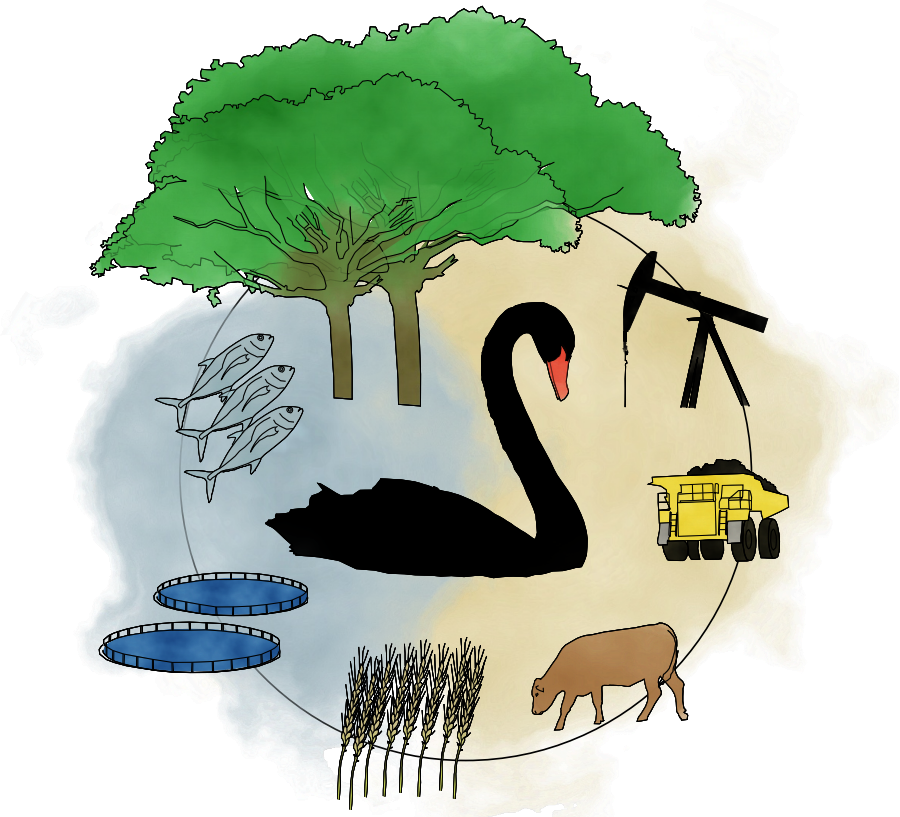
Stockholm University

Sustainability Risk

A social-ecological systems perspective

Emmy Wassénius



Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2024

Sustainability Risk

A social-ecological systems perspective

Emmy Wassénius

Academic dissertation for the Degree of Doctor of Philosophy in Sustainability Science at Stockholm University to be publicly defended on Friday 14 June 2024 at 13.00 in hörsal 4, hus 2, Albano, Albanovägen 18 and online via Zoom, public link is available at the department website.

Abstract

Today's world is characterised by new levels of complexity; however our societies remain deeply embedded in and dependent on a functioning biosphere. A biosphere that is increasingly being degraded by human activities. In this complex and intertwined world, acute shocks as well as chronic pressures of unsustainable activities have therefore become a prevalent feature. Together these shocks and chronic pressures create a complex risk landscape that we need to navigate with inter- and transdisciplinary solutions. However, the study of risk and the risk assessment tools in use, are siloed into scholarly disciplines and mismatched with the complexity at hand. In this thesis I tackle this mismatch, by using a social-ecological systems perspective and a variety of methodological approaches. Together the four papers of the thesis develop the interdisciplinary concept of sustainability risk and start to operationalise it through the application to national food systems and corporate sustainability risk assessment. Paper I introduces the concept of sustainability risk that I use and develop through-out the thesis. The paper also summarises some of the key definitions of risk within different disciplines and proposes five key dimensions that need to be adapted and developed in order for the existing risk assessment methods to fully capture risks in a complex world. Papers II-IV all represent applications of the concept of sustainability risk to different contexts. Paper II addresses national food supply risks and highlights how diverse risks to national self-sufficiency can come from low self-sufficiency (resulting in risk from trade disruptions) and low production diversity (resulting in risk from production shocks). Paper III addresses the data limitations we encounter when attempting to assess corporate sustainability risk and aims to overcome some of these limitations by developing fifteen novel reporting variables. These variables also contribute to the ongoing efforts to standardise corporate sustainability reporting. Paper IV builds on Paper III and develops an initial framework for assessing the risks to long-term natural resource production emanating from the impacts of corporate activities, thus broadening the conceptualisation of what risk is and how we assess it in the corporate sphere.

Keywords: *Sustainability risk, systemic risk, complex systems, social-ecological systems, corporate sustainability reporting, food security, resilience.*

Stockholm 2024
http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-228761

ISBN 978-91-8014-815-3
ISBN 978-91-8014-816-0

Stockholm Resilience Centre

Stockholm University, 106 91 Stockholm

SUSTAINABILITY RISK

Emmy Wassénius

Stockholm
University

Sustainability Risk

A social-ecological systems perspective

Emmy Wassénius

©Emmy Wassénius, Stockholm University 2024

ISBN print 978-91-8014-815-3
ISBN PDF 978-91-8014-816-0

Papers I, II and III are published under Creative Commons Attribution Licence (CC BY-NC-ND for Paper I and CC BY 4.0 for Papers II and III).

Cover image by Emmy Wassénius

Printed in Sweden by Universitetsservice US-AB, Stockholm 2024

"This is wisdom: to recognize what you know as what you know, and to recognize what you do not know as what you do not know."
- Confucius, Analects 2.17 *(Translation by Slingerland, 2003)*

Summary

Today's world is characterised by new levels of complexity; however our societies remain deeply embedded in and dependent on a functioning biosphere. A biosphere that is increasingly being degraded by human activities. In this complex and intertwined world, acute shocks as well as chronic pressures of unsustainable activities have therefore become a prevalent feature. Together these shocks and chronic pressures create a complex risk landscape that we need to navigate with inter- and transdisciplinary solutions. The study of risk and the risk assessment tools in use are however siloed into scholarly disciplines and thus mismatched with the complexity at hand. In this thesis I tackle this mismatch, by using a social-ecological systems perspective and a variety of methodological approaches. Together the four papers of the thesis develop the interdisciplinary concept of sustainability risk and start to operationalise it through the application to national food systems and corporate sustainability risk assessment. **Paper I** introduces the concept of sustainability risk that I use and develop throughout the thesis. The paper also summarises some of the key definitions of risk within different disciplines and proposes five key dimensions that need to be adapted and developed for the existing risk assessment methods to fully capture risks in a complex world. Papers II-IV all represent applications of the concept of sustainability risk to different contexts. **Paper II** addresses national food supply risks and highlights how diverse risks to national self-sufficiency can come from low self-sufficiency (resulting in risk from trade disruptions) and low production diversity (resulting in risk from production shocks). **Paper III** addresses the data limitations we encounter when attempting to assess corporate sustainability risk and aims to overcome some of these limitations by developing fifteen novel reporting variables. These variables also contribute to the ongoing efforts to standardise corporate sustainability reporting. **Paper IV** builds on Paper III and develops an initial framework for assessing the risks to long-term natural resource production emanating from the impacts of corporate activities, thus broadening the conceptualisation of what risk is and how we assess it in the corporate sphere.

