2030. The attainment of each target is the degree to which the gap between the target and the indictor at year 2015 is closed, expressed in percentage.

The left side of Figure S2 shows SDG targets and indicators at year 2015 and year 2030 used to assess target performance. Typically there will be a gap between the state of the indicator at year 2015 and the target (the desired state of the indicator). Target attainment is a measure of the degree to which the gap between the target and the indicator level at year 2015 is closed by year 2030, expressed in percentage terms. As an example, let us suppose that Indicator 1 in Figure S2 is annual agricultural production per unit of labor and that Target 1 is to double the level of the year 2015 production per unit of labor by year 2030. If agricultural production is 10.2 metric tons per unit labor per year and the target is to double this to 20.4, then there is a gap of 10.2 metric tons per unit labor per year. If production per unit labor increases to 12.9 at year 2030, then the performance, or attainment, for that target at year 2030 is approximately 27 percent. The performance, or attainment, of each SDG is the average of the performances for the targets under that SDG at year 2030 (in Figure S2 the average of the attainments of Targets 1 and 2). The overall, aggregated SDG performance is then the average of all the SDG performances at year 2030.

SDG performance and synergies for the three case studies Côte d'Ivoire, Senegal, and Malawi
Figures S3 and S4 show color-coded policy impacts across the 17 SDGs for Côte d'Ivoire and Senegal, the policy impact diagram for Malawi is shown in the main text. SDG attainment at year 2030 is shown with the black line. Synergies are shown in light purple.

Fig. S3. Policy impacts, business as usual performance, SDG attainment and synergies for Côte d'Ivoire. This diagram is from Pedercini et al. (3). Note the excursions exceeding 100% attainment for SDGs 6, 8, 9, and 17 accompanied with large dis-synergy. These instances of dis-synergy indicate opportunities for re-distributing investments to other SDG policies for improved overall SDG attainment and more efficient allocation of resources.

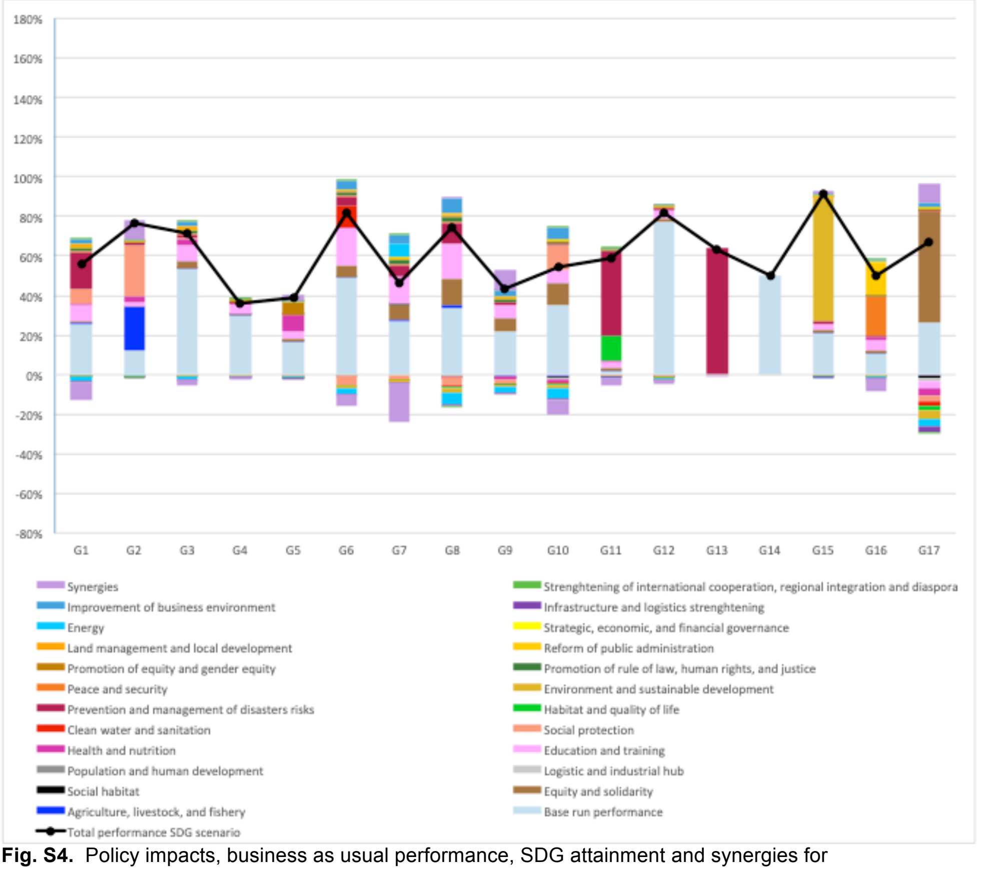


Fig. S4. Policy impacts, business as usual performance, SDG attainment and synergies for Senegal. In the case of Senegal several rounds of iterative simulations have been performed to eliminate exceedance of 100% attainment and associated dis-synergy.

Technical Note on iSDG Validation Process

The iSDG model is a System Dynamics based tool that has been designed to support national development planning. iSDG is structured to analyze medium-long term development issues at the nationwide level, and to provide practical policy insights. Specifically, the model provides policymakers and other users with an estimate of the consequences to be expected from current and alternative policy choices. Such estimates are not to be taken as exact forecasts (no model can accurately forecast long-term development trends) but as reasonable and coherent projections, based on a set of clear and well-grounded assumptions. In fact, the model's results inherently embed a high degree of uncertainty: over the time horizon considered in the simulation, a large variety of unforeseeable changes can take place, and a large number of parameters might take on different values than those observed in the past. The validation process of iSDG is therefore centered on strengthening the underlying assumptions based on currently available data and information, with a focus on improving its ability to provide insights to the key questions being addressed (1).

Validation is embedded in the broader model implementation process, and it includes structural and behavioral validation tests (8). Structural validation tests involve direct verification of structural assumptions and parameters. Behavioral validation tests involve the assessment of the model's ability to replicate the historical behavior of the main indicators for the period 1990-2017/8.

At the outset of the process, an integrated database is constructed including a few hundred time series for key indicators, covering the period 1990-2017/18 (depending on data availability). Data is initially collected from international databases (e.g., the World Bank's World Development Indicators, the International Financial Statistics database of the IMF, the FAOSTAT database of the FAO, the International Energy Association, etc.) and it is then reviewed and integrated by government experts. That process establishes confidence in the data being used, and the necessary assumptions to address data gaps are elaborated jointly with local experts. Based on that database, the model is then calibrated.

Calibration is performed by way of partial model calibration cycles (9), in which individual sectors first, and then combinations of sectors are simulated using exogenous inputs in substitution of inputs from other model sectors. Scientific literature and numerous prior applications of T21-family models provide reference ranges for most parameters in the model. Based on those reference ranges, rounds of multi-parametrical optimization are used to search for the combination of parameters values that is most compatible with the trends observed for relevant indicators in each sector.

In line with the purpose of the model, the goal of calibration is that of replicating medium to long-term trends in data; while less emphasis is given to shorter-term dynamics. The residual error from the calibration process is analyzed and broken down by component using Theil's statistics (10) into bias, unequal variation, and unequal covariation. That analysis guides further calibration towards the reduction of error of the first two types in order to properly capture medium and longer-term trends in data, with less weight on error of non-systematic nature, that is due to the inability of the model to capture short-term fluctuations.

The result of the calibration process is further reviewed by local experts, and parameters values are checked against evidence from local studies. Often, the initial core structure of the model, common to most applications, cannot replicate historical data sufficiently well for some indicators, indicating the need for a revision of the model's structure and assumptions. Modifications to algorithms as well as the introduction of additional sectors to the model are then allowed, until the proposed theory of change can explain past developments sufficiently well.

Finally, results from policy analysis are further tested by way of sensitivity analysis, i.e. performing Monte Carlo simulations in order to assess the sensitivity of the resulting policy recommendations to the set of parameter values being used. While the whole validation process as described above is significantly time consuming, it is essential not only to the structural validity of the model, but also to build confidence in the results produced, which is of prime importance for the success of the overall policy-support exercise.

References

1. J. W. Forrester, Industrial Dynamics, Cambridge, MA, Productivity Press (1961).

2. M. Pedercini, G. Barney, Dynamic analysis of interventions designed to achieve millennium development goals (MDG): The case of Ghana. Socio- Economic Planning Sciences 44: 89–99 (2010).

3. M. Pedercini, G. Zuellich, K. Dianati, S. Arquitt, Towards achieving the SDGs in Ivory Coast – simulating pathways to sustainable development. Sustainable Development (2018).

4. P. Martens, M. Raza, Is globalization sustainable? Sustainability 2(1), 280-293 (2010).

5. World Bank, Data. Accessed from https://data.worldbank.org/indicator/IC.FRM.BRIB.ZS 27 May 2019.

6. D. Kaufmann, A. Kraay, M. Mastruzzi, The Worldwide Governance Indicators : A Summary of Methodology, Data and Analytical Issues. World Bank Policy Research Working Paper No. 5430 (Washington D.C.: World Bank) (2010).

7. D. Kaufmann, A. Kraay, Worldwide Governance Indicators (WGI), (Washington D.C.: World Bank), http://info.worldbank.org/governance/wgi/index.aspx#home (deposited 2015).

8. Y. Barlas, Formal aspects of model validity and validation in system dynamics, System Dynamics Review, 12(3), pp. 183-210 (1996).

9. J. B. Homer, Partial-model testing as a validation tool for system dynamics (1983). System Dynamics Review, 28(3), 281–294 (2012).

10. J. D. Sterman, Appropriate summary statistics for evaluating the historical fit of system dynamics models, Dynamica, 10(2): 51-66 (1984).

III

Regional Achievements of Well-being SDGs in the Anthropocene

Regional Achievements of Well-being SDGs in the Anthropocene

David Collste [1,2,*], Sarah E. Cornell[1], Jorgen Randers[3], Johan Rockström[4] and Per Espen Stoknes[3]

[1] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[2] Centre D'Etudes et de Recherches sur le D´eveloppement International (CERDI-CNRS), Université Clermont-Auvergne, 65 Boulevard F. Mitterrand, 63000 Clermont-Ferrand, France
[3] BI Norwegian Business School, Oslo, Norway
[4] Potsdam Institute for Climate Impact Research, Potsdam, Germany
* Correspondence: david.collste@su.se

Non-technical summary: Transforming to sustainability requires measures of human well-being that are both well-grounded and socially accepted. We identify and track development of well-being SDG indicators towards GDP per person in seven world regions and the world as a whole. We find that well-being SDGs, and hence the associated well-being frameworks, are reached at an income threshold where earlier frameworks have identified that people are also reported as being satisfied with their lives.

Technical summary: The 2030 Agenda include global ambitions to meet human needs and aspirations. However, prospects are unclear for attaining the well-being oriented SDGs without worsening environmental deterioration, thereby threatening the success of the whole 2030 Agenda. Nascent World-Earth modelling efforts link human well-being with global environmental impacts through economic production, which is tracked by GDP - in modelling and real-world decision-making alike. This raises the question of how GDP per person relates to achievement of well-being as targeted by the SDGs. We examined historic correlations on five-year intervals, 1980-2015, between average income and the advancement on indicators on SDGs 1 to 7. This was done both for seven world regions and the world as a whole. We find uniform patterns of saturation for all regions above a clear income threshold around US$15 000 measured in 2011 US$ purchasing power parity (PPP)– a level where main human needs and capabilities are met, consistent with studies of life satisfaction and the Easterlin paradox. We observe stark differences with respect to scale: the patterns of the world as an aggregated whole develop differently from all its seven regions, with implications for World-Earth model construction - and sustainability transformations.

Keywords: Sustainable Development Goals; 2030 Agenda; Planetary Boundaries; Safe Operating Space; Human Needs; Capabilities approach; Easterlin paradox; Sustainability; Integrated Assessment Models; IAMs

1. Introduction

The global community has adopted the United Nations 2030 Agenda challenge to reach the 17 Sustainable Development Goals (SDGs) by 2030 (United Nations, 2015). However, global advances on human well-being SDGs in the context of the conventional GDP-based growth paradigm (Wiedmann et al., 2020) could generate systemic deterioration of the biophysical environment (O'Neill et al., 2018) or even trigger large-scale Earth system regime shifts (Steffen et al., 2018). This prospect would undermine social gains made under the 2030 Agenda and hinder future development. To avoid these risks, human development would have to take place within the biophysical constraints of the planetary 'safe operating space' (Raworth, 2012; Rockström et al., 2009; Steffen et al., 2015). But is this at all possible?

Current integrated modelling frameworks can provide valuable insights into the social, environmental and economic implications of pursuing multiple SDGs (Hughes, 2019), but they are not constructed and configured to deal with systemic interactions among all the SDGs (van Soest et al., 2019). Nor are these models constrained within the comparatively stable and predictable Earth system conditions of the Holocene highlighted by the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). There is, furthermore, a paucity of models with bidirectionally integrated social-ecological components (Hughes, 2019; Verburg et al., 2016). Zimm et al. (2018) as well as van Soest et al. (van Soest et al., 2019) have therefore called for integrated assessment models that meaningfully cover more human dimensions of the SDGs. The SDGs also starkly expose the gap between models appropriate for global policy contexts (energy/economy and climate-focused integrated assessment models are well-established examples), and models informing decisions at the national level of policy makers' typical scope and influence (Collste et al., 2017; Hughes, 2019; Pedercini et al., 2019). National actions taken independently may not add up to desired global outcomes, and 'problem shifting' and spillovers to other sectors and locations are recognized as a global implementation weakness (Engström et al., 2021).

Regional analysis can provide generalizable policy insights that are also relevant for national decision-makers, while remaining closer to representation of globally systemic relationships, such as tracking how global well-being goals influence pressures on the planetary boundaries. Our highly aggregated quantitative simulation model, *Earth3,* allows transparent exploration of pathways of future regional and global development (Goluke et al., 2018; Randers et al., 2018, 2019). *Earth3* builds on insights gained from earlier global system modeling endeavors (Meadows et al., 1972, 2004; Randers, 2013; Randers et al., 2016) to simulate linked socio-economic and environmental developments over time towards 2050, taking the 17 SDGs and nine planetary boundaries into consideration. It makes assessments for seven world regions and for the world as a whole (Randers et al., 2019). *Earth3*'s causal structure and parametrization provide insights on patterns of regional achievements on human well-being goals in the global context. Here, we discuss these insights with the aim to maximize transparency about the socio-economic features of the model, both for users of the model outputs in policy and practice contexts and for integrated model developers who may view *Earth3* as a prototype or skeleton for new-generation integrated World-Earth models (Donges et al., 2017, 2020) that connect human and Earth system dynamics. As this paper was written in conjunction with the development of the *Earth3* model, the findings have supported the model development including its parametrizations. However, the paper's analysis stands on its own and its quantitative exploration are based in the different sets of data assembled and transformed in the development of the model and not on model simulations.