Key words: Sustainability risk, systemic risk, complex systems, social-ecological systems, corporate sustainability reporting, food security, resilience

Sammanfattning

Världen idag karakteriseras av nya nivåer av komplexitet, men våra samhällen är fortfarande djupt beroende av en välfungerande biosfär. En biosfär som i ökande grad förstörs av mänskliga aktiviteter. Detta har lett till att både chocker och kronisk ohållbar stress på vår planet och våra samhällen har blivit mer påtaglig. Tillsammans har det skapat ett komplext risklandskap som vi behöver navigera med tvärvetenskapliga verktyg och lösningar. Studien av risk och riskbedömningsverktygen som används idag är dock grundade i vetenskapliga discipliner och överensstämmer därför inte med komplexiteten vi ser. I den här doktorsavhandlingen jobbar jag mot denna obalans (mellan komplexiteten av problemen och smalheten i verktygen) genom att använda ett social-ekologiskt systemperspektiv och en mängd olika metodologier. Tillsammans utvecklar de fyra artiklarna i avhandlingen det tvärvetenskapliga konceptet hållbarhetsrisk och börjar arbetet med att tillämpa detta genom studier av nationella livsmedelssystem och företagens hållbarhetsriskbedömning. **Artikel I** introducerar konceptet hållbarhetsrisk som jag sen använder och utvecklar genom hela avhandlingen. Artikeln sammanfattar även några av nyckeldefinitionerna av risk inom olika vetenskapliga discipliner och föreslår fem dimensioner som behöver anpassas och utvecklas för att de befintliga riskbedömningsmetoderna fullt ut ska kunna fånga risker i en komplex värld. Artiklarna II-IV tillämpar sedan konceptet av hållbarhetsrisk i olika kontexter. **Artikel II** tar upp nationella livsmedelsförsörjningsrisker och belyser hur olika risker för nationell självförsörjning kan komma från låg självförsörjningsgrad (som skapar risk från handelsstörningar) och låg mångfald (som skapar risk från produktionschocker). **Artikel III** adresserar de databegränsningar vi har för att bedöma företagens hållbarhetsrisk, och bidrar till att minska dessa genom att utveckla femton nya rapporteringsvariabler. Dessa variabler bidrar också till det pågående arbetet med att standardisera företags hållbarhetsrapportering. **Artikel IV** bygger vidare på resultaten i Artikel III och utvecklar ett ramverk för att bedöma risken för långsiktig naturresursproduktion som skapas av företagsaktiviteters påverkan på miljön. Genom detta ramverk breddar jag också idén av vad hållbarhetsrisk är och hur vi bedömer den inom företag.

Nyckelord: Hållbarhetsrisk, systemrisk, komplexa system, social-ekologiska system, företagsrapportering, hållbarhetsrapportering, livsmedelsförsörjning, resiliens

List of Paper

Papers included in the thesis

Paper I
Wassénius, E., Crona, B.I., 2022. Adapting risk assessments for a complex future. One Earth 5, 35–43. https://doi.org/10.1016/j.oneear.2021.12.004

Paper II
Wassénius, E., Porkka, M., Nyström, M., Søgaard Jørgensen, P., 2023. A global analysis of potential self-sufficiency and diversity displays diverse supply risks. Global Food Security 37, 100673. https://doi.org/10.1016/j.gfs.2023.100673

Paper III
Wassénius, E., Crona, B., Quahe, S., 2024. Essential environmental impact variables: A means for transparent corporate sustainability reporting aligned with planetary boundaries. One Earth 7, 211–225. https://doi.org/10.1016/j.oneear.2024.01.014

Paper IV
Wassénius, E and Crona, B. Aggravation Risk: A tool to capture multiple pathways of corporate sustainability risk (Manuscript).

Contributions to papers included in the thesis, according to the Contributor Roles Taxonomy (CRediT)

For **Paper I,** Conceptualization, Investigation, and Visualization (alone), Writing and Review & Editing (lead but together with co-author). For **Paper II**, Data curation, Software/Coding, Formal analysis, and Visualization (alone), Methodology (lead but together with co-author MP), Conceptualization and Writing (lead but with input from whole author team). For **Paper III**, overall lead and project administration. Conceptualization and Writing (lead but with co-author BC), Methodology and Review & Editing (lead, but with all co-authors), Investigation, Validation, Data curation and Visualization (lead but with co-author SC). For **Paper IV,** Conceptualization, Investigation and Visualization (alone), Writing (lead but together with co-author).

List of additional papers

Jouffray, J.-B., Crona, B., **Wassénius, E.**, Bebbington, J., Scholtens, B., 2019. Leverage points in the financial sector for seafood sustainability. Science Advances 5, eaax3324. https://doi.org/10.1126/sciadv.aax3324

Crona, B., **Wassénius, E.,** Troell, M., Barclay, K., Mallory, T., Fabinyi, M., Zhang, W., Lam, V.W.Y., Cao, L., Henriksson, P.J.G., Eriksson, H., 2020. China at a Crossroads: An Analysis of China's Changing Seafood Production and Consumption. One Earth 3, 32–44. https://doi.org/10.1016/j.oneear.2020.06.013

Blasiak, R., Dauriach, A., Jouffray, J.-B., Folke, C., Österblom, H., Bebbington, J., Bengtsson, F., Causevic, A., Geerts, B., Grønbrekk, W., Henriksson, P.J.G., Käll, S., Leadbitter, D., McBain, D., Crespo, G.O., Packer, H., Sakaguchi, I., Schultz, L., Selig, E.R., Troell, M., Villalón, J., Wabnitz, C.C.C., **Wassénius, E.**, Watson, R.A., Yagi, N., Crona, B., 2021. Evolving Perspectives of Stewardship in the Seafood Industry. Frontiers in Marine Science 8. https://doi.org/10.3389/fmars.2021.671837

Crona, B., **Wassénius, E**., Lillepold, K., Watson, R.A., Selig, E.R., Hicks, C., Österblom, H., Folke, C., Jouffray, J.-B., Blasiak, R., 2021. Sharing the seas: a review and analysis of ocean sector interactions. Environmental Research Letters 16, 063005. https://doi.org/10.1088/1748-9326/ac02ed

Crona, B.I., **Wassénius, E**., Jonell, M., Koehn, J.Z., Short, R., Tigchelaar, M., Daw, T.M., Golden, C.D., Gephart, J.A., Allison, E.H., Bush, S.R., Cao, L., Cheung, W.W.L., DeClerck, F., Fanzo, J., Gelcich, S., Kishore, A., Halpern, B.S., Hicks, C.C., Leape, J.P., Little, D.C., Micheli, F., Naylor, R.L., Phillips, M., Selig, E.R., Springmann, M., Sumaila, U.R., Troell, M., Thilsted, S.H., Wabnitz, C.C.C., 2023. Four ways blue foods can help achieve food system ambitions across nations. Nature 616, 104–112. https://doi.org/10.1038/s41586-023-05737-x

Wassénius, E., Bunge, A.C., Scheuermann, M.K., Resare Sahlin, K., Pranindita, A., Ohlsson, M., Blandon, A., Singh, C., Malmcrona Friberg, K., Villarrubia-Gómez, P., 2023. Creative destruction in academia: a time to reimagine practices in alignment with sustainability values. Sustainability Science 18, 2769–2775. https://doi.org/10.1007/s11625-023-01357-6

Wood, A., Queiroz, C., Deutsch, L., González-Mon, B., Jonell, M., Pereira, L., Sinare, H., Svedin, U., **Wassénius, E**., 2023. Reframing the local–global food systems debate through a resilience lens. Nature Food 4, 22–29. https://doi.org/10.1038/s43016-022-00662-0

Contents

Summary i
Sammanfattning ii
List of Paper iii
Introduction 1
Development of the papers and scope of the thesis 3
Theoretical and conceptual background 5
Risk 5
Sustainability and Sustainability Science 6
Complex adaptive and social-ecological systems 7
Resilience thinking 8
Food systems 9
Corporate sustainability reporting and risk assessment 10
Methodological approaches 13
Exploratory data analysis 13
Literature review 14
Conceptual modelling 15
Expert elicitation 16
Summary of Papers 17
Paper I 17
Paper II 19
Paper III 20
Paper IV 21
Discussion 22
Developing the concept of sustainability risk 22
Navigating the space between uncertainty and risk: when to use the concept of sustainability risk 26
Operationalising sustainability risk: Contributions to different fields 29
Gaps remaining 31
Further applications of sustainability risk 31
From idea to practice 31

Concluding remarks 33
Positionality statement 34
Acknowledgements 36
References 37
Thank you 50

Introduction

A global pandemic, steadily rising CO_2 emissions, record-breaking global temperatures, conflict, trade disruptions, and an ever-expanding demand for natural resources – these are all events of the last five years. The ongoing crises and events of the complex world we have built have acted as a backdrop during this thesis and, unfortunately, with each new impactful event, the thesis topic seems increasingly relevant.

Today's world is characterised by new levels of complexity; however, our societies remain deeply embedded in and dependent on a functioning biosphere. A biosphere that is increasingly being degraded by human activities. In this complex and intertwined world, shocks and disturbances have become a prevalent feature. These disturbances have both multifaceted drivers, but equally multifaceted outcomes and consequences that connect not just across human societies but across human and natural systems. Taking the covid-19 pandemic as a recent example, this event had obvious impacts on human health, but also impacted workers' rights (Dobbins 2020, Dobbins et al. 2023, Cortes and Forsythe 2023) and created large trade disruptions with knock-on effects on the economy (Verschuur et al. 2021, Mena et al. 2022). The drivers of the pandemic can also be viewed at different scales, from the proximate driver of contact with an individual with covid-19, to global travel patterns and the transition from an epidemic to a pandemic (Tatem et al. 2006, Tuite et al. 2020), all the way to the interactions between people and nature that likely triggered the initial zoonotic jump (Gottdenker et al. 2014, White and Razgour 2020, Plowright et al. 2021). This one example, among many today, highlights the complex pathways of shocks and disturbances and the need to understand these to navigate the world today.

In addition to dealing with shocks (which are events causing disruption), we are also facing issues that cannot be traced to single events, but rather cause disruption through the gradual pressure on ecosystems and the planet over long periods of time. Many of the issues of sustainability, or rather unsustainability, falls in this category of gradual and initially incremental change. Including the ever-increasing emissions of greenhouse gases fuelling climate change (Calvin et al. 2023), land use change leading to changes in carbon, nutrient, and hydrological cycling (Hasan et al. 2020) as well as biodiversity loss (de Chazal and Rounsevell 2009). Today's challenges therefore highlight the need to not only assess the risks of short-term shocks, but also of slow and gradual pressures that push us away from trajectories needed to secure human wellbeing into the future. These slow and gradual pressures can also result in sudden and large-scale change, such as ecological regime shifts or climate tipping points (Lenton et al. 2008, Biggs et al. 2009, Rocha et al. 2015, Armstrong McKay et al. 2022). If these changes were to

happen, they would drastically change the biosphere conditions upon which our societies depend.

Due to these complexities and the intertwined nature of societies and the environment, many scholars in the field of sustainability science argue that solutions will need to come from interdisciplinary (the integration of knowledge from multiple different academic disciplines) or transdisciplinary (the integration of knowledge from academic and non-academic experts) endeavours (Spangenberg 2011, Brandt et al. 2013, Norström et al. 2020).

Despite a risk landscape characterized by complexity, the study of risk is nonetheless characterized by many, narrow definitions and assessment methods, generally rooted in single disciplines with little interaction between them (Bernstein 1996, Aven 2012). Although risk is a word commonly used in our everyday language, and with a long legacy of use (Bernstein 1996, Althaus 2005), this disciplinary siloing has been noted to create miscommunication between researchers hindering interdisciplinary risk research (Kaplan 1997, Aven and Thekdi 2021). It also creates a mismatch between the narrowness of the existing approaches and the complexity of the issues at hand, reducing our ability to address them. These issues are particularly poignant for the field of sustainability science as it is an inherently interdisciplinary field. Thus, to assess risks in relation to sustainability issues (sustainability risk) further research is needed to address this mismatch and contribute to conceptual and methodological solutions.

In this thesis I aim to address this mismatch by answering two overarching research questions (RQs):

RQ1: How is risk conceptualised in different fields and how well suited are these concepts to address sustainability risk in the complex world of today?

RQ2: What types of data and methods are used in different fields to assess risk, and are they suitable for assessing sustainability risk?

Development of the papers and scope of the thesis

The topic of this thesis, sustainability risk, was developed out of Paper I. Paper I was the first paper that I undertook in the thesis and the initial ambition behind it was to review different risk assessment methods that could be used to assess risk in sustainability science and address the complex events and pressures we see today. While undertaking the review and engaging with the field of risk science, it however became clear that although risk as a term is often used in sustainability science scholarship, most articles do not draw on a single definition of risk (and often do not provide a definition) or refer to specific methods to assess risk. The papers that clearly define what risk is and outline tools to assess it instead contribute to single disciplinary fields (that are not sustainability science). I therefore realised that there is a mismatch between the complexity of the risk landscape sustainability science is trying to address with the narrow and disciplinary definitions and methods of risk that we currently have at our disposal. I also realised that this mismatch could be broken down into two components. The first is what we view or define as a risk and refers to how we think and reason (cognitive processes) about what risk is. For example, is risk only the likelihood that a single undesirable event will happen in the future or is risk the combination of multiple interacting events? Or, for example in the corporate context, is risk only that which affects financial returns or is risk everything that can affect anything we (as a society) want to maintain? I choose to call this the 'cognitive mismatch' and it forms the basis for the first research question, how we should conceptualise risk for sustainability. This research question is answered partly through Paper I, but also through the contribution of all papers to the development of a concept of sustainability risk (Figure 1).