2. Materials and Methods

2.1. A common tracker for human well-being, consumption and production and social-ecological disruptions

In all global models, the selection of indicators and parametrizations embeds fundamental assumptions and encodes structural accounts of how society works. The systems diagram in Figure 1 portrays a high-level conceptualization of key feedbacks and influences in World-Earth modeling, as implemented in *Earth3* and compatible with understandings of sustainable development as meeting people's needs *"(...)while safeguarding Earth's life-support system (...)"* (Griggs et al., 2013). The diagram displays how long-term human well-being depends on balancing the reinforcing loop of production (incorporating food, industrial and service systems) against the counteracting loop of social-ecological disruptions. Production is at the center of the diagram as it enables the provision of some of people's needs required for human well-being, and it also links to pressures on planetary boundaries through the required material throughput – with the consequent risk of large-scale, abrupt and potentially irreversible social-ecological disruption.

In development policy and in integrated assessment modelling alike, the Gross Domestic Product (GDP) has long been the most widely used measurement of the value of production. GDP per person, also referred to as income per person or average income, is also the most widely used indicator of economic progress – and has also been used as a proxy for human well-being (Fanning & O'Neill, 2019; Weil, 2009). An advantage of using GDP and average income in modeling is that they have excellent worldwide data availability (Feenstra et al., 2015). However, the limitations of using a production metric as a well-being measurement are well-known (GDP was never meant for that purpose (Costanza et al., 2009)). It does not adjust for the distribution of incomes and wealth within countries, an essential element of well-being (Wilkinson & Pickett, 2009). It only counts activities that pass through official, organized markets (Himmelweit, 2017), and does not include unpaid domestic work (Himmelweit, 2017), nor leisure time(Costanza et al., 2009) which clearly contribute to human welfare. It also counts the "bads" that hamper well-being as well as the socially beneficial "goods" in economic activity. For instance, polluting activities that harm well-being can be double-counted as GDP measures the clean-up activities (if these are paid for by the government) as well as the activity itself (Costanza et al., 2004; Islam & Clarke, 2002).

Nevertheless, a key question for SDG modelling (and World-Earth modelling more generally) is what are the implications of using GDP per person as the common tracker for well-being? Here, we investigate this question, studying average income in different world regions and its correlation with indicators of human well-being as targeted by SDGs 1-7, in our examination of achievements of the 2030 Agenda (Table 1). Earlier studies, including Lamb and Rao (2015) as well as Steinberger et al. (2020) have looked at the correlations between human development indicators, climate impact and income levels. However, they have not used the plethora of indicators that overlap SDGs as well as human well-being frameworks in their studies.

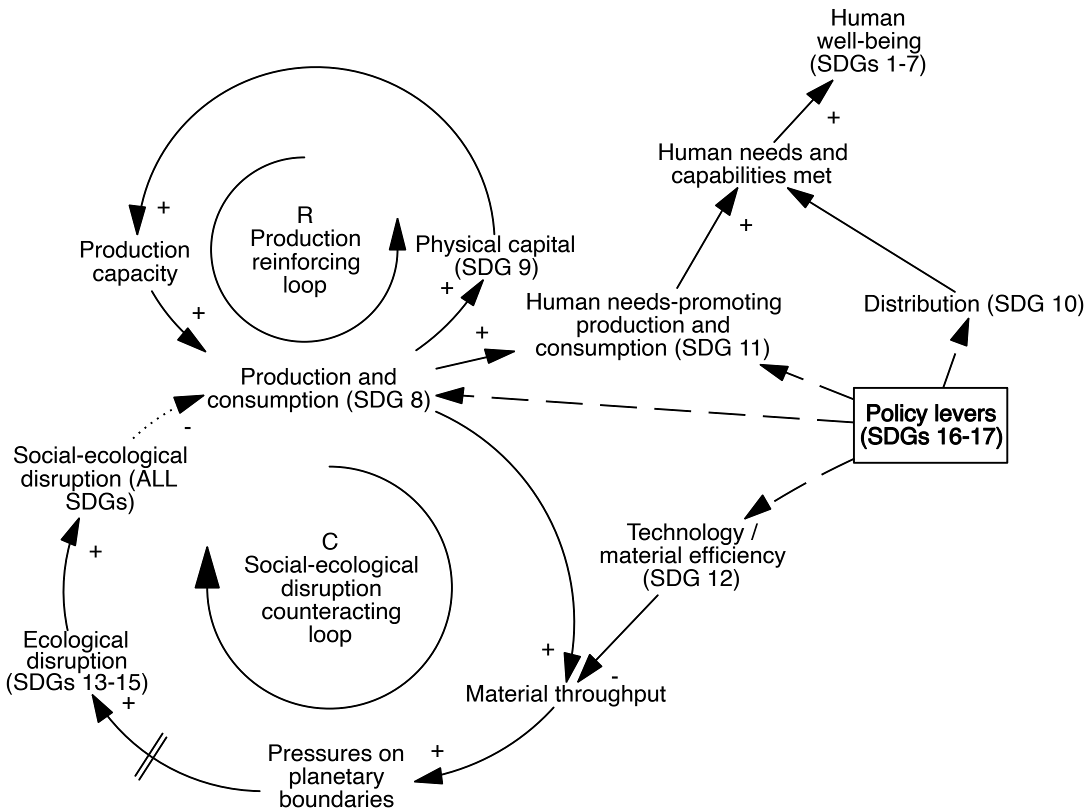


Figure 1. Conceptual sketch of key global feedbacks and influences in World-Earth modeling within the Earth3 model representing SDGs within planetary boundaries. Each arrow represents a causal relationship. The '+' signs at the arrowhead indicate that the effect is positively related to the cause (e.g., 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 in counteracting, hence the loop polarity identifier C.

2.2. The basis of well-being in SDG modelling

The 2030 Agenda resolution calls for shifting the world on to a *"sustainable and resilient path"* where *"all human beings can fulfil their potential in dignity and equality and in a healthy environment"* (United Nations, 2015). Representing SDGs 1 to 7 in World-Earth modelling thus requires sustainability measures and frameworks that go beyond preference satisfaction theories of conventional welfare economics (Penz, 1986), but that can still be linked to measures of production and average income. In preference satisfaction theory, individual preferences and well-being are best judged by individuals themselves, and people are primarily seen as self-interested and rational. Objective monetary measures such as average income are useful as all well-being satisfaction options are seen as interchangeable. Real-world problems with preference satisfaction theory are that preferences often change when available options change (as people become richer they may seek yet higher incomes to satisfy new preferences)(Easterlin, 1974, 2003). It is also impossible to quantify, compare and weight one person's preference satisfaction against others'. In addition, there are limits to knowledge and people oftentimes do not act according to economists' account of rationality (Gough, 2015; Kahneman, 2012).

The life satisfaction approach has been proposed as an alternative basis(Diener, 1994; Layard, 2005), where well-being is measured subjectively by the extent to which people are happy with their lives. Easterlin (1974, 2003) argued early that income affects life satisfaction only up to a certain level. The Easterlin paradox is the observation that while there is a clear positive correlation between average incomes and life satisfaction within a population, the same pattern does not hold over time as these incomes increase beyond a given threshold. At lower levels, income has a strong effect on life satisfaction as it may mediate the satisfaction of *"…the most basic of physiological needs"* (Howell & Howell, 2008, p. 538). Frey and Stutzer (2010) argue that the relationship between income and life satisfaction levels off somewhere around US$15,000 of average income per person per year (converted to purchasing power parity, PPP, constant 2011 US$, as used in previous *Earth3* studies and all the following discussion). At this level, the correlation between average income and measures of life satisfaction breaks down. Others have however argued that the positive correlation between life satisfaction and income is still positive beyond this level, although the relationship is weaker (Deaton, 2008).

The capabilities approach sees freedom to achieve well-being as society's primary goal and focuses on people's capabilities to achieve outcomes that they themselves value and *"have reasons to value"* (Sen, 2001, p. 291). This resonates with the text of the 2030 Agenda resolution: *"a world […] of equal opportunity permitting the full realization of human potential and contributing to shared prosperity"* (United Nations, 2015). However, the operability of this approach in World-Earth modelling is limited. While 'core capabilities' have been defined (Nussbaum, 2011), measuring them would entail enumerating not just the freedoms that individuals choose but also the almost infinite number of open opportunities they have to choose from (Gough, 2015). Brock (2009) argues that for the basic requirements for a decent life (such as those partly covered under SDGs 1 to 7), the capabilities approach converges with the human needs approach (Doyal & Gough, 1991; M. A. Max-Neef, 1992), which better allows for operationalization. The human needs approach proposes minimum levels of fundamental provisions that should be met for all people, and which can be objectively measured.

In Table 1, we show how SDGs 1 to 7 relate to some of Doyal and Gough's (Doyal & Gough, 1991; Gough, 2017) indicators for human needs and Nussbaum's (Nussbaum, 2011) core capabilities. Doyal and Gough's list of prerequisite basic needs, and indicators for intermediate need-satisfaction, converges well with the indicators for the SDGs that we have chosen for inclusion in *Earth3* (see Table 1). In other words, the objective indicators for SDGs 1-7 used in our study have many overlaps with both a human needs framework and the capabilities approach.

Table 1. Indicators and threshold values for the UN Sustainable Development Goals 1-7 used in *Earth3*, and how they relate to Doyal and Gough's(Doyal & Gough, 1991; Gough, 2017) indicators for human needs and Nussbaum's(Nussbaum, 2011) core capabilities. More details are available in supplementary information.

SDG	Indicator for SDG achievement	Earth3 SDG threshold value	Indicator for human need (Doyal & Gough, 1991)	As referred to in core capabilities (Nussbaum, 2011)
1. No poverty	Fraction of population living below 1.90$ per day (%)	Less than 2%.	Economic security, "% in absolute poverty" under indicators for intermediate need-satisfaction, p.190	Central Capability 10. Control over one's environment (…) (B) Material. Being able to hold property (both land and movable goods), and having property rights on an equal basis with others; having the right to seek employment on an equal basis with others;
2. Zero hunger	Fraction of population undernourished (%)	Less than 7%.	Appropriate nutritional intake, "Calorie consumption below FAO/ WHO requirements", p. 219	"to be adequately nourished" under Central Capability 2. Bodily health. p.33
3. Good health	Life expectancy at birth (years)	More than 75 years.	Physical health, Mental health and Appropriate healthcare "Life expectancy at various ages", p. 190	"Being able to live to the end of a human life of normal length", under Central Capability 1. Life. p. 33
4. Quality education	School life expectancy (years)	More than 12 years.	Appropriate education and Cultural understanding/teachers "Years of formal study", p.220	"adequate education", under Central Capability 4. Senses, imagination, and thought. p. 33
5. Gender equality	Gender parity in schooling (1) The ratio between expected schooling for boys and girls respectively.	More than 0.95. (1.0 implies perfect equality in expected years of schooling).	Procedural, material and distributional preconditions "Gender differences in need satisfaction", p. 267	"provisions of nondiscrimination on the basis of (…) sex" under Central Capability 7 Affiliation, and "seek employment on an equal basis with others" under Central Capability 10. Control over one's environment. p. 34
6. Safe water	Fraction of population with access to safe water (%)	More than 98%.	Clean water "% lacking access to adequate safe water", p. 219	"to be adequately nourished" under Central Capability 2. Bodily health. p.33
7. Enough energy	Fraction of population with access to electricity (%)	More than 98%.	Procedural, material and distributional preconditions "Energy consumption per capita", p. 261	Not included as a Central Capability

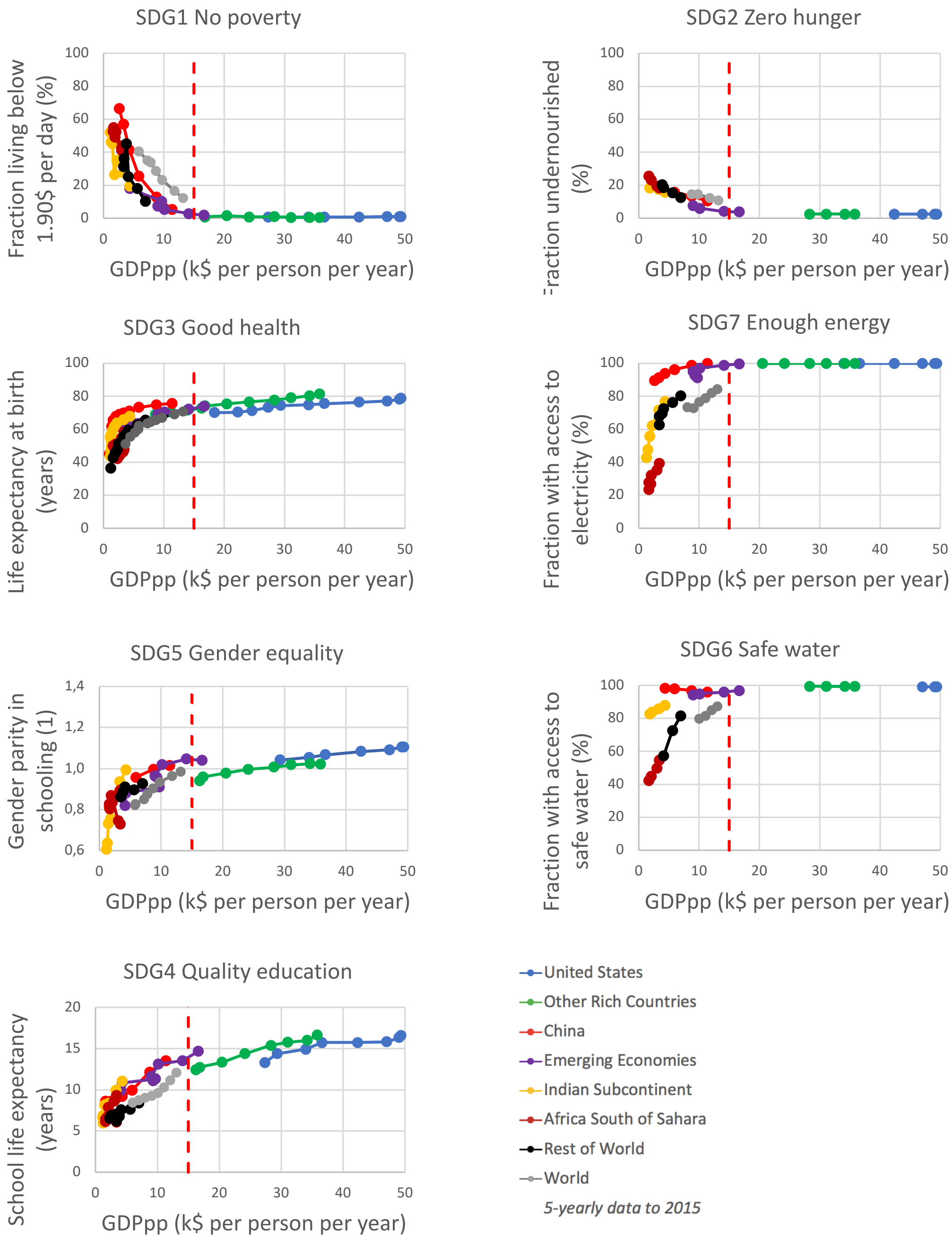


Figure 2. All regions develop to increased GDPpp (measured in constant 2011 PPP $). For data time range, see Supplementary information. Vertical line represents GDPpp at 15k$, based on Frey and Stutzer (Frey & Stutzer, 2010). Data sources: adapted from World Development Indicators, The World Bank,World Bank EdStats, UN Population statistics and Penn World Tables (Feenstra et al., 2015).

3. Results

The graphs presented in Figure 2 show the observed historic relationships between average income and the respective SDG indicators over five-year intervals, from 1980-2015.

The *regional* data in Figure 2 indicates clear saturation levels and patterns of diminishing returns, where income per capita levels off with respect to progress on the seven SDGs. Poverty (SDG 1) reach levels under 2 % at average incomes per person around $15,000, and undernourishment (SDG 2) gets under the 7 % threshold between $10,000 and $15,000. Effects on health (SDG 3) are reached between $10,000 and $15,000, with life expectancy passing the 75 years threshold. Educational attainment (SDG 4) above 12 years of expected schooling is reached between $10,000 and $15,000. Gender equality in expected years of schooling (SDG 5) is correlated with a GDP per person of less than $10,000 for China and the Indian subcontinent. Africa South of Sahara and Rest of World can be assumed to reach gender equality in expected schooling at similar income levels, if we assume that the trends depicted in the graph continue. For widespread (more than 98%) access to safe water (SDG 6), the patterns are not as uniform, and saturation patterns not as clear. However, trends seem to suggest that access to safe water is correlated with a GDP level of around $15,000. Finally, the electricity access threshold (more than 98%, SDG 7) is correlated with GDP levels of less than $10,000 for all regions.

From the data portrayed in Figure 2 we can derive three main insights: there is a relatively low level of average incomes above which the seven SDGs are met, there are scale differences apparent when comparing world data with regional data, and regions differs from each other. These are elaborated on below.

4. Discussion

4.1. The well-being-production relationship

Our observations indicate a level of average income per person at which the seven SDGs are met. We have added red dashed lines marking where the relationship between income and life satisfaction levels off according to Frey & Stutzer (2010) to the graphs in Figure 2. The 'levelling off point' of US$15,000 was achieved in the United States before 1965, in Other Rich Countries around 1975, and in Emerging Economies in 2010. It is above the most recent income data for China ($11,370 for 2015), and just above the World average ($13,130 in 2015). Based on the regional patterns, this can seem to point towards that if we would treat the World as a region, we could reach the human-well-being SDGs very soon. Furthermore, to the extent that the indicators we use converge with the notions of human needs and capabilities, the deeper social vision of the 2030 Agenda would could be reached around 2022, half-way to the 2030 Agenda goal-line, given the current size of the world economy. However, these World averages are evidently hiding the large inter and intra-country and regional inequalities that need to be effectively tackled in order to get close to eradicating global poverty and reaching the SDGs, as has earlier been shown by Woodward (2015).

The human-well-being threshold in our data can be related to what Max-Neef (M. Max-Neef, 1995) has referred to as a threshold beyond which economic growth does not bring about significantly more life quality but may even begin to deteriorate, in his data this lies between $15,000 and $25,000 translated to 2011 PPP $. The related concept genuine economic progress (GPI) that is measuring economic welfare has been argued to peak around $8,000 (Kubiszewski et al., 2013).

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

4.2. Differences between scales

The picture looks different if we consider the World data average. For the world as a whole (grey in the graphs in Figure 2), progress on the seven SDGs appears to be linear with respect to income per person, with no indication of saturation with respect to higher rates of income per person.

A fallible hypothesis derived from the linear behavior of World data, without considering the regional behaviors, would be that increasing the income per person growth rates would be an effective way to improve performance on the seven SDGs. There is here a need for caution as there may be many reasons to why the World data does not indicate the same pattern of saturation as the regional data depict. It is likely that inequality plays a major role. That is, the minority with high incomes living predominantly in United States and Other Rich Countries and their increase in wealth play a significant role in the increase of global average income as depicted with the World data, but have a limited effect on attainment of aggregated human well-being SDGs as the relevant SDGs are already met for these people/regions. An increased size of the world economy may hence not significantly affect the achievement of SDGs – especially not in a carbon-constrained world, which has been highlighted before (Woodward, 2015). This finding also highlights the need for regional dis-aggregation when drawing policy conclusions from world-Earth models. Besides, the World data's highest level of income per person is the most recent data point for 2015 at US$13,130 - and the saturation effect is likely to be seen only at yet higher levels. The World data does therefore not indicate any level of income per person for which human-well-being SDGs are attained. A similar scale effect would likely be observed if we zoomed in further and looked at national and local levels.

4.2. Regional differences

Finally, there are some consistent differences between the regions, despite the degree of uniformity of the level of income per person at which most of the seven human-well-being SDGs are met. We may phrase it as that the regions differ in their productivity in human-needs SDG performance per unit of GDP per person (a related concept is the environmental efficiency of well-being, see Knight & Rosa, 2011). If countries move towards the goal of directly reaching human-well-being SDGs and ensuring human capabilities instead of focusing on maximizing income levels, studying these regional differences and the underlying causes can give advice on delivering on more human wellbeing at lower levels of income. The problems of differences of scale as mentioned above does nevertheless also play out on the regional levels: the regions differ in population size and number of countries that are covered. It is likely that we would find even more divergences if we were to move to less aggregated data levels. Also, inequality between countries within regions play out. This pose a challenge to both analysis and model development and calls for inclusion of appropriate inequality measures in comparison and modeling – and, yet again, the relevance of considering different scales of SDG attainment. For all indicators, the United States and Other Rich Countries are on one side of the dividing line and other regions on the other.

4.2. Trade-off between human well-being and a flourishing planet?

If consumption and production - measured as GDP per person - is used as a proxy for both planetary boundaries pressures and human well-being, there is a clear trade-off between the two, and the two loops in Figure 1 have to be balanced against each other. If, instead, human well-being is based on a more inclusive framework such as the life satisfaction approach, human needs (Doyal & Gough, 1991; M. A. Max-Neef, 1992) or capabilities (Nussbaum, 2011; Sen, 2001), the levelling off portrayed in Figure 2 can be used as an argument for sufficiency. This would suggest us to not focus on GDP per person as a measure for SDG delivery, especially not beyond the indicated threshold. Instead, a focus on life satisfaction, human needs or capabilities can - help us finding inclusive sustainability pathways combining human well-being and a flourishing planet. This focus needs to be combined with increased material and energy efficiencies.

5. Conclusions

With regards to the development of our sparse set indicators of human-well-being, our data patterns are strikingly uniform across regions. As well as assisting us in building a more robust model (see Randers et al., 2019), this analysis has yielded some insights that should be taken into account in future global sustainability modelling. Analyses at the regional level can facilitate bridging national policy making with the planetary scale of the 2030 Agenda's ambitions and of the shifting Earth's system dynamics of the Anthropocene. The ways that societies react to emerging problems vary among the world's regions, hence we have traced trends in indicators of the human-well-being SDGs by region. The observed patterns give an indication of the 'business as usual' relationship between income per person and the respective SDG indicators. Through correlation analysis of these trends, we have obtained parameters both for the seven regions and for the world as a whole, that are used for the Earth3 model.

Above a certain level of income per person, well-being SDG thresholds are met for the indicators we use. Income increases above this level do not lead to significantly better achievement of well-being SDGs. This observation holds across all studied SDGs and regions, and our identified well-being SDG threshold income level is similar to those presented with regards to the life satisfaction approach - where national income increases are no longer strongly correlated with higher life satisfaction. There are pronounced regional differences in the bivariate correlations, especially when it comes to the level at which the effect of income on human-well-being SDG achievements level off.

The functional patterns are sensitive to scale. That is, the degree of aggregation hides differences and inequalities between countries. Thereby, the story of the relationship between per capita income and attainment of SDGs 1 to 7 differs if we look at the world level or at regional levels. Linear relationships emerge for the aggregated world level, and the relationships look exponential for the regions.

In 1848, John Stuart Mill argued that a future stationary-state economy could imply considerable improvements to human conditions: "It is scarcely necessary to remark that a stationary condition of capital and population implies no stationary state of human improvement. There would be as much scope as ever for all kinds of mental culture, and moral and social progress; as much room for improving the Art of Living and much more likelihood of its being improved, when minds cease to be engrossed by the art of getting on." (Mill, 1848)

It is time to shift the world's focus away from maximizing material production and GDP, to assuring human well-being – and achieving the SDGs within planetary boundaries.

Author Contributions: Conceptualization, D.C., S.C. and J. Ra.; writing—original draft preparation, D.C.; all authors have contributed to the writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The work was made possible by a grant from the Global Challenges Foundation in Stockholm. D.C. thanks the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No 675153 (ITN JD AdaptEconII).

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: The authors declare no conflict of interest.

References

Brock, G. (2009). *Global justice: A cosmopolitan account*. Oxford University Press.

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

Costanza, R., Erickson, J., Fligger, K., Adams, A., Adams, C., Altschuler, B., Balter, S., Fisher, B., Hike, J., Kelly, J., Kerr, T., McCauley, M., Montone, K., Rauch, M., Schmiedeskamp, K., Saxton, D., Sparacino, L., Tusinski, W., & Williams, L. (2004). Estimates of the Genuine Progress Indicator (GPI) for Vermont, Chittenden County and Burlington, from 1950 to 2000. *Ecological Economics*, *51*(1–2), 139–155. https://doi.org/10.1016/j.ecolecon.2004.04.009

Costanza, R., Hart, M., Talberth, J., & Posner, S. (2009). Beyond GDP: The need for new measures of progress. *The Pardee Papers*.

Deaton, A. (2008). Income, Health, and Well-Being around the World: Evidence from the Gallup World Poll. *Journal of Economic Perspectives*, *22*(2), 53–72. https://doi.org/10.1257/jep.22.2.53

Diener, E. (1994). Assessing subjective well-being: Progress and opportunities. *Social Lndicators Research*, *31*, 103–157.

Donges, J. F., Heitzig, J., Barfuss, W., Wiedermann, M., Kassel, J. A., Kittel, T., Kolb, J. J., Kolster, T., Müller-Hansen, F., Otto, I. M., Zimmerer, K. B., & Lucht, W. (2020). Earth system modeling with endogenous and dynamic human societies: The copan:CORE open World–Earth modeling framework. *Earth System Dynamics*, *11*(2), 395–413. https://doi.org/10.5194/esd-11-395-2020

Donges, J. F., Winkelmann, R., Lucht, W., Cornell, S. E., Dyke, J. G., Rockström, J., Heitzig, J., & Schellnhuber, H. J. (2017). Closing the loop: Reconnecting human dynamics to Earth System science. *The Anthropocene Review*, *4*(2), 151–157. https://doi.org/10.1177/2053019617725537

Doyal, L., & Gough, I. (1991). *A theory of human need*. Macmillan.

Easterlin, R. A. (1974). Does Economic Growth Improve the Human Lot? Some Empirical Evidence. In P. A. David & M. W. Reder (Eds.), *Nations and Households in Economic Growth: Essays in Honor of Moses Abramovitz* (pp. 89–125). Academic Press. https://doi.org/10.1016/B978-0-12-205050-3.50008-7

Easterlin, R. A. (2003). Explaining happiness. *Proceedings of the National Academy of Sciences*, *100*(19), 11176–11183.

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), 18. https://doi.org/10.1038/s42949-020-00002-w

Fanning, A. L., & O'Neill, D. W. (2019). The Wellbeing–Consumption paradox: Happiness, health, income, and carbon emissions in growing versus non-growing economies. *Journal of Cleaner Production*, *212*, 810–821. https://doi.org/10.1016/j.jclepro.2018.11.223

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2015). The Next Generation of the Penn World Table. *American Economic Review*, *105*(10), 3150–3182. https://doi.org/10.1257/aer.20130954

Frey, B. S., & Stutzer, A. (2010). *Happiness and economics: How the economy and institutions affect human well-being*. Princeton University Press.

Goluke, U., Randers, J., Collste, D., & Stoknes, P. E. (2018). *The Earth3 model system. Https://osf.io/a8mvf/*. https://osf.io/a8mvf/

Gough, I. (2015). Climate change and sustainable welfare: The centrality of human needs. *Cambridge Journal of Economics*, *39*(5), 1191–1214. https://doi.org/10.1093/cje/bev039

Gough, I. (2017). *Heat, greed and human need: Climate change, capitalism and sustainable wellbeing*. Edward Elgar Publishing.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M. C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., & Noble, I. (2013). Policy: Sustainable development goals for people and planet. *Nature*, 305–307. https://doi.org/10.1038/495305a

Himmelweit, S. (2017). Feminist economics: Why all economists should be feminist economists. In *Rethinking Economics* (pp. 60–75). Routledge.

Howell, R. T., & Howell, C. J. (2008). The relation of economic status to subjective well-being in developing countries: A meta-analysis. *Psychological Bulletin*, *134*(4), 536–560. https://doi.org/10.1037/0033-2909.134.4.536

Hughes, B. B. (2019). *International futures: Building and using global models*. Academic Press (Elsevier Ltd). https://doi.org/10.1016/C2014-0-04231-1

Islam, S. M., & Clarke, M. (2002). The relationship between economic development and social welfare: A new adjusted GDP measure of welfare. *Social Indicators Research*, *57*(2), 201–229.

Kahneman, D. (2012). *Thinking, fast and slow*. Penguin Books.

Knight, K. W., & Rosa, E. A. (2011). The environmental efficiency of well-being: A cross-national analysis. *Social Science Research*, *40*(3), 931–949. https://doi.org/10.1016/j.ssresearch.2010.11.002

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., & Aylmer, C. (2013). Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics*, *93*, 57–68. https://doi.org/10.1016/j.ecolecon.2013.04.019

Lamb, W. F., & Rao, N. D. (2015). Human development in a climate-constrained world: What the past says about the future. *Global Environmental Change*, *33*, 14–22. https://doi.org/10.1016/j.gloenvcha.2015.03.010

Layard, P. R. G. (2005). *Happiness: Lessons from a new science*. Allen Lane.

Max-Neef, M. (1995). Economic growth and quality of life: A threshold hypothesis. *Ecological Economics*, *15*(2), 115–118. https://doi.org/10.1016/0921-8009(95)00064-X

Max-Neef, M. A. (1992). *From the outside looking in: Experiences in "barefoot economics."* Atlantic Highlands, New Jersey, USA : Zed Books.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). *The Limits to Growth: A Report for THE CLUB OF ROME'S Project on the Predicament of Mankind*. Universe Books.

Meadows, D. H., Randers, J., & Meadows, D. L. (2004). *Limits to Growth: The 30-Year Update* (3 edition). Chelsea Green Publishing.

Mill, J. S. (1848). *Principles Of Political Economy*. John W. Parker.

Nussbaum, M. C. (2011). *Creating Capabilities: The Human Development Approach*. Harvard University Press.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95. https://doi.org/10.1038/s41893-018-0021-4

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

Penz, G. P. (1986). *Consumer sovereignty and human interests*. Cambridge University Press.