The second mismatch is about the data and tools available to assess risk. In terms of scope, it could be argued to fall within the first one since how risk is defined will inevitably influence which data and which methods you use to assess it. This mismatch is a result of how risk assessment tools have been developed in single disciplinary fields, that individually have a narrow definition of risk and thus use methods that address those specific narrow definitions. For example, if you define risk as a likelihood, the assessment tools you develop are all going to be different ways to calculate or estimate probability of something happening. These tools are therefore not appropriate to assess risk defined in a more complex way. This data and methods mismatch is the departure point for the second research question, which asks how different fields assess risk. In the thesis I delve into two different fields to answer this question, the scholarship on food systems (Paper II), particularly risks to food supply, and the transdisciplinary field of corporate sustainability (Paper III and IV, see Figure 1).

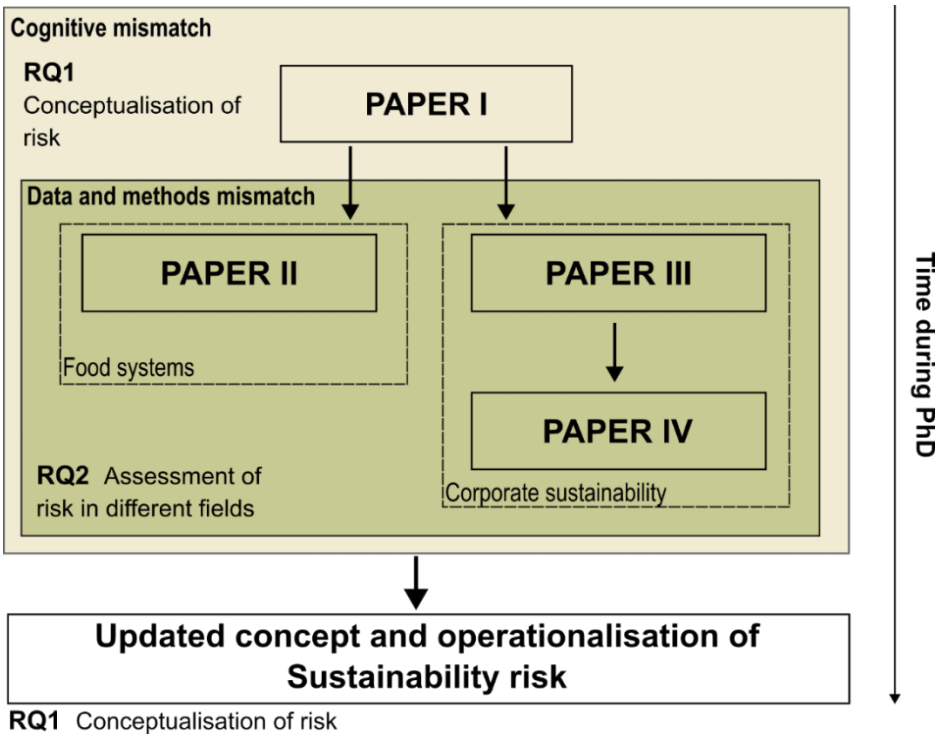


Figure 1. The scope of thesis covers two mismatches of the risk landscape; one being the cognitive mismatch, the other being a mismatch in data and methods. The figure highlights the two research questions, the two different fields and target audiences I address in the different papers, as well as the chronological and intellectual development of the papers and ideas in the thesis.

In addition to the scope of the thesis, Figure 1 also highlights the chronological and intellectual development of the four papers. Paper I initiated the thinking around sustainability risk that permeates all papers. Paper II and III were then conducted in tandem, addressing different target audiences and domains. Paper IV further developed what sustainability risk means in the corporate risk sphere and followed on from the findings in Paper III. Together all papers contribute to the development of the concept and operationalisation of sustainability risk that I discuss in this introductory chapter of the thesis.

Theoretical and conceptual background

In this section I introduce key concepts and theoretical underpinnings used in this thesis, as well as the scholarly fields of literature which the thesis draws on and contributes to.

Risk

Risk is a concept without a universal definition, or a common understanding of the origins of the word, and is therefore used in many different ways (Althaus 2005, Aven and Renn 2009, Aven 2012). However, one of the most general definitions is the possibility of an undesirable outcome (Aven 2012, Becker 2014). It is therefore very difficult, or arguably impossible, to define what the field of risk is, as it is any academic (or non-academic) text or discourse that uses the word and gives it any meaning. There are many articles in both academic and grey literature that fall into this category and use risk but without specifying the definition they use. This almost paradoxical case of assigning meaning without defining the concept arises because risk is commonly used (with meaning, but without a clearcut definition) in everyday language. There is however a subset in this broad field of risk, the relatively young scholarly field of risk science, that specifically addresses the different scholarly definitions of risk, and the methods used to assess them, and aims to develop an inter- and transdisciplinary understanding of risk (Aven 2020, Aven and Thekdi 2021). Some of the main disciplinary definitions of risk brought up by risk science scholars are for example:

- Risk as the probability distribution of an adverse outcome, also known as Knightian risk (used in economics) (Knight 1964).
- Risk as expected loss, i.e. the probability multiplied by the sum of loss (also used in economics) (Bernstein 1996).
- Risk as the combination of probability and consequence (used in engineering) (Ayyub 2003).
- Risk as the combination of hazard, exposure, and vulnerability (used in disaster risk studies) (UN/ISDR 2004, Dilley et al. 2005).

Each of these, as well as the many other disciplinary definitions of risk, are associated with whole scholarly fields that develop assessment tools and knowledge of risk within that field and that particular conception of risk. The field of risk science deals with the disciplinary siloing this creates and tries to elucidate the differences between conceptualisations and methods to develop an interdisciplinary concept of risk (Aven and Thekdi 2021). However, contrary to most of sustainability science, the field of risk science does not depart from an understanding of the world as a complex adaptive and a social-ecological system (these concepts are described further in the coming two sections). There is therefore a research gap that relates to what an

interdisciplinary concept of risk would be, that particularly takes this complex social-ecological systems perspective. This is therefore the topic of the thesis.

Within sustainability science, the concept of systemic risk has gained traction in recent years. Systemic risk is a concept and a research field that has developed over the last 10-15 years, and encompasses the idea of networked and cascading risks (Helbing 2013, Centeno et al. 2015, Sillmann et al. 2022). Networked risks are risks connected to and influencing each other (Helbing 2013) and cascading risks is where one risk can trigger another, and another, into a cascade (Centeno et al. 2015). Similarly, the concept of Anthropocene risk is a recent development that addresses how systemic risks are created through anthropogenic changes and affected by social-ecological connectivity (Keys et al. 2019). An example of Anthropocene risk that also highlights the complexity of the risk landscape, is how irrigation of crops in India contributes substantially to the levels of precipitation in East Africa affecting rain-fed agriculture there. Irrigation-based agricultural systems in India risk collapsing from exhaustion of wells or salinization of soils, but if irrigation is discontinued it would dramatically decrease rainfall in East Africa, creating large risks to the East African agricultural systems (Keys et al. 2019). Both the concept of systemic and Anthropocene risk greatly contribute to broadening the view on risk and help describe the risk landscape of today, however they stop at risk description, and do not connect with literature on risk assessment. In other words, there is still a knowledge gap in relation to how we should operationalise these broadened risk descriptions and thus how we should assess them.