Randers, J. (2013). *2052 – A Global Forecast for the Next Forty Years using a mix of models*. http://www.cse.iitb.ac.in/~damani/ctaraReading/RandersFuture2052.pdf

Randers, J., Golüke, U., Wenstøp, F., & Wenstøp, S. (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. https://doi.org/10.5194/esd-7-831-2016

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

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), 1–11. https://doi.org/10.1017/sus.2019.22

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.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2), Art. 32. http://www.ecologyandsociety.org/vol14/iss2/art32/

Sen, A. (2001). *Development as Freedom*. Oxford University Press.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., &

Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855–1259855. https://doi.org/10.1126/science.1259855

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Steinberger, J. K., Lamb, W. F., & Sakai, M. (2020). Your money or your life? The carbon-development paradox. *Environmental Research Letters*, *15*(4), 044016. https://doi.org/10.1088/1748-9326/ab7461

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development, General Assembly resolution 70/1* (Resolution A/RES/70/1). undocs.org/en/A/RES/70/1

van Soest, H. L., van Vuuren, D. P., Hilaire, J., Minx, J. C., Harmsen, M. J. H. M., Krey, V., Popp, A., Riahi, K., & Luderer, G. (2019). Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. *Global Transitions*, *1*, 210–225. https://doi.org/10.1016/j.glt.2019.10.004

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. van der, Seitzinger, S., Steffen, W., & Syvitski, J. (2016). Methods and approaches to modelling the Anthropocene. *Global Environmental Change*, *39*, 328–340. https://doi.org/10.1016/j.gloenvcha.2015.08.007

Weil, D. N. (2009). *Economic Growth*. Pearson.

Wiedmann, T., Lenzen, M., Keyßer, L. T., & Steinberger, J. K. (2020). Scientists' warning on affluence. *Nature Communications*, *11*(1), 3107. https://doi.org/10.1038/s41467-020-16941-y

Wilkinson, R. G., & Pickett, K. (2009). *The Spirit Level: Why More Equal Societies Almost Always Do Better*. Allen Lane.

Woodward, D. (2015). Incrementum ad Absurdum: Global Growth, Inequality and Poverty Eradication in a Carbon-Constrained World. *World Economic Review*, *4*, 43–62.

Zimm, C., Sperling, F., & Busch, S. (2018). Identifying Sustainability and Knowledge Gaps in Socio-Economic Pathways Vis-à-Vis the Sustainable Development Goals. *Economies*, *6*(2), 20. https://doi.org/10.3390/economies6020020

Supplementary information:

Regional Achievements of Well-being SDGs in the Anthropocene

David Collste, Sarah E. Cornell, Jorgen Randers, Johan Rockström, Per-Espen Stoknes

Abstract

This technical note contains supplemental material to *Regional Achievements of Well-being SDGs in the Anthropocene*. This includes data selection, sources, and analysis.

1. Introduction: Data selection and sources

Transparent world models require simple yet responsive indicators. Our choices of indicators to assess achievements on SDGs 1 to 7 were based first on the goal formulations in the UN 2030 Agenda resolution[1]. Where these formulations are not compatible with quantitative system modelling, we drew upon the SDG Index and Dashboards Reports[i]. As we wanted to combine a global and regional focus, we were also constrained by the availability of historical data. 2015 was the most recent year for which data were available for both our suite of SDG indicators and the planetary boundaries processes (the latter used for the wider Earth3 model). Most fundamentally, we chose indicators that were straightforward and comprehensible for an interested public in order to make our analysis (and the *Earth3* model) as accessible as possible. The data sources we came to use are all publicly available via The World Bank and UN population statistics. For the GDP tracker, we used the Penn World Tables' *Real GDP measured in expenditures in PPP-adjusted 2011 USD* (RGDPe), which is suitable *"to compare relative living standards across countries and over time"*[ii]. The regional data is weighted by population size when aggregating (the primary) national data to regional levels.

Table 1 lists the modelled indicators we have used to track the degree to which the 7 human-needs SDGs are achieved, by region. Details on each SDG is presented in section 2 below. We use the seven world regions as specified in section 0, and weight by population size when aggregating (the primary) national data to regional levels.

SDG		Indicator
The 17 goals for humanity agreed by the UN in 2016		***Indicator for the achievement of each Sustainable Development Goal***
1	**No poverty**	Fraction of population living below 1.90$ per day (%)
2	**Zero hunger**	Fraction of population undernourished (%)
3	**Good health**	Life expectancy at birth (years)
4	**Quality education**	School life expectancy (years)
5	**Gender equality**	Gender parity in schooling (1)
6	**Safe water**	Fraction of population with access to safe water (%)
7	**Enough energy**	Fraction of population with access to electricity (%)

Table 1: The SDG and the chosen indicators.

2. Data analysis of the 17 SDGs

In general, the following procedure has been followed with some alterations for the different SDGs as specified under each goal:

- We portray the historical data as a function of GDP per person (GDPpp, measured in 2011 Purchase Power Parity adjusted US$). Country data has been averaged over five-year periods. As there are shortages of historical data for many countries, we have averaged the numbers based on the population sizes of countries where data is available, as part of the respective regions.

SDG1 – No poverty

For SDG1 – No poverty we use the commonly used definition *Fraction of population living below 1.90$ per day*. The SDG target is to "eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day"[iii]. In the latest World Bank data this has however been updated to $1.90 per day using 2011 international prices. This indicator is also included in the *SDG Index and Dashboards Report* 2017[iv] in relation to SDG1. Furthermore, data availability is good. We have retrieved data per region from the World Bank DataBank[v] for the following years for the respective regions (displayed in manuscript):

- 1980–2015:
  - United States
- 1985–2015:
  - Other Rich Countries
  - Emerging Economies
  - Indian Subcontinent
  - Africa South of Sahara
- 1990–2015
  - China
  - Rest of World

SDG2 – Zero hunger

For SDG2 – Zero hunger we use the indicator *Fraction of population undernourished*. Undernourishment is also used as one of the indicators in the *SDG Index and Dashboards Report* 2017[vi]. We have obtained three data points for all regions, for 2000–2015, retrieved from the World Bank[vii].

SDG3 - Good health

For SDG3 – Good health we use the indicator *Life expectancy at birth*. Data is retrieved from the UN Population Statistics from 1965[viii] and portrayed in manuscript. The SDG Index and Dashboard Report 2017[ix] includes a similar variable, *Healthy life expectancy at birth*. We found data availability for *healthy life expectancy* not as good as for *life expectancy*. Our threshold values of 75 years are based on *SDG Index and Dashboards Report* 2017 and the average difference between data for *Life expectancy* and *Healthy life expectancy* for different countries.

SDG4 – Quality education

For SDG4 – Quality education we use the indicator *School life expectancy, primary to tertiary, both sexes* as our indicator. *School life expectancy* is included in the calculations of the Human Development Reports[x] and the *SDG Index and Dashboards Report* 2017[xi]. The threshold level of 12 is consistent with the *SDG Index and Dashboards Report* 2017. It also corresponds well with the explicit mentioning of secondary education in the Agenda 2030 resolution[xii]. We retrieved the data from the World Bank[xiii] for 1980–2015 for all world regions.

SDG5 - Gender equality

For SDG5 – Gender equality we use *School life expectancy, primary to tertiary, gender parity index (GPI)* as our indicator. The data was retrieved from the World Bank DataBank[xiv] for 1980–2015 for all world regions except United States (1985–2015) and Rest of World (1995–2015) and is portrayed in the manuscript. Note that we use the indicator *expected years of schooling* and *not* years of schooling for both SDG5 and SDG4. Gender parity of expected years of schooling is the expected years of schooling for women, divided by the expected years of schooling for men. A value of 1 indicates that both men and women have the same expected years of schooling, a value below 1 indicates that men have higher expected years of schooling and a value above 1 that women have higher expected years of schooling.

SDG6 – Safe water

For SDG6 – Safe water we use *People using at least basic drinking water services (% of population)* as our indicator. The data was retrieved from the World Bank[xv] for 2000–2015 for all regions except United States and Rest of World (both 2005–2015), and are plotted in the manuscript. The *SDG Index and Dashboards Report* 2017 includes the similar indicator: *Access to improved water*. We use the threshold value that the *SDG Index and Dashboards Report* 2017 suggests for this indicator, 98%.

SDG7 – Enough energy

For SDG7 we use the indicator *Access to electricity (% of population)* that we retrieved from the World Bank[xvi] for 1990–2015 for all our regions, see plot in manuscript. Access to electricity is also included as an indicator for SDG7 in the *SDG Index and Dashboards Report* 2017. We use the same threshold value as in the *SDG Index and Dashboards Report* 2017[xvii], 98%.

3. Specification of the seven regions

We developed a regional database of historical performance on all SDG indicators and analyzed the relationships between historical income levels and outcomes on the human-needs SDGs. We used seven world regions and the world as a whole, giving us eight geographic categories.

The source of the national economic data we have used is the Penn World Tables, version 9[xviii], that is available for download at www.ggdc.net/pwt. All GDP data are in 2011 PPP $, in the table below 2011 PPP G$/y. (1 G$ = 1 billion $ = 1000 million $.) Population data is from UN Population Division: https://esa.un.org/unpd/wpp/DataQuery/

We have used seven regions for our analysis: United States, Other Rich Countries, Emerging Economies, China, Indian Subcontinent, Africa South of Sahara and Rest of World. The sequence in Table 2 follows an order of descending GDPpp per region average.

We have disregarded "region 8", which consists of a few super-rich countries outside the OECD. This cluster of countries is small (<1% of world population), and they are statistical outliers that distort the analysis.

Table 2: Regionalization of the Earth3 model.

REGION	Country	Population	GDP	GDPpp
		2015	2015	2015
		Mp	G$/y	$/p-y
		UN	PWT	(=D/C)
1. United States (USA)				
	US, Including Puerto Rico and US Virgin Islands	327	16 705	*51 100*
	SUM USA	***327***	***16 705***	***51 100***
2. Other Rich Countries (ORC)				
	Australia	23,8	1 017	*42 700*
	Austria	8,7	407	*46 800*
	Belgium	11,3	490	*43 400*
	Canada	36,0	1 507	*41 900*
	Chile	17,8	383	*21 500*
	Czech Republic	10,6	336	*31 700*
	Denmark	5,7	254	*44 600*
	Estonia	1,3	38	*29 200*
	Finland	5,5	221	*40 200*
	France	64,5	2 603	*40 400*
	Germany	81,7	3 707	*45 400*
	Greece	11,2	286	*25 500*
	Hungary	9,8	256	*26 100*
	Iceland	0,3	14	*46 700*
	Israel	8,1	264	*32 600*
	Italy	59,5	2 141	*36 000*
	Japan	128,0	4 483	*35 000*

	Luxembourg	0,6	53	*88 300*
	Netherlands	16,9	797	*47 200*
	New Zealand	4,6	156	*33 900*
	Norway	5,2	331	*63 700*
	Poland	38,3	972	*25 400*
	Portugal	10,4	296	*28 500*
	Slovakia	5,4	155	*28 700*
	Slovenia	2,1	63	*30 000*
	South Korea	50,6	1 758	*34 700*
	Spain	46,4	1 567	*33 800*
	Sweden	9,8	433	*44 200*
	Switzerland	8,3	480	*57 800*
	UK	65,4	2 589	*39 600*
	SUM ORC	***748***	***28 057***	***37 500***
3. Emerging Economies (EE)				
Characteristic: big mid-income countries				
	Argentina	43,4	869	*20 000*
	Brazil	206,0	3 064	*14 900*
	Iran	79,4	1 215	*15 300*
	Kazakhstan	17,8	407	*22 900*
	Malaysia	30,7	692	*22 500*
	Mexico	125,9	1 988	*15 800*
	Russia	143,9	3 448	*24 000*
	Romania	19,9	409	*20 600*
	Thailand	68,7	946	*13 800*
	Turkey	78,3	1 491	*19 000*
	Ukraine	44,7	465	*10 400*
	Venezuela	31,2	434	*13 900*
	SUM EE	**890**	**15 428**	***17 300***
4. China				
	Taiwan	23,5	1 039	*44 200*
	China	1 397,0	17 080	*12 200*
	Hong Kong	7,3	374	*51 200*
	SUM CHINA	**1 428**	**18 493**	***13 000***
5. Indian Subcontinent				
Characteristic: poor and populous				
	Bangladesh	161,2	459	*2 800*
	India	1309,0	6 767	*5 200*
	Pakistan	189,4	860	*4 500*
	SUM INDIAN SC	**1 660**	**8 086**	***4 900***
6. Africa South of Sahara (ASoS)				
Characteristic: poor and resource rich				

	Angola	27,9	193	*6 900*
	Cameroon	22,8	61	*2 700*
	Congo	76,2	91	*1 200*
	Cote d'Ivoire	23,1	74	*3 200*
	Ethiopia	99,9	128	*1 300*
	Ghana	27,6	96	*3 500*
	Kenya	47,3	124	*2 600*
	Madagascar	24,2	29	*1 200*
	Mozambique	28,0	31	*1 100*
	Nigeria	181,2	976	*5 400*
	Sudan	38,6	190	*4 900*
	South Africa	55,3	655	*11 800*
	Tanzania	53,9	112	*2 100*
	Uganda	40,1	69	*1 700*
	SUM AFRICA SoS	**746**	**2 829**	***3 800***
7. Rest of the World – 120 (RoW)				
Sum world (from other data)		7 383	103 866	*14 100*
Sum of regions 1–8		5 847	92 380	*15 800*
=	***SUM ROW 120***	**1 536**	**11 486**	***7 500***
8. Super-rich outside OECD				
Characteristic: "authoritarian wealth"				
	Quatar	2,5	314	*125 600*
	Saudi Arabia	31,6	1 483	*46 900*
	Singapore	5,5	400	*72 700*
	UAE	9,2	585	*63 600*
	SUM SUPER-RICH	**49**	**2 782**	***57 000***
MEMO				
The following countries have more than .3% of total population or GDP. That is >22Mp or >300G$/y				
But have still been left in the Rest of World category				
	Afghanistan	33,7		
	Algeria	39,9	499	*12 500*
	Colombia	48,2	602	*12 500*
	Egypt	93,8	888	*9 500*
	Indonesia	258,2	2 470	*9 600*
	Iraq	36,1	427	*11 800*
	Morocco	34,8	243	*7 000*
	Myanmar	52,4	286	*5 500*
	Nepal	28,7	61	*2 100*
	North Korea	25,2		
	Philippines	101,7	660	*6 500*

	Uzbekistan	31,0	241	*7 800*
	Vietnam	93,6	495	*5 300*
	Yemen	26,9	88	*3 300*
	SUM BIG in ROW120	**904**	**6 960**	***7 700***

[i] Sachs J. et al. (2016): *SDG Index and Dashboards - Global Report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). And Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[ii] Feenstra, R. C., Inklaar, R. & Timmer, M. P. The Next Generation of the Penn World Table. American Economic Review **105**, 3150–3182 (2015).
[iii] United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development A/RES/70/1*. New York: United Nations General Assembly.
[iv] Sachs J. et al. (2016): *SDG Index and Dashboards - Global Report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). And Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[v] https://data.worldbank.org/indicator/SI.POV.DDAY
[vi] Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[vii] https://data.worldbank.org/indicator/SN.ITK.DEFC.ZS
[viii] http://data.un.org/Data.aspx?d=PopDiv&f=variableID%3A68
[ix] Sachs J. et al. (2016): *SDG Index and Dashboards - Global Report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). And Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[x] United Nations Development Programme Human Development Reports, http://www.hdr.undp.org
[xi] Sachs J. et al. (2016): *SDG Index and Dashboards - Global Report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). And Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[xii] United Nations General Assembly Resolution A/RES/70/1 Transforming our world: the 2030 Agenda for Sustainable Development
[xiii] http://datatopics.worldbank.org/education/
[xiv] http://datatopics.worldbank.org/education/
[xv] https://data.worldbank.org/indicator/SH.H2O.BASW.ZS
[xvi] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS
[xvii] Sachs J. et al. (2016): *SDG Index and Dashboards - Global Report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN). And Sachs, J.et al. (2017): *SDG Index and Dashboards Report 2017*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).
[xviii] Feenstra, Robert C., Robert Inklaar and Marcel P. Timmer (2015), "The Next Generation of the Penn World Table" American Economic Review, 105(10), 3150-3182

IV

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

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

David Collste, Ana Paula D. Aguiar, Zuzana Harmáčková, Diego Galafassi, Laura M. Pereira, Odirilwe Seloman, and Sander van Der Leeuw

ABSTRACT. One of the current challenges of human society lies in navigating the safe operating space defined by the planetary boundaries while reaching the aspirational Sustainable Development Goals (SDGs). This is not a challenge that can be tackled everywhere in the same way. It is thus vital to ground the pursuit of the SDGs in locally prevalent worldviews and reflect specific contexts in developing coherent pathways. In addressing the need to couple global concerns with local aspirations and conditions, this paper introduces a stakeholder-based approach for visioning and exploring sustainable development pathways to meet the SDGs, facilitating context-sensitive exploration of alternative futures. The approach builds on but departs from the Three Horizons framework, a participatory approach developed for groups to think about transformative change. We present the benefits and challenges of the adapted approach in relation to an illustrative case study, the 2018 African Dialogue on The World In 2050, deliberating future pathways for agriculture and food systems in Africa. The key contribution of the paper is twofold. First, we detail the premises and steps of the Three Horizons for the SDGs (3H4SDG) approach. Second, we summarize the results of a pilot application of the approach - four alternative pathways for how food systems and agriculture can contribute to meeting the SDGs in Sub-Saharan Africa, integrated with the worldviews entangled in the narratives of the participating stakeholders. We conclude that participatory approaches grounded in systems thinking represent a promising way to link local aspirations with global goals.