Sustainability and Sustainability Science

Sustainability or sustainable development, and the field of sustainability science has been argued to have started in the 1980s (Bettencourt and Kaur 2011), triggered in part by seminal reports such as the UN report "Our Common Future", commonly referred to as the Brundtland Report (World Commission on Environment and Development 1987). The Brundtland report was one of the first to define sustainable development and defined it 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), a definition still widely used. Sustainability science scholarship has grown from its origins in the 1980s, and has from the start had contributions from a wide range of academic disciplines and geographical contexts (Bettencourt and Kaur 2011), highlighting the interdisciplinarity of the field. Today sustainability science is described as a problem-focused and solutions-oriented discipline aiming to fit into the Pasteur's Quadrant of both basic and applied research (Clark and Harley

2019). In their review of the field of sustainability science, Clark and Harley (2019) highlight that the concept that the world is a complex adaptive system (CAS) as well as a social-ecological system (SES) underpin many studies in this field.

Complex adaptive and social-ecological systems

Social-ecological systems is a concept used to describe the interconnectivity between human and natural systems. It views human and natural/ecological systems as parts of a whole rather than as separate systems and was developed through interdisciplinary collaboration in the early 1990s (Biggs et al. 2021). Social-ecological systems (SES) are importantly defined by the fact that societies and our economy (social systems) are embedded in, and dependent on, the biosphere (ecological system) (Folke 2016, Folke et al. 2021), i.e. that the systems are deeply intertwined rather than merely combined (Biggs et al. 2021). Thus SES are inherently complex, and defined as complex adaptive systems (Preiser et al. 2018).

Complex adaptive systems (CAS) are defined by principles of connectivity (relationality), adaptiveness, dynamisms and non-linear relationships, open boundaries, contextuality and complex causalities leading to emergence (Preiser et al. 2018) and highlights that there are emerging consequences that come out of the complex feedbacks in these systems. In the context of risk and due to this complexity, I posit in this thesis that we are currently in a complex risk landscape. Building on the principles of CAS, I mean that risks are connected through complex causality and feedback across scales (both geographical scales such as local and global, but also time scales, such as long and short) and where the boundaries are hard to determine. That risks continuously change with changing circumstances, where these changes can be non-linear, and new risks can emerge.

The understanding of the world as a SES and CAS, has shaped thinking in Earth system science, and lead to the seminal work on developing the planetary boundaries (Rockström et al. 2009, Steffen et al. 2015b, 2015a, Richardson et al. 2023), a concept I draw on in this thesis. The planetary boundaries framework highlights that earth system processes are changed by human activities, and that beyond a certain point (a boundary) this change is possibly non-linear. The existence of non-linear dynamics thus result in the potential for non-reversable (or hard to reverse) change if we push the system beyond the boundaries (Rockström et al. 2009, Steffen et al. 2015b, 2015a). The planetary boundaries concept, and the boundaries themselves, are set around maintaining a Holocene-like state. Where the Holocene is the only period of geological time in which human societies have been able to develop (Rockström et al. 2009). Thus, it is important to remember, that this concept,

as arguably the whole concept of sustainability, is human-centred. It focuses on maintaining, or sustaining, the earth system and our integrated social-ecological systems in a state that allows for complex human societies to continue. Acknowledging the integration of humans in the biosphere, is thus highlighting how human societies and human well-being ultimately depends on the state and functioning of the natural system (Folke 2016, Folke et al. 2021). This is also the perspective of this thesis, namely that human societies are deeply dependent on healthy natural systems, but that the functions we are aiming to sustain are primarily for humans.

Resilience thinking

The scholarship of CAS and SES are also strongly linked to the scholarship on resilience. Resilience is (similarly to risk) a concept that is used differently in different fields, where some fields define it narrowly as the return rate to equilibrium after a disturbance (Folke 2016). However, the dominant view of resilience in sustainability science is the notion of ecological resilience, originally developed by Holling (Holling 1973, 1978), but has since developed to address many different types of systems (Folke 2016). Over the years it has developed to be strongly associated with the concepts of SES and CAS, and the definition has expanded to encompass the ability of a system to maintain the same functions in face of change, through absorption, adaptation, and transformation – sometimes referred to as resilience thinking (Biggs et al. 2015, Folke 2016, Reyers et al. 2018). Thus resilience thinking is also about how systems handle disturbances, and is (I argue in this thesis) a complementary approach to risk. A key difference between the two concepts, risk and resilience, is however that resilience thinking is focused on the system itself and that both undesirable and desirable systems can be resilient (Folke 2016, Oliver et al. 2018).

***

To answer the second research question, on how different fields address and assess risk I delve in to two separate fields. One is the research on food systems, particularly food production and supply and the other is the transdisciplinary field of corporate sustainability reporting and risk. These two fields were selected due to their importance for our global societies, and their dependency and impact on the biosphere. Food systems, and the production of food fulfils and integral and irreducible need for humans, but it also a system that is inherently dependent on the ecosystem capacity to generate food. The current food production system has impacted and shaped both ecosystems (Nyström et al. 2019) and social systems, including globalised food trade (D'Odorico et al. 2014) to create a new risk landscape. Corporations, especially large corporations, today have a disproportionate impact on both the global economy (The Economist 2016) and on shaping the biosphere (Folke et al. 2019). This impact is creating risks to societies, our planet and to the companies themselves. Below I give brief introductions to each of these fields.

Food systems

Research on food systems in sustainability science is very diverse. I have myself contributed to several different perspectives, such as the roles of "blue" (aquatic) foods in national food systems (Crona et al. 2023), the role of China as a leader in blue food production (Crona et al. 2020) and the need to build resilient food systems at both local and global scales (Wood et al. 2023). In this thesis however, I contribute to the field of research on the barriers to and solutions for achieving a stable national food supply. Stable food supply is dependent on both what is produced domestically and on imports through international trade. Global food trade has expanded greatly (D'Odorico et al. 2014) and around 80% of the world's population is today dependent on food trade to some extent (Porkka et al. 2013). With recent large-scale disruptions in trade, such as the COVID-19 pandemic (Laborde et al. 2020), the grounding of the containership Ever Given in the Suez canal (Leggett 2021), and trade disruptions due to war and conflict (Al-Saidi 2023, Zhang et al. 2023), it is increasingly important to understand how domestic production can support domestic populations. The capacity of a country to produce food domestically to cover their own needs is referred to as their self-sufficiency (Clapp 2017).

Risks to domestic food production, and self-sufficiency can be addressed by looking at how shocks affect the total weight of production (Puma et al. 2015) or through investigating how much food in kcal is domestically produced (Porkka et al. 2013, Schramski et al. 2019, Beltran-Peña et al. 2020). An important aspect of research on food production is to also make the distinction

between food production rich in calories or production rich in necessary nutrients (Haddad et al. 2016, Herrero et al. 2017, Hicks et al. 2019). Although this perspective is seldom taken in self-sufficiency studies, it is integral for understanding how shocks and risks to food supply will manifest. The scholarly contributions to food system resilience, although not generally connected to the self-sufficiency literature, also tackles how able food systems are to handle shocks. These include what food system resilience means (Hodbod and Eakin 2015, Tendall et al. 2015), the multiple different dimensions of food system resilience (Seekell et al. 2017), how the food system handles shocks (Cottrell et al. 2019), and how to operationalise and assess food system resilience (Cabell and Oelofse 2012, Jacobi et al. 2018, Meuwissen et al. 2019).

The separation of these different research strands, that arguably aim to address similar issues, creates a research gap and an opportunity to gain insights into food supply risks by thinking about these topics in a more integrated way. I address this research gap in Paper II.

Corporate sustainability reporting and risk assessment

Due to the large impact companies today have on the biosphere, it is integral that companies report on these impacts and how they work with sustainability. Corporate sustainability reporting is a transdisciplinary space bridging sustainable accounting scholarship and a diverse set of practitioners, including global and regional standard-setting bodies, accountants, consultancies, companies, and investors. Milne and Gray (2013) argue that consultancies and standard-setting bodies have been central to how the discourse around sustainability in the corporate sphere has developed. The scholarly field of sustainability or environmental accounting dates from the 1990s (Bebbington et al. 2021) and investigates how corporate accounting and reporting does, or does not, capture companies' impacts on our planet (Milne and Gray 2013, Bebbington et al. 2021). Reporting that deals with sustainability information, is often dubbed "non-financial reporting" and has in the scholarship been discussed under a range of different terminology (as reviewed by Turzo et al. 2022). This breadth in terminology and thus in scholarship is due to the wide divergence in what companies report on sustainability and what they call this reporting. There are many different reporting frameworks that have been developed to delineate what companies should report. These include both voluntary, market-led initiatives (such as the Taskforce on Nature-related Financial Disclosures (TNFD) and Global Reporting Initiative (GRI)) and lately regulatory frameworks (such as the European Financial Reporting Advisory Group (EFRAG)). There is currently a push within corporate accounting and standard-setting bodies in the EU, US and internationally to

standardise reporting standards (EFRAG 2022, GRI 2022, IFRS 2023, TNFD 2024). This push for standardisation in reporting was largely driven by the large divergence in sustainability ratings (often referred to as ESG ratings) provided by ESG rating agencies (Chatterji et al. 2016, Crona and Sundström 2021, Berg et al. 2022). Given that such ratings were, and still are, based on sustainability reporting the divergence can be traced back to the diverse ways of reporting sustainability by companies, as well as to the lack of transparency in how rating agencies integrate sustainability into their metrics (Escrig-Olmedo et al. 2019). To adequately assess and rate sustainability performance in companies, it is therefore necessary to standardise how sustainability reporting is done. In this process it is also important to look at which information is standardised on and who is influencing this discussion. The development of sustainability reporting has been argued to be business-centred rather than sustainability-centred, leading to a skew in what information is included (Gray and Bebbington 2000, Young and Tilley 2006). I, together with my coauthors for Paper III and IV, note that there has been a lack of involvement of sustainability science scholars in these processes, and as environmental accountants have pointed out, it is currently not possible to infer a company's impacts on the planet and environment from their sustainability reports (Gray and Milne 2002, Milne and Gray 2013).

One of the key concepts influencing what information is included in sustainability reports is the concept of materiality. Materiality is a term that denotes what information is considered important, or "material", for investors to be aware of as it can affect a company's core business value (EFRAG 2022, FASB 2022, TNFD 2024). Information that is considered material is therefore included in reporting. The traditional approach to materiality has been financial materiality, where essential information is that which affects the financial returns of the company. However recently increasing attention has been given to double materiality (financial and impact materiality), where the information considered essential to disclose is both information that is financially material but also information on large impacts (e.g. on the environment) by the company (EFRAG 2023, TNFD 2024). It is important to note however that both of these materiality assessments depart from the company perspective, as is standard in corporate accounting (Gray and Milne 2002). The appropriateness of this company-centred perspective for sustainability issues is something I address in this thesis. I also address what types of data we would need from companies, through their sustainability reports, to determine both their impact and thus level of sustainability, but also their exposure to sustainability risks.

With the emergence of sustainable impact reporting framework there has been a parallel development in frameworks for sustainability risk (TCFD 2022, TNFD 2023). These highlight that corporate sustainability risks can generally

be broken down into two domains, physical and transition risks (Sjåfjell 2018, TCFD 2022). Physical risks are those in which the company is physically affected (e.g. through their assets or operations) by changes in the environment, such as climate change and extreme weather events. Transition risks are instead those risks that affect the company through changes in society (in turn due to climate or environmental change) such as changes in regulation, litigation, technology, reputation or consumer behaviour (TCFD 2022). As part of the development of corporate sustainability risks, there has been increasing acknowledgement that companies are dependent on nature for their business through natural capital, and that these dependencies create risks to companies and investors, so called nature-related risks (Natural Capital Finance Alliance 2022, Smith et al. 2024). Similarly, nature-related financial risks are risks to financial institutions (e.g. credit, business and liquidity risks) that stem from loss or degradation of natural capital by virtue of the financial effect this has on companies (due to the company dependency on this natural capital) (Rudgley and Seega 2021). In my thesis I contribute to this nascent field of nature-related risks by further developing how companies depend on and impact the environment.

Methodological approaches

To answer the research questions posed in this thesis I employ a mixed methods approach, drawing both on quantitative methods and large quantitative datasets, as well as qualitative methods and data creation. In the section below I present the different methods that I have used in papers I-IV.

Exploratory data analysis

Exploratory data analysis is a data-driven analysis method introduced by John Tukey (1977). Its development came along with the increasing capacities of computer coding and the possibilities it created for investigating large datasets. Rather than testing individual hypotheses exploratory data analysis is instead as Tukey puts it, detective work, or graphical detective work (Tukey 1977). Exploratory data analysis is therefore where, quantitative, datasets are analysed through various ways of plotting the data and looking at patterns in these plots (Tukey 1977, Morgenthaler 2009, Jebb et al. 2017). Since exploratory data analysis is not aiming to confirm or reject a specific hypothesis, and is rather a tool to create hypotheses from descriptions of data, it must not be conflated with questionable research methods such as "p-hacking" (Jebb et al. 2017).

Still today, exploratory data analysis is largely associated with coding (e.g. in R) and often used with large datasets that are difficult, if not impossible to otherwise fully view (Albert 2022, Wickham et al. 2023). In this thesis, I used exploratory data analysis to understand the different risks to national food supply, by viewing patterns in self-sufficiency and diversity in national food production data in **Paper I.**

To do this I first built a database that links together data on food production (based on weight per food item/species) with nutritional data (nutritional content per food item/species). The database includes both terrestrial food production (agriculture and livestock) and aquatic food production (fisheries and aquaculture) to get a full picture of the food production portfolio of each nation. This linking of diverse datasets of food production is seldom done and thus provides a novel and potentially more widely useful output in itself. This database, now openly available, thus forms a starting point for new answers to be gained (by myself and others). This high-resolution dataset (all nations across the globe, over time, for 2479 unique food products) was used to compare the levels of nutritional self-sufficiency with the levels of diversity in national food production. Nutritional self-sufficiency was calculated based on the nutritional values of the domestically produced foods, the size of the national population, and the known per capita nutritional sufficiency needs. A metric (ranging from 0 to 9 nutrients fulfilled) was designed to highlight the

extent of nutritional self-sufficiency within countries, but also which nutritional components were lacking in domestic production. Food production diversity was calculated in two ways, taxonomic diversity (the number of food items produced per nation per year) and a diversity metric based on the H-index, as used by (Seekell et al. 2017), to capture the evenness of food production.