Key words: 2030 Agenda; Africa; futures; scenarios; SDGs; SDG interactions; Sustainable Development Goals; three horizons; transformations;

INTRODUCTION

The United Nations' 2030 Agenda (UN 2015) was agreed by almost all countries, but its development has generally followed a top-down process. The Agenda represents an unprecedented global outline for sustainable development that has been argued to require transformative changes for its realization (Randers et al. 2018, O'Neill et al. 2018, Linnér and Wibeck 2019). Despite the Agenda's aspiration of inclusiveness in the goal formulation process (Caballero 2019), it represents a vertical approach to global agenda setting where goals are formulated at a high political level - to be realized at lower levels. Furthermore, it has been pointed out that the Agenda incorporates a uniform vision that is dominated by the idea of "progress" and what it entails (van der Leeuw 2020) - including a criticized goal on economic growth (Weber 2017). The Agenda predominantly reflects the economic discourses of Keynesianism and neoliberalism and neglect alternative economic visions (Carant 2017, Weber 2017). This uniformity could cause a backlash in societies set to implement the Agenda while not fully accepting its premises.

Nevertheless, a promising feature of the Agenda is its focus on *integration* and relationships between goals. In the resolution, the goals are described as "universal and indivisible" (United Nations 2015, Stafford-Smith et al. 2017, Scoones et al. 2020). Siloed approaches and tools to handle the Agenda may overlook this system complexity - with the risk of unintended consequences, policies not sufficiently accounting for synergies or trade-offs (Maes et al. 2019, Pedercini et al. 2019) and goal spill-overs across temporal and spatial scales (Engström et al. 2019). While there are many ways of integrating the goals, including e.g. rating connections (Nilsson et al. 2016, 2018), using cross-impact matrices (see e.g.Weitz et al. 2018), and tracing and quantifying causal connections across policies and targets (Collste et al. 2017, Pedercini et al. 2018, Pradhan et al. 2017), few take the overarching systems perspective needed to grasp the transformation of domains and dimensions of sustainability (see e.g. Sachs et al. 2018, TWI 2018, 2019 and 2020 and United Nations 2019). This lack of overarching systems perspective comes with a risk of tools being overly technical and not practically useful for the 2030 Agenda's implementation (for an overview of 2030 Agenda tools, see Di Lucia et al. 2020).

The 2030 Agenda can nevertheless also be seen as a broad framework for transformative strategies. For the Agenda to foster discussions about transformations at different scales and contexts, it requires approaches which are at the same time systemic and open to diversity and contexts. There is a need to dive deep into the current challenges, their underlying causes and transformations already going on (van der Leeuw 2020). Local and cultural knowledge is critical in this process to find context-appropriate framings (Cvitanovic et al. 2019) that are grounded in culture-contingent narratives (van der

Leeuw 2019). Without allowing and embracing alternative pathways, sustainability futures stay uniform and only reflect the views of a limited group of people, often the privileged who have access to the forums of discussion. For instance, global modellers' background is often from universities and research institutions in the Global North and they may envisage futures which lack local groundings in the Global South (Pereira et al. 2018). This may influence the selection of acknowledged worldviews and the information that is included in the uncovering of pathways. As worldviews influence how we act and how futures unfold, exclusion of critical voices comes with the risk of missing critical information and values on what the future may look like. A crucial challenge for research and practice lies in this context in how to couple the global overarching sustainability perspectives with local aspirations, visions, cultures and values.

Pathways approaches offer tools for transformative thinking. It is in this context that Scoones et al. (2020) suggest three types of approaches to transformations: structural, systemic and enabling. Structural approaches focus on underlying socio-political foundations and the need for complete ideological overhaul. Systemic approaches focus on identifying particular systems features that are enabling transformations. Enabling approaches emphasize the creation of capacities to empower individuals as well as communities to take action (Scoones et al. 2020). Given the context of the contested landscape of futures in relation to the 2030 Agenda, participatory and transformative pathways approaches are particularly suitable for advancing on the discussions and bringing the 'missing voices' to the fore. A range of participatory methods, which give different emphasis on approaches to transformations, have been discussed in sustainability science literature. Pathway approaches (Leach et al. 2010), with a grounding in science and technology studies ('STS') literature, brings to the center the inherent political and procedural nature of visions of the future (Lele 2011). These participatory approaches are typically within the scope of systemic approaches focusing on system structures and system elements such as feedbacks. They are however also lending themselves to more structural analyses by incorporating discussions on system boundaries and social justice elements (Leach et al. 2010).

Participatory scenario building is an example of a prominent early approach in social-ecological studies, taking a systemic approach to transformations, which emphasises how multiple kinds of uncertainties can give rise to different development trajectories (Carpenter et al. 2015, Harmáčková and Vačkář 2018). Furthermore, 'Future Design' uses imaginary future generations to envision sustainable futures that are radically different from the current - enabling its participants to see alternatives (Saijo 2020). The Three Horizons approach (Sharpe et al. 2016, Sharpe and Williams, 2013, Sharpe 2020, Pereira et al. 2018), is an approach widely used in business management and increasingly in research. It has been increasingly embraced as a viable framework for bringing increased understanding of how to move from what is known to new ways of thinking and acting (Colloff et al. 2017). The Three Horizons method can invite structural approaches to transformations as it brings a focus to the potential for alternative futures. It is also systemic as it brings an overarching frame, though it does not explicitly use systems concepts such as feedback loops. It could be argued that all the above-mentioned participatory techniques are engaging with enabling approaches to transformations as they enable participants to engage in critical discussions of alternative futures.

Incorporating stakeholder perspectives in SDG processes in a participatory manner has been identified as a key policy challenge. There have been a few initial steps of applying participatory approaches on the 2030 Agenda (Bennich et al. 2020, Di Lucia 2020). Examples of studies include Hutton et al. (2018) that combines integrated assessment modeling in coastal Bangladesh with stakeholders to elucidate value conflicts regarding policy prioritization, and trade-offs between different policies with regards to the 2030 Agenda implementation. They find significant trade-offs between several SDGs that need to be taken into consideration for implementation. Kanter et al. (2016) provide another example of an integrated SDG study with a focus on the Uruguayan beef sector. They use a backcasting approach that incorporates stakeholders to develop national agricultural transformation pathways. Hodes et al. (2018) use participatory visual methods with HIV-positive adolescents to shed light on stakeholders' aspirations across the domains of health and social development. Glover et al. (2016) take a more overarching perspective using foresight methods and imaginative storytelling involving development scholars in discussing the interactions between inequality, security, and sustainability. The approach presented by Weitz et al. (2018) uses a cross-impact matrix to assess systemic and contextual interactions between SDGs and has been used in case studies in Colombia, Mongolia and Sri Lanka (TWI2050 2020)

These examples of participatory SDGs approaches are promising but they do not explicitly incorporate global multidimensional narratives and what they might entail to the particular systems under examination. They thereby do not seek to open up a wider discussion on overarching and systemic 2030 Agenda pathways. Neither do they engage with dynamics happening across different scales, but are typically situated and narrowing down to particular areas or issues. There is here an identified urgent need to incorporate an integrated perspective and promote systems thinking in such participatory processes (Bennich et al. 2020). That is, there is a research gap that needs to be filled, combining elements of structural, systemic and enabling approaches to transformations with the multidimensional challenges set out in the 2030 Agenda.

To fill this research gap, we set out to develop an approach designed to explore a plurality of future narratives on the 2030 Agenda through sustainability transformations at different scales, including global and regional ones. The approach we propose and develop puts an emphasis on exploring and formulating alternative pathways grounded in narratives that may be missing in the debates on futures relating to the SDGs. Our *Three Horizons for the SDGs* (3H4SDG) approach is integrative and engaging with the systems perspective present in the 2030 Agenda resolution (United Nations 2015). It also takes an enabling approach to transformations by inviting participants' ownership of the process. Furthermore, 3H4SDG is building on insights from sustainability participatory approaches, particularly the systems focus of sustainability pathways (Leach et al. 2010) and the enabling features of the Three Horizons approach (Sharpe 2020). The approach is applied on the 2030 Agenda but not limiting itself to specific goal formulations of the Agenda as it takes an overarching perspective and invites critical standpoints. Finally, with the 3H4SDG approach we further aim to provide relevant insights to practitioners and policy makers involved in SDG implementation processes by shedding light on the option space, including tensions, around alternative sustainability pathways.

In the following sections we provide a theoretical background, present and detail the participatory approach of 3H4SDG and illustrate its application using the 2018 African Dialogue on The World In 2050 (Aguiar et al. 2019) as a pilot case study.

THEORETICAL BACKGROUND

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). It thereby contrasts with the so-called 'business as usual', which is an extension of current, often undesirable, trajectories. The 'business as usual' (BAU) no longer appears to be a desirable course of global development; BAU is highly unsustainable as shown by recent large-scale sustainability assessments (e.g. IPBES 2019). In addition, looking backwards societal development has historically been characterized by shocks and major transitions and as such this BAU trajectory is unlikely to unfold (Vergragt and Quist 2011). Furthermore, technological advances alone do not include the fundamental changes necessary for sustainability (Page et al. 2016) and reaching the 2030 Agenda thus requires more profound transformations (Randers et al. 2018, Sachs et al. 2019, Linnér and Wibeck 2019). It is, however, also in the context of structural approaches to transformations that it has been argued that the SDGs are *not* transformational and as they defend the current status quo (Weber 2017). Weber (2017) claims that the goals are formulated to consolidate a neo-liberal version of development, and Weber and Weber (2020) argue that the Agenda rests on a notion of sustainability informed by an Ecological Modernization Theory resting on privileging economic growth over social and environmental concerns. While being aware of these concerns, we argue that the Agenda can be seen as inviting discussions on transformations, as has also been discussed by Linnér and Wibeck (2019). Such discussions benefit from being informed by a multiplicity of voices and multidimensional narratives that shape societies and cultures (van der Leeuw 2019), and perhaps also question and challenge formulations in the Agenda.

Inviting multiple perspectives can initiate grounded processes of change by overcoming knowledge barriers (Voinov and Bousquet 2010, Voinov et al. 2016). Future visioning can in such contexts provide platforms for developing integrated perspectives. One critical question however is *who* participates and what contesting values and narratives are brought together (Vergragt and Quist 2011). Vergragt and Quist (2011) ask the rhetorical question *"Can [visioning] be left to experts, or should it be a democratic or a deliberative process involving stakeholders and citizens?"* (Vergragt and Quist 2011 p. 749). Envisioning the future can lift voices not heard or deprived, including the local voices and voices of indigenous, gender and ethnic minorities (Cvitanovic et al. 2019), and question the status quo. It can also play an emancipatory role for the involved, through the exploration of potential futures and discovering of leverage points previously not acknowledged (Meadows 1997, Ulrich 2003, Leach et al. 2010). Work on adaptation pathways has also highlighted the need to recognize multitudes of actors and the need to work with plurality of values (Fazey et al. 2016).

The concept of narratives is central to our recognition of a plurality of perspectives and values. In this study, we define narratives as accounts of series of related events that are used for sense-making (according to the definition used by Linnér and Wibeck 2019). Narratives can explicitly incorporate framings of the system and its dynamics, as well as how development or transformations can look like for a desired outcome to be realized (Leach et al. 2010). All individual and collective decisions are framed by the context of locally predominant narratives (van der Leeuw 2019). The 2030 Agenda, while grounded in global policy discourse on sustainability, does not necessarily feature in narratives prevalent in varying contexts around the world, which may hamper its influence on regional and local dynamics. We argue that shared and transformative understanding can be enhanced through stakeholder methods that include multiple perspectives. Our study is thereby an empirical exploration of how the 2030 Agenda can be meaningfully integrated into narratives of different contexts (van der Leeuw 2019).

A METHOD TO EXPLORE SUSTAINABLE DEVELOPMENT PATHWAY NARRATIVES: THREE HORIZONS FOR THE SDGS (3H4SDG)

Reflecting the context introduced above, in developing our approach for transformative, integrated perspectives on the 2030 Agenda, we embarked from the following premises:

A. Systems perspective and SDG integration
    - We wanted the approach to explicitly embrace a systems perspective of sustainability pathways (Leach et al. 2010), to address a spectrum of

transformational challenges related to achieving the 17 SDGs, so as to minimize potential conflicts among them and to reap the benefits of potential synergies.

B. Multiple perspectives
   - As systems look different from different perspectives, we wanted the approach to facilitate the exploration of multiple and alternative pathways, including ones proposed by non-dominant voices, and narratives from different contexts and at different scales. In addition, we wanted the approach to use the 2030 Agenda as a boundary object to deliberate differences between pathways that would achieve multiple sustainability goals emerging from global and lower scales, without imposing prevalent top-down global perspectives.

C. Participant's ownership of the pathway narratives
   - We wanted the participants to feel ownership over the pathway narratives so that the envisioned pathways and change processes would actually matter to them, thereby increasing the likelihood of implementation.