These different diversity and sufficiency indices were then plotted, and patterns described and analysed. All analysis was performed in R, with the associated code made available through GitHub.

Literature review

Literature reviews are methods to review and summarize or synthesize information on a particular topic. There are many different ways to do literature reviews, but there is a general distinction between systematic and non-systematic reviews (Huelin et al. 2015, Cook 2019). Systematic reviews are intended to capture "all" literature on a topic with a pre-determined scope. These therefore use a set of predetermined search words, or search strings and review all articles that come up from this search. There is often a hierarchy of reviewing first abstracts and then making a decision to read and include the full paper based, again, on a series of predetermined criteria, a so-called screening process (Huelin et al. 2015). In many fields, especially the medical sciences, systematic literature reviews are seen as the gold standard (Huelin et al. 2015). However they are mainly useful when the topic is and, can be, adequately delimited a priori (Cook 2019). Non-systematic reviews on the other hand are often used when the topic is not as readily pre-determined, or when there is a need to draw insights from different fields who may use different terminology and when it is useful to let the insights gained while undertaking the review guide which further articles should be included (Huelin et al. 2015, Cook 2019). Non-systematic literature reviews are sometimes called "traditional" (Jesson et al. 2011), "purposive" (Cook 2019), "targeted", or "focused" (Huelin et al. 2015) due to the, in some fields, perceived judgement regarding the term non-systematic. There are therefore strengths and weaknesses of each approach. I have performed a systematic literature review in one of the papers outside my thesis (Crona et al. 2021), however due to the disciplinary siloing, and the exploratory nature of my thesis research, non-systematic literature review was more appropriate.

In **Paper I** I conducted a non-systematic literature review through snowball sampling to investigate the different conceptualisations of risk. This approach was selected due to the non-systematic way in which risk is discussed and addressed in the different fields (for example, different words are used to mean the same thing). In **Paper III** my co-authors and I undertook a non-systematic

review of the impact of corporate activities in seven primary sector industries (agriculture, livestock, fisheries, aquaculture, forestry, mining, and oil and gas) on the environment. The review was mainly based on two comprehensive databases, the ENCORE database (Natural Capital Finance Alliance 2022) and the database developed by Maniatakou et al. (2024). Here the non-systematic approach was taken since there was already extensive existing work in these databases. We structured the review around the planetary boundaries framework, to also contribute to the field of operationalising the planetary boundaries (Rockström et al. 2009, Steffen et al. 2015b). In **Paper IV**, I built upon the review of impact in Paper III and expanded upon it in the three case sectors of Paper IV (agriculture, aquaculture, and fisheries).

Conceptual modelling

Conceptual modelling is a method to distil information about the investigated system into an, often graphical, representation of links between components. Conceptual modelling has a long history of use in multiple different fields, including simulation modelling (Robinson 2004, 2011) and environmental assessment (Holling 1978). Despite this long history there is no single definition of what a conceptual model is. Robinson (2004) argues that this is likely because it is viewed more as an art than a science, and is an iterative process based on the knowledge of the modeller and the specific problem at hand. However, all conceptual modelling relies on the narrowing down of reality into somethings that can be modelled or assessed.

I used conceptual modelling in **Paper III**, building on the literature review, to create seven different conceptual systems diagrams, or conceptual models, of how a company in each of the seven sectors investigated impact the environment. In **Paper IV** I used conceptual modelling to determine different risk pathways affecting a company. Conceptual modelling is considered a useful method for developing risk assessment frameworks for complex problems (Suter 1999, Kashuba et al. 2021). In Paper IV I draw particularly on the environmental risk assessment literature, where conceptual models are considered instrumental (Suter 1996, 1999). This field assesses risks from contaminants on the environment, where the contamination either create risks for humans or non-human species (Suter 2007). The conceptual models are here graphical representations, usually flow charts, that depict the sources, recipients and routes of a contaminant that creates the environmental risks (Suter 1996). The routes described in a conceptual model are often causal, even though at the stage of the conceptual model, causality may be hypothesized rather than known (Suter 2007).

Conceptual modelling is thus similar, and could be argued to encompass, the method of causal loop diagramming used in system dynamics modelling (Lade et al. 2021). Using methods, like conceptual modelling, that trace causal

pathways have also been argued to be useful ways to explain and build theory in sustainability science (Biesbroek et al. 2017, Schlüter et al. 2022).

Expert elicitation

Expert elicitation is a method by which, experts in the topic of the elicitation are asked to provide information based on their expertise and experience. It can be used when information is sparse or absent (Hemming et al. 2018) or to succinctly condense information from a particular scholarly field. It is a method that has been commonly used in sustainability scholarship (see for example; Lenton et al. 2008, Chrysafi et al. 2022). When conducting expert elicitations, information biases can occur and several different structured elicitation protocols have been designed to overcome these (Hemming et al. 2018, O'Hagan 2019).

In **Paper III**, my co-authors and I used an expert elicitation method to both assess the scientific validity and comprehensiveness of the literature review and decide which of the impacts of corporate activities (summarised in the review) were considered greatest. Due to the breadth of the different impacts, as well as the complex nature of determining the greatest impacts, a workshop format was deemed the most appropriate. Survey-based elicitation methods (which are more common) would have meant that the interpretation of different expert perspectives would have had to been done by the author team rather than by the experts themselves, which we (the author team) considered less robust. However since we could not find any workshop-based expert elicitation methods for eliciting qualitative information I adapted the methodology and protocol from the well-established Sheffield elicitation method (Oakley and O'Hagan 2019). Seven different elicitation workshops were conducted, one for each sector, with a total of 22 experts.

Summary of Papers

This thesis is composed of four papers, three published (Papers I-III) and one manuscript (Paper IV). As mentioned in the scope, each of the papers addresses either the cognitive mismatch (Paper I) or both the cognitive and data and methods mismatches (Papers II-IV) to answer the two overarching research questions. I used a mixed methods approach, where I used literature review and scoping (Paper I and Paper IV), exploratory data analysis (Paper II), as well as conceptual modelling (Paper III and Paper IV), and expert elicitation (Paper III). In this section I summarise each of the four papers.

Paper I

Paper I is a review of risk and a synthesis of how well existing risk concepts address notions of complexity and social-ecological interactions. In this paper I review and give an overview of different disciplinary risk concepts and the field of risk science. Since scholars in sustainability science often come from separate academic disciplines but work in interdisciplinary teams, this review is a key contribution to helping scholars bridge their linguistic and cognitive (what they view as a risk) divide. Through the review it was also clear that definitions and assessment methods are very siloed in their academic disciplines. These disciplinary definitions and methods are very useful if we want to understand the risk landscape from a particular angle, e.g. which risk factors are correlated with heart disease. However, if we want to understand the dynamics between different risks, and the complex causal pathways that many risks today take, we need an interdisciplinary definition. Particularly we need an interdisciplinary definition suitable for sustainability issues (if it is to be applied in and contribute to sustainability science). In this paper I therefore develop and introduce the concept of sustainability risk. I define it as "risk that arises from events and actions that erodes the capacity of systems to maintain desirable functions in the long term" (Wassénius and Crona 2022). This definition is rooted in the idea that risk involves deviations from what is desirable, which is a common component of most of the perspectives (and definitions) of risk.