The Three Horizons for the SDGs (3H4SDG)

Our approach departs from the Three Horizons framework (Sharpe and Williams 2013, Sharpe et al. 2016), providing the overarching systematic and integrated structure to our approach (premise A). The Three Horizons approach simultaneously handles complexity, multiple and contrasting perspectives and values (premise B) and still allows for imagination, creativity and emergence (contributing to premise C) (Sharpe 2020, Sharpe et al. 2016, Fazey et al. 2018). We appreciate the Three Horizons framework as an intuitive tool to engage stakeholders in discussing change.

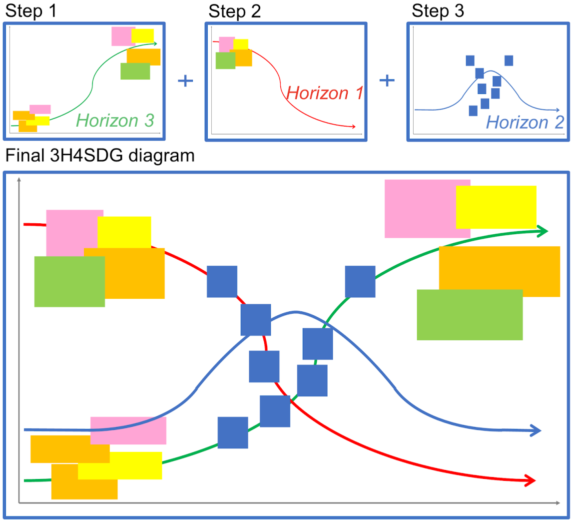
We adapted the approach and refer to it as *The Three Horizons Framework for the SDGs (3H4SDG),* combining the Three Horizons framework with multi-scale backcasting methods as applied in Aguiar (2015) and Folhes et al. (2015), and insights from pathways approaches (as discussed above, e.g. Leach et al. 2010). We were also inspired by SwedBio's Multi-Actor Dialogue Seminars that emphasize the role of dialogue in contributing to transformative social learning (Schultz et al. 2016), as well as systems thinking and approaches (Meadows 2008, Reynolds and Holwell 2020). Below we present the approach in further detail.

3H4SDG approach outline

To promote fruitful dialogues and the participation of all involved in a 3H4SDG process, participants need to be divided into smaller groups (we propose around six to eight people each, with each group undertaking the exercise in parallel). Ideally, a variety of perspectives are represented in each group, allowing for diverse views and narratives through which to discuss the 2030 Agenda. We therefore suggest pre-allocating people into groups so that each group incorporates the sought diversity of perspectives.

In this approach, the Three Horizons framework (Sharpe 2020) is used as a device to facilitate conversation between the participants and for capturing their ideas. As such, the participants have the Three Horizons diagram in front of them in all sessions and gradually populate its three lines representing the horizons with their contributions, in the form of post-it notes (Figure 1).

Fig. 1. The Three Horizons diagram showing the different horizons, steps and post-it notes colors used during Step 1 and Step 2 of the process. The horizons represent respectively: The system we want to transform from (Horizon 1), the changes that are needed to break the current dominant patterns that are undesirable and to reach desirable alternative patterns (Horizon 2); and the system we want to transform to (Horizon 3). Pink post-it notes represent people (SDGs 1-6), Yellow represents Prosperity (SDGs 7-12), Green represents Planet (SDGs 13-15), Orange represents Peace and Partnerships (SDGs 16-17) and Blue represents changes (these are only used during Step 3).



We suggest using a color scheme that accounts for the spectrum of transformational challenges related to the 17 SDGs. In our case, the four colours represent the “five SDG P’s”: People (SDGs 1-6), Planet (SDGs 13-15), Prosperity (SDGs 7-12), and Peace and Partnership (SDGs 16-17) (UN Sustainable Development 2015, United Nations 2015). The color categories are chosen to enable facilitators to keep an overarching view and ensure that different domains are covered.

Building the diagram in three steps

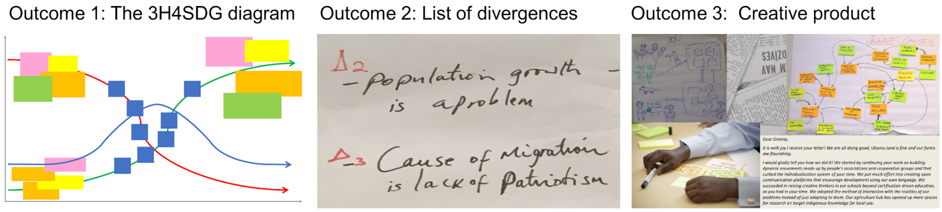
The approach is divided into three main steps. In each step, facilitators ask the guiding questions that the participants answer by writing down their ideas on the color-coded post-it notes and adding these in the appropriate place on the Three Horizons diagram (Figure 2, Outcome 1).

Step 1 of the process focuses on visions for the future (Horizon 3). Starting from a future focus can avoid anchoring the discussions in today’s concerns and norms and supports the exploration of what may be currently non-dominating visions. Guiding questions are: “What are our visions for the future of agriculture and food systems?” and “What do you see of the desired future already existent in the present (initiatives, project, proposals etc.)? Note that the agriculture and food systems focus is an example derived from the illustrative case study from the 2018 African Dialogue on The World In 2050 (Aguiar et al. 2019), further detailed below.

Step 2 focuses on present concerns (Horizon 1). This step includes clustering notes into related issues to enable a focused discussion on root causes of the participants’ concerns. Guiding question: “What concerns do we have about the present agriculture and food system?” (note, again, that the agriculture and food systems focus is an example derived from the illustrative case study from the 2018 African Dialogue on The World In 2050, further detailed below).

Step 3 focuses on how to achieve the desired future through either incremental or transformational change actions (Horizon 2). Guiding questions: “How do we change the present system to transform to the desired futures?” and “Which measures and actions are required (consider the root causes)?”. During step 3, only one color of the post-its is used as the focus is on integrative change and not on specific domains. During the diagram-populating process, facilitators note points of disagreement or different views among participants on a flipchart (see Figure 2, Outcome 2).

Fig. 2. Illustrations of the outcomes from each step of the 3H4SDG process.



At the end of each step, a synthesis activity takes place. This synthesis represents an artistic part of the process in which the groups develop a creative product, such as letters, drawings, newspaper headlines or hashtags. (Figure 2, Outcome 3). During this phase of the discussions, facilitators leave the groups to encourage participants' ownership of the outcomes in line with the process followed in Folhes et al. (2015) and Aguiar et al. (2015).

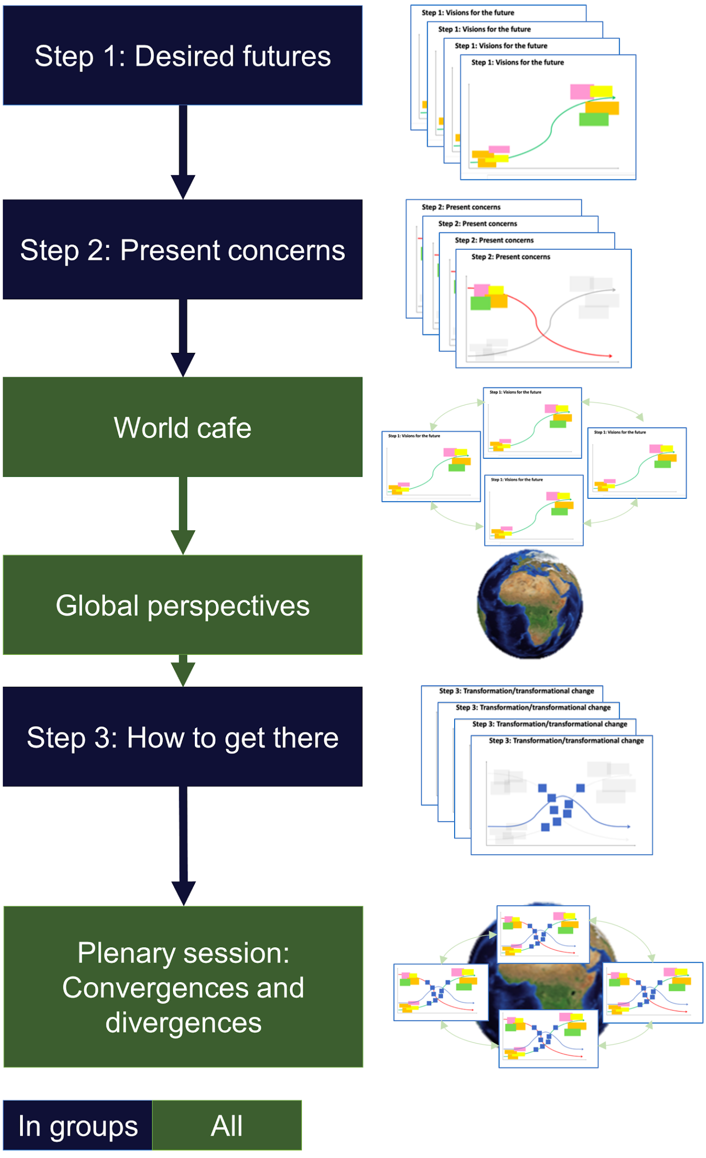
Implementing the 3H4SDG approach

Figure 3 illustrates the complete process, combining the construction of the 3HSDG diagrams in parallel groups, with integrative larger group activities. A key aspect of the 3H4SDG approach is highlighting the *convergences* and *divergences* among the pathways (grounded in the importance of working with a plurality of values, see e.g. Fazey et al. 2016). *Convergences* are common elements among different pathways. *Divergences* may entail branching points of different future pathways as seen differently by participants. An example of branching points may be a society where a big part of the population lives in rural areas versus a future with massive urbanization, or a future in which community relations stay important with extensive local trade transactions versus a future in which an extensive part of products are exported and imported. *Convergences* can indicate points where agreement prevails and which may mandate specific actions, while *divergences* are the points which need to be further discussed.

There are three proposed integrative cross-group activities (Fig. 3):

- A '**World Cafe**' session, in which group participants rotate between the groups allowing the sharing of results and taking note of contrasting perspectives. Thereby participants are exposed to issues they may not have considered.
- A '**Global Perspectives**' session exposes participants to assumptions underpinning recent global scenario studies and their implications for the context under discussion. This step is carried out through a presentation prepared by the facilitators. This session takes place after Step 2 to avoid constraining the thinking of participants as they brainstorm their preferred future system. During Step 3,

Fig. 3. The complete process to uncover multiple pathways using the 3H4SDG.



participants discuss and take note of possible divergences between their perspectives and global scenarios.

- A ‘**Final plenary**’: In the final plenary group results are presented. *Convergences* and *divergences* within and across the groups and in relation to the global perspectives are discussed in the context of narratives.

A facilitated evaluation session at the end provides participants with time to reflect upon the dialogue process, and gives organizers feedback to improve the dialogue process. In the next section, we briefly present how the approach was applied in an illustrative case study.

An illustrative case study: The 2018 African Dialogue on The World In 2050

The 2018 African Dialogue On The World In 2050 was held in Kigali, Rwanda, October 2018, over two days. The Dialogue theme was attaining the SDGs within planetary boundaries in agriculture and food systems (Rockström et al., 2009, Steffen et al. 2015; TWI 2018, 2019, 2020) . The event was organized with financial support from the Swedish International Development Cooperation Agency, Sida, through SwedBio at Stockholm Resilience Centre. The Dialogue 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. The stakeholders were selected based on their expertise and experience (relevant to African agriculture and agro-biodiversity); and for having understanding and influence over related policy processes (e.g., social and economic development strategies, spatial planning, research-development-innovation, conservation and resource management). The Dialogue took place over a span of two days, with the first two steps of the process and the World Cafe taking place on the first day, and the presentation of global perspectives, the third step and the synthesis, taking place the second day (Fig. 3).

The participants were divided into four regionally focused sub-groups, based on Sub-Saharan African regionalization from the African Union, including:

(i) West and Central Africa (combining the two African Union zones),
(ii) East Africa,
(iii) Southern Africa, *and*
(iv) (Sub-Saharan) African continent.

The goal of this division was to increase the multiplicity of perspectives and enrich the cross-scale comparison (global, Africa-wide, and regional). The division of participants among the groups considered various aspects such as the location of the participant, professional background, and the practical requirement of having manageable groups (in line with Pereira et al. 2018). Diversity within groups was also sought, so as to include a variety of competencies, values and narratives, in the respective groups. Each group incorporated around eight stakeholders and two facilitators. Facilitators were trained to guide the process, and not to contribute with expertise in the themes being discussed.

The presentations of global perspectives about pathways to reach multiple goals were based on IIASA's The World in 2050 report (2018) and is further deliberated and compared to the outcome of the 2018 African Dialogue in Aguiar et al. (2020). At the end of the Dialogue, an evaluation form was provided for all the participants (see Appendix for the form, replies available on: https://osf.io/prj8v/) and after the Dialogue, results were shared and compiled in a report (Aguiar et al. 2019).

RESULTS AND DISCUSSION OF
THE 2018 AFRICAN DIALOGUE ON THE WORLD IN 2050

In this section, we extract results from the case study to provide practitioners and policy makers involved in SDG implementation processes with guidance in approaches applicable to explore a variety of pathways towards SDGs. Other aspects of the results providing input to scenario building processes are detailed in Aguiar et al. (2019) and Aguiar et al. (2020).

Process outcomes

The 3H4SDG process resulted in future visions for the respective groups, lists of current challenges and their root causes (in some cases transferred to a systems diagram), and lists of changes needed to attain a sustainable future. The process also resulted in narrative drafts and a diversity of visual and creative products such as "tweets" from the future (see Aguiar et al. 2019). To illustrate the process outcomes, below we provide a brief description of the resulting visions.

The West and Central Africa group named their pathway *the Ubuntu pathway* after the word in Nguni (a group of Bantu languages spoken in Southern Africa) for the quality of human inter-dependence and connectivity. The Ubuntu pathway describes a future of African agriculture and food systems dominated by farmers associations and cooperatives. Africa embraces its diversity and the right to land is inclusive. Agroecology takes the lead and the farming systems are fully organic. In the pathway developed by the group focusing on Eastern Africa, *the Peaceful and Prosperous East Africa Pathway*, food security is assured through either small-scale agriculture or large-scale commercial farming as this is one of the divergences that emerged from the process. Investments in agriculture and education enable a prosperous future. Agriculture is private-sector led and gender-balanced. Farmers are secured financial resources. The Southern Africa group named their pathway after the Swahili and Kinyarwanda word for pathway or direction: *the Urugendo pathway*. In *the Urugendo pathway*, agriculture provides livelihoods and drives the economy. Agriculture is private-led and peace is emphasized as a precondition for a prosperous future. Both cooperatives and private businesses are participating and the government provides preconditions through enabling credit and enabling legal frameworks. The final group had an overarching focus on Sub-Saharan Africa and named their pathway *the Rainbow pathway*. In *the Rainbow pathway*, 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 be accountable to their citizens. Citizens are actively participating in society and collaboration platforms are provided.

Fig. 4. An illustrative photo from the 2018 African Dialogue on The World in 2050. The Three Horizons diagram is in the middle of the group discussion.

The pathways are presented in *Table 1* below and reported in detail in Aguiar et al. (2019). The core present concerns *convergent* among all groups included the impacts of climate change, land degradation, food insecurity, inadequate governance, inadequate infrastructure, low level of financing and issues related to technology (including the dichotomy between Western and indigenous knowledge), and youth migration/brain-drain. Furthermore, the overall vision of a peaceful and prosperous Africa capable of feeding itself and the world emerged convergently across the groups. Other *convergent* themes that emerged across all groups were: a strong emphasis on education/skills, youth, women and population empowerment, the consolidation of cooperatives and cooperation between farmers, the need for infrastructure, generation and sharing of reliable data, structuring of local to global markets, financing and insurance for agriculture, independence from foreign donors, regional cooperation, transparency and accountability of governments – and not least, political will.

Table 1. A summary of the four pathways explored during the 2018 African Dialogue on The World In 2050.

Pathway and unique features	Future visions	Present concerns & seeds of the positive future	Change actions
Ubuntu (West and Central Africa) Fully organic and cooperatives dominating.	Agriculture and food systems dominated by farmers' associations and cooperatives. Future characterized by diversity, inclusiveness, and agroecology.	Environmental degradation, the low interest in agriculture among youth, growing inequalities and the collapse of social values in communities. Seeds of a positive future lie in organic farming systems.	Building dynamic movements through empowered farmers' organizations and cooperatives and intensify farmers' relations and interaction for better communal agriculture. Leaving fossil resources in the ground.
Peaceful and Prosperous East Africa 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. Science collaborates with the local community to solve problems community is important.	East African countries suffer from food insecurity because production is low as a consequence of low technology adoption and inadequate investments and research.	Investments in agriculture and education enable a prosperous future. Farmers' financial resources are secured and mobilized.
Urugendo (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 emphasized as a precondition for a prosperous future. Farmers organized in cooperatives, no hunger.	Lack of investments in agriculture, many governance problems within cooperatives and governments are constraining a positive development.	Both cooperatives and private businesses are participating and the government provides preconditions through enabling credit and enabling legal frameworks.
Rainbow (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.	Low human capital as a consequence of poor educational quality and brain drain causes high population growth. Climate change and environmental degradation threaten production and well-being.	Building infrastructure, implementing education programs, and promoting local solutions stimulate the necessary innovation. Agro-forestry is promoted and upscaling programs emphasized. Cultural and behavioral changes powered by synergies, cooperation and coordination, and increased access to finance and insurances.

Divergences identified within and across groups included five themes: (i) Population growth; (ii) Consumption patterns; (iii) Actors involved in the agriculture of the future; (iv) Dominating agricultural practices; (v) Governance - Role of the State and Private sector. No clear region-specific aspects emerged – except in the language, names and places chosen to synthesize the work in the summaries. Nevertheless, the African Continent group, when compared to the sub-regional groups, emphasized more aspects related to regional cooperation, including data generation/sharing and the importance of alliances for change (across Africa and with the other continents). In Aguiar et al. (2020) the divergences are discussed in relation to global target-seeking scenarios.

Reflections on the 3H4SDGs approach: Participants' evaluation
Evaluating participatory approaches is challenging and there is a risk of over-focusing on quantitative measures. In addition, when assessing the outcomes of participatory approaches, the complexity of the context makes it difficult to trace the causal relationships between actions and outcomes (Norström et al. 2020).

In the context of our overarching project aim to provide alternative perspectives on the 2030 Agenda implementation, grounded in locally prevalent narratives, much of the value of the approach lies in the communication of the alternative perspectives after the Dialogue, and of the identified divergences and convergences. The participants' opinions expressed in the evaluation can indicate whether or not the approach is perceived as contributing to narrative groundedness, whether or not it brings a transformative systems perspective and whether or not it incorporates multiple perspectives.

An evaluation of the Dialogue in the form of a written survey was submitted by 58 % of the participating stakeholders (submitted replies available on: https://osf.io/prj8v/). Some participants had to leave early and could not participate in the evaluation, and this may have skewed the results. The results nevertheless indicated that the approach was received positively and perceived as useful, discussing relevant questions and worth applying in different contexts (median 4 on a scale between 1 and 5 in the survey). Most of the respondents would also recommend that the process be used by others (median 5 on a scale 1 to 5).

In the following subsections, we detail selected qualitative details of the participants' responses, related to the three above-mentioned premises of the study: Systems perspective and SDG integration, multiple perspectives and participants' ownership of the pathway narratives.

Systems perspective and SDG integration
Throughout the overall case-study process, including the colored post-it notes assisted the coverage of various sustainability dimensions. This facilitated the integration of diverse

issues in the explored pathways. Participants emphasized the value of 'holistic' and 'multi-sectoral approach' (indicated by the answers to the survey question 'What was the most important moment(s) for you during this workshop?', including *"Holistic approach in addressing SDGs; Interdependence of SDGs"*).

The uncovered pathways succeeded in maintaining an integrative perspective and not over-focusing on specific details at the cost of losing the broader picture. This is well in line with our premisse, as well as the Bennich et al. (2020) call for SDG interaction studies to engage stakeholders in integrated perspectives.

In support of the integrative perspective, participants also noted that agriculture can enable transformations of other sectors (responses to the evaluation question "*What ideas or insights do you look forward to share at work?"* included: *"Pathways [...] to sustainable social-economic transformation through modernizing agriculture"* and *"That transforming agriculture requires a multi-sectoral approach")*. This wider focus on linkages across sectors has been argued to be missing in SDG interaction studies to date (Bennich et al. 2020).

Multiple perspectives

The approach not only strives to represent a diversity of stakeholders, but also to make it explicit for the participants that including multiple perspectives is beneficial for the exploration of pathways towards SDGs.

In this respect, the systems lens central to the 3H4SDG approach represents a beneficial addition because it can facilitate an overarching view of systems and allow for explorations of multiple perspectives, which in turn can reveal novel future alternatives. In future iterations of the 3H4SDG approach, an explicit focus on power relations, both in the design of the process and in terms of the focus on power as a factor influencing decisions and actions in systems, may provide useful insights into which and whose perspectives are more likely to be represented.

A systems lens, combined with a diversity of participant backgrounds, incorporated innovative thinking about change and transformations in the process. This may be exemplified by the widespread use of the scope and details of the future regional pathways, and was a recurring theme in the evaluations. Participants highlighted this in their answers to the question 'What ideas and insights do you take home from this workshop?' with the following responses: "*Embracing our diversification;…*"; "*The group work was nicely formed with a different range of expertise which helped the discussion among the group members.*"; "*It is possible to achieve something tangible if we bring people together*".).

Participant's ownership of the pathway narratives

The participants' evaluations also suggest that the alternative futures were not felt as imposed from outside but as emerging from the realities experienced by the participants (as an example, one respondent in the evaluation referred to the dialogue as a "*People-led initiative*"). Participants' ownership of the resulting pathways was facilitated by the fact that the futures emerged from a participatory process (one participant referred as the main insight to bring from the dialogue that "*communities need to be empowered [through participative processes]*"). Participants further highlighted deliberations of the future as important because it created shared understanding among participants. (Similar sentiments are discussed in Voinov and Bosquet (2010); Voinov et al. (2016); for instance, one of the participants answered the question 'What was the most important moment(s) for you during this workshop?' by stating "*All the interesting discussions and sharing knowledge"*). The aspects focusing on creativity may have increased participants' feeling of ownership (several of the participants mentioned the letters from the future as main highlights). Participants were invited to read the workshop report before it was published.

Discussion of the methodological contributions

From the perspective of sustainability pathways, the proposed 3H4SDG approach advances the Three Horizons by: (a) focusing explicitly on the SDGs and sustainability pathways in an integrative way instead of general future visioning; and (b) proposing an array of group/plenary activities allowing the participants to explore novel aspects of sustainability pathways; and incorporating cross-scale considerations.

The approach brings an explicit recognition of conflict and tension and thereby avoids assuming a pre-determined consensus. This is in line with the 'opening up' of possible futures, also emphasized in the sustainability pathways approach (Leach et al. 2010). Thereby, conflicting problem framings are allowed to co-exist, even promoted and made palpable (see also Pereira et al. 2020). Simultaneously, a significant strength of the 3H4SDG approach that was noted by the facilitator team is that it is effective even when participants' perspectives differ, in line with earlier literature on the Three Horizons approach (Sharpe 2020).

The politics of transformations

Pathways development and discussions on transformations, including such where the 3H4SDG is applied, involve power relationships, as systemic changes create winners and losers. Transformations are therefore not apolitical but rather underpinned by political processes (Blythe et al. 2018, Patterson et al. 2017). Linnér and Wibeck have framed it in the following way: "We share the same boat - planet Earth - but are not on the same deck geopolitically or in political-economic terms" (Linnér and Wibeck 2019, p. 187).

Conflicting paradigms, for example around the use of various agricultural technologies in the context of various international assessments such as the IAASTD, are often situated within uneven processes of deliberation where resourceful actors take part besides less resourceful actors, shaping the discourses (Vanloqueren and Baret 2009). Conflicting paradigms also play out in 'the politics of anticipation', e.g. around choices over the inclusion of negative emission technologies by the IPCC (Beck & Mahony 2018), as well as competing framings and discourses within the context of global discussions on biodiversity within IPBES (Borie & Hulme 2015). Furthermore, the significance of how values and paradigms influence the behavior of global models was early emphasized in the history of global models (see, e.g. Meadows et al. 1982: Groping in the dark: the first decade of global modelling). There is in global modeling a continuous danger that this is not acknowledged (see Saltelli et al. 2020, who also point to the need to acknowledge stakeholders and multiple views in model formulation). In the case of the 2030 Agenda, this risks the production of overly technocratic outlooks that do not incorporate the possibilities for radically different futures, of which some are already emphasized and desired by communities (see Wyborn et al 2020). One strength of the 3H4SDG approach is that it explicitly highlights divergences and thereby gives room for alternative political perspectives. However, dialogues such as the 2018 African Dialogue on The World in 2050 do not take place in a vacuum but are inevitably affected by surrounding paradigms and perspectives. We have compared the outcomes from the 2018 African Dialogue on The World in 2030 with other sustainability pathways in a separate paper (Aguiar 2020). The paper points towards the potential of 3H4SDG to bring a diversity of considerations to the front (Aguiar 2020).

Limitations

Reaching a desirable level of diversity of pathways that are explored may prove difficult due to various constraining factors, including time, financial capacity, geographic representation, language barriers, etc. (Turcotte and Pasquero 2001, Reed 2008).

Although the 2018 African Dialogue participants' group covered different parts of the African continent (across eleven countries) and was diverse when it comes to participants' origin, residence and home organization, East Africa was overrepresented, and Southern Africa was represented by only a few participants. This occurred despite a conscious strategy of invitations to individual African sub-regions mentioned above. This implies that the sub-regional representativeness of the resulting pathways may not represent a diversity of all sub-regions in Africa. Thus, in future case studies, a better design of the invitation process and more considerations of who to invite would be recommended (this has been emphasized in earlier participatory literature, see e.g. Pereira, 2018). Alternatively, the process can be repeated in different locations (or regions if the aim is regional representation), later synthesizing the convergences and divergences across multiple Dialogues from these locations. Future case studies would also benefit from including follow-up workshop(s) in connection to the dialogue, in which the results can be presented and further discussed and related to existing governance processes.

We see the overarching frame and systems perspective as a strength of the approach as called for elsewhere (e.g. Bennich et al. 2020). It facilitates the visualization of alternatives to the prolongation of societal trends - which has been identified as an asset in future studies (Andersson and Westholm 2019). From another perspective, however, this strength can be seen as a weakness as there is no clear receiver that will implement the suggestions, and the impact is difficult to measure, and often results in 'small wins' (Turcotte and Pasquero 2001). Nevertheless, we argue that the proposed approach is versatile enough to be possible to target in a particular decision-making context.

Future use of the 3H4SDG approach

Can the process we have developed contribute to real-world sustainability transitions? The 2030 Agenda negotiations have been hailed as having been inclusive and providing civil society with possibilities to engage as few other international negotiation processes (Chasek et al. 2016). It has furthermore been referred to as an agenda "proposed and championed by a country from the Global South [and] for the first time defined development as a universal agenda" (Caballero 2019 p. 138). The inclusiveness of the outcome has, nevertheless, been questioned and, as already mentioned, the Agenda has been criticized for incorporating a narrow range of perspectives (see Carand 2017 and Weber 2017). A question that still remains is how the implementation phase of the 2030 Agenda can be an inclusive process grounded in the prevalent narratives. The 3H4SDG approach can serve as a meaningful way to provide stakeholder inputs and visioning to implementation, that not only offers advice on a detailed level but enables a systems view of development. The approach can also open the debate about the adequacy of targets contributing to desired sustainability visions (and even critically assessing sustainability visions put forward), as opposed to sustainability visions imposed top-down. We see the approach as adaptable to different circumstances and with different themes and questions, and it has already been taken up and adopted in different settings by the Dialogue participants (Graziani 2019).

With respect to the future application of the approach, we designed the 2018 African Dialogue as a pilot case study but argue that the approach can efficiently be used as part of an existing decision, or governance, process with an existing implementation agency. It is up to the future users to which extent the process is led by a topic- and region-wise focus of the groups. In a way, this is the stakeholder-based aspect of the approach: the stakeholders can diverge from the original focus and go narrower or broader if they wish.

CONCLUSIONS

This study presents a novel approach providing a structure for discussing the SDGs and uncovering pathways to reach them, Three Horizons for the SDGs (3H4SDG). The approach democratizes visioning and can be easily adapted to a variety of contexts, or efficiently complement existing decision- or governance processes. As a pilot case study, we applied this approach in the 2018 African Dialogue on The World In 2050.

The approach has proved to have multiple assets. First, it facilitates deliberation, collaboration and shared understanding and visioning in a diverse group of stakeholders. Second, it provides a novel way of looking at the SDGs from a systems perspective in which the agenda is seen as a coherent whole, as a direction for the uncovering of sustainability pathways, while integration is being placed at the core. Third, it fosters ownership and creativity as it motivates participants to develop different forms of syntheses (including artistic ones). Finally, it can benefit practitioners and policy makers by promoting a systems perspective and a bird's eye view of uncovered pathways and thereby assist in the planning of coherent SDG policies and actions.

One of the key aspects of the proposed approach is its ability to identify alternative pathways in a stakeholder-based, bottom-up way, by focusing on convergent and divergent opinions and issues identified by the participants. The convergences and divergences identified by this approach can be used both as points for deliberation among diverse voices and for further specification of sustainability pathways. Furthermore, it allows for comparisons with global pathways and facilitates their integration at sub-global scales. The 2018 African Dialogue case study provides examples of both convergent and divergent topics, including the commonly raised need for infrastructure investments and improved governance, and the divergent issues of whether population growth should be seen as an asset or a barrier for the well-being of African societies.

We envision the method to be used in policy making in the future as a strategic tool that allows for inclusive discussions and assisting in the direction towards not only sustainable but also just futures.

LITERATURE CITED

Aguiar, A. P. 2015. Transition to sustainability: are participatory multi-scale scenarios a useful tool? *GLP news*(11).

Aguiar, A. P., D. Collste, D. Galafassi, Z. Harmáčková, K. Houngbedji, 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. Open access: https://swed.bio/reports/the-second-african-dialogue-on-the-world-in-2050/

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. https://doi.org/10.1016/j.gloenvcha.2020.102198

Andersson, J., and E. Westholm. 2019. *Slaget om framtiden: Forskningens roll i konflikten mellan tillväxt och miljö*. Santérus förlag, Stockholm.

Beck, S., and M. Mahony. 2018. The politics of anticipation: the IPCC and the negative emissions technologies experience. *Global Sustainability* 1:e8.

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*. Open access: https://doi.org/10.1016/j.scitotenv.2020.138405

Blythe, J., J. Silver, L. Evans, D. Armitage, N. J. Bennett, M.-L. Moore, T. H. Morrison, and K. Brown. 2018. The Dark Side of Transformation: Latent Risks in Contemporary Sustainability Discourse. *Antipode* 50(5):1206–1223.

Borie, M., and M. Hulme. 2015. Framing global biodiversity: IPBES between mother earth and ecosystem services. *Environmental Science & Policy* 54:487–496.

Caballero, P. 2019. The SDGs: Changing How Development is Understood. *Global Policy* 10(S1):138–140.

Carant, J. B. 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.

Carpenter, S. R., E. G. Booth, S. Gillon, C. J. Kucharik, S. Loheide, A. S. Mase, M. Motew, J. Qiu, A. R. Rissman, J. Seifert, and Others. 2015. Plausible futures of a social-ecological system: Yahara watershed, Wisconsin, USA. *Ecology and Society* 20(2).

Chasek, P. S., L. M. Wagner, F. Leone, A.-M. Lebada, 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.

Colloff, M. J., S. Lavorel, L. E. van Kerkhoff, C. A. Wyborn, I. Fazey, R. Gorddard, G. M. Mace, W. B. Foden, M. Dunlop, I. C. Prentice, J. Crowley, P. Leadley, and P. Degeorges. 2017. Transforming conservation science and practice for a postnormal world. *Conservation biology: the journal of the Society for Conservation Biology* 31(5):1008–1017.

Collste, D., M. Pedercini, and S. E. Cornell. 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

Cvitanovic, C., M. Howden, R. M. Colvin, A. Norström, A. M. Meadow, and P. F. E. Addison. 2019. Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. *Environmental science & policy* 94:20–31.

UN Sustainable Development. 2015. 2030 Agenda for #SustDev is officially adopted!! 4 People, Planet,

Prosperity, Peace, Partnership! #SDGs #Globalgoalspic. twitter.com/BPL2U5mcnt.
Di Lucia, L., L. J. Nilsson, J. Khan, and R. Slade. 2020. Knowledge of Sustainable Development Goal interactions for decision making – are current approaches fit for purpose? *SocArXiv*. 2020 Open access: https://osf.io/seq8n
Downing, A. S., A. Bhowmik, D. Collste, S. Cornell, J. F. Donges, I. Fetzer, T. Häyhä, J. Hinton, S. J. Lade, and W. Mooij. 2019. Matching scope, purpose and uses of planetary boundaries science. *Environmental research letters: ERL*.
Engström, R., G. Destouni, M. Howells, V. Ramaswamy, H. Rogner, and M. Bazilian. 2019. Cross-Scale Water and Land Impacts of Local Climate and Energy Policy—A Local Swedish Analysis of Selected SDG Interactions. *Sustainability: Science Practice and Policy* 11(7):1847.
Fazey, I., N. Schäpke, G. Caniglia, J. Patterson, J. Hultman, B. van Mierlo, F. Säwe, A. Wiek, J. Wittmayer, P. Aldunce, H. Al Waer, N. Battacharya, H. Bradbury, E. Carmen, J. Colvin, C. Cvitanovic, M. D'Souza, M. Gopel, B. Goldstein, T. Hämäläinen, G. Harper, T. Henfry, A. Hodgson, M. S. Howden, A. Kerr, M. Klaes, C. Lyon, G. Midgley, S. Moser, N. Mukherjee, K. Müller, K. O'Brien, D. A. O'Connell, P. Olsson, G. Page, M. S. Reed, B. Searle, G. Silvestri, V. Spaiser, T. Strasser, P. Tschakert, N. Uribe-Calvo, S. Waddell, J. Rao-Williams, R. Wise, R. Wolstenholme, M. Woods, and C. Wyborn. 2018. Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. *Energy Research & Social Science* 40:54–70.
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.
Glover, D., K. Hernandez, and A. Rhydderch. 2016. A Foresight Scenario Method for Thinking About Complex Sustainable Development Interactions. *IDS bulletin* 47(4).
Graziani, G. 2019, February 16. In prima linea per lo sviluppo sostenibile! #Agenda2030 #SDGs #pontassieve @ASviSItalia @JacopoBencini @ItalianClimatepic.twitter.com/dOqlOxVrjA.
de Haan, J. (hans), and J. Rotmans. 2011. Patterns in transitions: Understanding complex chains of change. *Technological forecasting and social change* 78(1):90–102.
Hanssen, L., E. Rouwette, and M. M. van Katwijk. 2009. The Role of Ecological Science in Environmental Policy Making: from a Pacification toward a Facilitation Strategy. *Ecology and Society* 14(1):art43.
Harmáčková, Z. V., and D. Vačkář. 2018. Future uncertainty in scenarios of ecosystem services provision: Linking differences among narratives and outcomes. *Ecosystem Services* 33:134–145.
Hodes, R., J. Doubt, E. Toska, B. Vale, N. Zungu, and L. Cluver. 2018. The stuff that dreams are made of: HIV-positive adolescents' aspirations for development. *Journal of the International AIDS Society* 21(S1):e25057.
Hutton, C. W., R. J. Nicholls, A. N. Lázár, A. Chapman, M. Schaafsma, and M. Salehin. 2018. Potential Trade-Offs between the Sustainable Development Goals in Coastal Bangladesh. *Sustainability: Science Practice and Policy* 10(4):1108.
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.
Kanter, D. R., M.-H. Schwoob, W. E. Baethgen, J. E. Bervejillo, M. Carriquiry, A. Dobermann, B. Ferraro, B. Lanfranco, M. Mondelli, C. Penengo, R. Saldias, M. E. Silva, and J. M. S. de Lima. 2016. Translating the Sustainable Development Goals into action: A participatory backcasting approach for developing national agricultural transformation pathways. *Global Food Security* 10:71–79.
Leach, M., I. Scoones, and A. Stirling. 2010. Governing epidemics in an age of complexity: Narratives,

politics and pathways to sustainability. *Global environmental change: human and policy dimensions* 20(3):369–377.
Lele, S. 2011. Dynamic Sustainabilities: Technology, Environment, Social Justice. *Journal of Integrative Environmental Sciences* 8(2):140–143.
van der Leeuw, S. 2020. *Social Sustainability, Past and Future*. Cambridge: Cambridge University Press. Open access: https://doi.org/10.1017/9781108595247
van der Leeuw, S. 2019. The role of narratives in human-environmental relations: an essay on elaborating win-win solutions to climate change and sustainability. *Climatic change https://doi.org/10.1007/s10584-019-02403-y*.
Linnér, B.-O., and V. Wibeck. 2019. *Sustainability Transformations: Agents and Drivers across Societies*. Cambridge University Press.
Maes, M. J. A., K. E. Jones, M. B. Toledano, and B. Milligan. 2019. Mapping synergies and trade-offs between urban ecosystems and the sustainable development goals. *Environmental science & policy* 93:181–188.
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. 1997. *Leverage Points: Places to Intervene in a System*. Page 21. The Sustainability Institute, Hartland VT.
Meadows, D.H. 2008. *Thinking in Systems: A Primer*. Chelsea Green.
Nilsson, M., E. Chisholm, D. Griggs, P. Howden-Chapman, D. McCollum, P. Messerli, B. Neumann, A.-S. Stevance, M. Visbeck, and M. Stafford-Smith. 2018. Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustainability Science* 13(6):1489–1503.
Nilsson, M., D. Griggs, and M. Visbeck. 2016. Policy: Map the interactions between Sustainable Development Goals. *Nature News* 534(7607):320.
Norström, A. V., C. Cvitanovic, M. F. Löf, S. West, C. Wyborn, P. Balvanera, A. T. Bednarek, E. M. Bennett, R. Biggs, A. de Bremond, B. M. Campbell, J. G. Canadell, S. R. Carpenter, C. Folke, E. A. Fulton, O. Gaffney, S. Gelcich, J.-B. Jouffray, M. Leach, M. Le Tissier, B. Martín-López, E. Louder, M.-F. Loutre, A. M. Meadow, H. Nagendra, D. Payne, G. D. Peterson, B. Reyers, R. Scholes, C. I. Speranza, M. Spierenburg, M. Stafford-Smith, M. Tengö, S. van der Hel, I. van Putten, and H. Österblom. 2020. Principles for knowledge co-production in sustainability research. *Nature Sustainability*.
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.
Page, G. G., R. M. Wise, L. Lindenfeld, P. Moug, A. Hodgson, C. Wyborn, and I. Fazey. 2016. Co-designing transformation research: lessons learned from research on deliberate practices for transformation. *Current Opinion in Environmental Sustainability* 20:86–92.
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.v
Pedercini, M., S. Arquitt, D. Collste, and H. Herren. 2020. Harvesting synergy from sustainable development goal interactions. *PNAS* Open access: *https://doi.org/10.1073/pnas.1817276116*.
Pedercini, M., H. M. Kleemann, N. Dlamini, V. Dlamini, and B. Kopainsky. 2018. Integrated simulation for national development planning. *Kybernetes. The International Journal of Cybernetics, Systems and Management Sciences* 48(1):208–223.
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).

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.

Pradhan, P., L. Costa, D. Rybski, W. Lucht, and J. P. Kropp. 2017. A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Future* 5(11):1169–1179.

Randers, J., J. Rockström, P. E. Stoknes, U. Golüke, D. Collste, and S. 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*. Open access: https://www.stockholmresilience.org/download/18.51d83659166367a9a16353/1539675518425/Report_Achieving%20the%20Sustainable%20Development%20Goals_WEB.pdf

Reed, M. S. 2008. Stakeholder participation for environmental management: a literature review. *Biological conservation* 141(10):2417–2431.

Reynolds, M., and S. Holwell. 2020. *Systems Approaches to Making Change: A Practical Guide*. Springer London.

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. 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* 14(2):Art. 32.

Sachs, J. D., G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, and J. Rockström. 2019. Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability* 2(9):805–814.

Saijo, T. 2020. Future Design: Bequeathing Sustainable Natural Environments and Sustainable Societies to Future Generations. *Sustainability* 12(16):6467. https://www.mdpi.com/2071-1050/12/16/6467

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.

Schultz, M., T. Hahn, N. Hällström, and C. Ituarte-Lima. 2016. The biggest single opportunity we have is dialogue-Dialogue seminars as a methodology for transformative social learning and conflict resolution in international environment negotiations, SwedBio at Stockholm Resilience Centre. *This is a modification of a paper with a similar name under review in International Journal of Biodiversity Science, Ecosystem Services & Management*.

Scoones, I., A. Stirling, D. Abrol, J. Atela, L. Charli-Joseph, H. Eakin, A. Ely, P. Olsson, L. Pereira, R. Priya, P. van Zwanenberg, and L. Yang. 2020. Transformations to sustainability: combining structural, systemic and enabling approaches. *Current Opinion in Environmental Sustainability* 42:65–75.

Sharpe, B., A. Hodgson, G. Leicester, A. Lyon, and I. Fazey. 2016. Three horizons: a pathways practice for transformation. *Ecology and Society* 21(2).

Sharpe, B., and J. Williams. 2013. *Three horizons - the patterning of hope*.

Sharpe, B. 2020. *Three horizons: the patterning of hope.* Triarchy Press

Stafford-Smith, M., D. Griggs, O. Gaffney, F. Ullah, B. Reyers, N. Kanie, B. Stigson, P. Shrivastava, M. Leach, and D. O'Connell. 2017. Integration: the key to implementing the Sustainable Development Goals. *Sustainability Science* 12(6):911–919.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, 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*:1259855.

TWI2050 - The World in 2050. 2018. *Transformations to Achieve the Sustainable 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.
Turcotte, M.-F., and J. Pasquero. 2001. The Paradox of Multistakeholder Collaborative Roundtables. *The Journal of applied behavioral science* 37(4):447–464.
Ulrich, W. 2003. Beyond methodology choice: critical systems thinking as critically systemic discourse. *The Journal of the Operational Research Society* 2003(54):325–342.
United Nations (UN). 2015. *Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015*. Page 35.
United Nations. 2019. *Global sustainable development report 2019: the future is now : science for achieving sustainable development.*
Vanloqueren, G., and P. V. Baret. 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. *Research Policy* 38(6):971–983.
Vergragt, P. J., and J. Quist. 2011. Backcasting for sustainability: Introduction to the special issue. *Technological forecasting and social change* 78(5):747–755.
Voinov, A., and F. Bousquet. 2010. Modelling with stakeholders☆. *Environmental Modelling & Software* 25(11):1268–1281.
Voinov, A., N. Kolagani, M. K. McCall, P. D. Glynn, M. E. Kragt, F. O. Ostermann, S. A. Pierce, and P. Ramu. 2016. Modelling with stakeholders – Next generation. *Environmental Modelling & Software* 77:196–220.
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.
Wyborn, C., F. Davila, L. Pereira, M. Lim, I. Alvarez, G. Henderson, A. Luers, M. J. Martinez Harms, K. Maze, J. Montana, M. Ryan, C. Sandbrook, R. Shaw, and E. Woods. 2020. Imagining transformative biodiversity futures. *Nature Sustainability* 3(9):670–672.

Stockholm Resilience Centre
Sustainability Science for Biosphere Stewardship

Stockholm University

SwedBio
A programme at Stockholm Resilience Centre

THE SUSTAINABLE DEVELOPMENT GOALS CENTER FOR AFRICA

Evaluation and Feedback:
2nd African Dialogue on The World In 2050

30-31 October 2018, Park Inn by Radisson, Kigali, Rwanda

1. What was the most important moment(s) for you during this workshop?

………

………

………

2. What ideas and insights do you take home from this workshop?

………

………

………

3. What ideas or insights do you look forward to share at work?

………

………

………

4. What was missing from this workshop?

………

………

………

5. What is your view on the 3 Horizons approach (the tools and methods used for the dialogue)?

………

………

………

How do you evaluate the following aspects of the workshop?

	Very poor	Poor	Average	Good	Very good
6. Facilitation	☐	☐	☐	☐	☐
7. Organization	☐	☐	☐	☐	☐
	Not at all	Barely	Unsure	Mostly	Very well
8. Were the questions discussed useful for your work?	☐	☐	☐	☐	☐
9. Would you recommend this process to others?	☐	☐	☐	☐	☐

10. Please add if you have any other comments?

……………………………………..…………………………………………..……………………………

…………..……………………………………..……………………………………………..………………

………………………..………………………………………..…………………………………………..

Thank you for your participation!

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.

David Collste
holds a joint European Master in System Dynamics from the University of Bergen and the New University of Lisbon and a MSc in Political Sciences from Uppsala University.

Stockholm Resilience Centre, Stockholm University
Centre for Studies and Research in International Development, University of Clermont Auvergne
ISBN 978-91-7911-492-3