Through the review and synthesis, I also argue that the existing disciplinary risk assessment methods face challenges to deal with the complexity of the risk landscape we see. I thus propose and describe five key challenges that need to be addressed for the existing risk assessment methods to fully capture risks in a complex world. These are 1) Addressing randomness and how predictable the assessed system is. 2) Addressing if back-casting or forecasting is the most appropriate method to assess these risks. 3) Addressing which time horizon is the most appropriate to fully cover these risks. 4) Addressing if both

social and ecological risks, including social-ecological dynamics, are assessed. And finally, 5) If both proximate and distal risks, including cross-scale dynamics, are assessed. These five challenges are phrased as questions in the paper with the intention to spur thinking, discussion and further development of risk assessment methods.

Paper I thus addresses research question one and forms the starting point and basis for much of the further thinking and development of sustainability risk is this thesis.

Paper II

Paper II addresses food system risk and the gap that exists between different perspectives on food systems. To assess risk in times of trade disruptions the paper builds up a hypothetical case where food could not be obtained through trade, and food exports were temporarily redirected to national consumption. Even though this is a hypothetical scenario, with recent major disruptions to trade, such as the covid-19 pandemic and the blockage of the Suez Canal, this scenario is plausible and provides important information about national supply risks. Even if, were a situation like this to occur, trade will likely in many situations still be able to at least partially contribute to food supply. Through investigating the composition of the food system (which food items/species are produced as well as the distribution in volume and nutritional content between different food items) it provides an indication of how able national food systems are to deal with supply disturbances. Our results show that most of the world (127 countries and territories, 87% of the global population) achieves high levels of potential self-sufficiency, however only 33% of the world population are full self-sufficient. Of countries with a high level of self-sufficiency, fruit and vegetable production (which is also a proxy for many micronutrients) is the most common "missing" sufficiency. Sixty-six countries (6% of the global population) have a low degree of self-sufficiency, highlighting potential vulnerability to trade-related disruptions. The relationship between sufficiency and diversity is not homogenous, highlighting that some production systems are reliant on very few products. A low diversity system, where a large majority of nutritional requirements are filled by a single or a few food items, is more at risk of not being able to provide sufficient nutrients if a shock to production, such as an extreme weather event or a pest, disrupts this particular food item. If you have a more diverse system the risk of losing the desirable function (balanced nutritional food supply) is lowered.

The paper provides two things. First, it provides a summary of which nations are at risk from low self-sufficiency (resulting in risk from trade disruptions) and low production diversity (resulting in risk from production shocks). Second, it builds an open access database for further investigation, which is also supported by an online data tool that allows users to quickly get an overview of each nation (https://emmywas.shinyapps.io/food_supply_risks/). Together these are a starting point for identifying which of the types of risks investigated in this paper are most prevalent in each nation (and therefore require targeted focus and action).

As a contribution to the thesis, Paper II addresses research question two by digging into and creating data that can be used to assess diverse risks in a particular field (food system research).

Paper III

Paper III addresses corporate sustainability risk, or rather what data is made available by companies through their sustainability reporting to assess it. Using literature review, conceptual modelling, and expert elicitation, the paper summarises the environmental impact of corporate activities in seven primary sector industries (agriculture, livestock, fisheries, aquaculture, forestry, mining, and oil and gas). From the conceptual maps of impacts, a set of fifteen reporting variables were developed. We call these Essential Environmental Impact Variables (EEIVs) and we argue that disclosure of information on these 15 impact variables would greatly improve our collective ability to assess actual environmental performance of companies. Contrary to variables in the existing reporting frameworks, these variables are based on what is material for staying within the planetary boundaries (which we refer to as Planetary Materiality) as well as are based on absolute data in order to be able to aggregate and assess the cumulative impact of corporate activities. The paper therefore contributes with a different perspective to the current ongoing efforts to standardise corporate sustainability reporting. If companies were to report in line with the EEIVs it would greatly improve our ability to compare impacts on the environment (environmental sustainability) as well as assess environmental risks.

Sustainability risk, as assessed within corporations has a very narrow definition in that it assesses what impacts (e.g. from environmental hazards) can negatively affect the financial returns of the company. This single (financial) focus does not take into account that activities by corporate actors influence other functions that we as a society desire, such as the need and desire for planetary stability. To expand the notion of sustainability risk within corporations it was therefore necessary to first challenge this underlying premise, as well as provide guidance on what kinds of data would be needed.

Thus, Paper III addresses both the cognitive mismatch (what is viewed as risk, based on what is viewed as desirable), but also the data mismatch (in that the data provided through existing reporting frameworks would not have been able to assess these wider notions of risk). Thus, the work in Paper III contributes to answering both research questions. It helps answer RQ1 by highlighting the current business-centred approach to risk that currently dominates and to RQ2 by discussing what types of data would be necessary to assess wider notions (beyond to the business) of corporate sustainability risk. However, Paper III does not go into how we could use this data to assess risks, this is what Paper IV does.

Paper IV

Paper IV addresses the field of corporate sustainability risk, and particularly the recent developments of the concept of nature-related risk. The concept of nature-related risk represents a good first step within corporate sustainability risk assessment in that it acknowledges companies' dependencies on natural resources and functioning ecosystems. However, together with my co-author, I argue in Paper IV that there are still two key missing components in these assessments. The first is that the assessments do not consider that it is company practices, and the impacts they create on the environment, that themselves create these risks. The second is a lack of a long-term perspective, that goes beyond addressing risks that are financially material right now, but also includes risks that accumulate over time and space, including the risk to ecosystems overall capacity to generate natural resources. Paper IV therefore develops a novel risk assessment tool to address these knowledge gaps.

To do this, Paper IV takes a sequential three-step methodological approach, that starts with conceptual modelling (step 1), is followed by a literature deep dive into the three case sectors (fisheries, aquaculture and agriculture) (step 2), to then develop a risk assessment framework (step 3). The resulting framework highlights how different risk pathways contribute to overall risk, by first providing a risk score for each pathway and then providing an estimate of overall risk (low, medium, or high) based on the combination of scores. The risk assessment framework or tool developed in Paper IV assesses long-term risk to natural resource production and highlights that companies (in the primary sector) affect the environment and natural resources both today and in the future through their activities. It also highlights that due to their own dependencies on these resources these long-term risks could evolve into shorter-term financial risks if no mitigation action is taken.

Paper IV addresses research question two by answering how nature-related risks are traditionally assessed, and how these methods are suitable, or unsuitable, for the complex sustainability problems of today. It also contributes to this field by suggesting an assessment tool that would bridge some of the gaps identified.

Discussion

Developing the concept of sustainability risk

A key contribution of this thesis is the development of the concept of sustainability risk. As noted above, the development of this concept is a response to the perceived mismatch between the complexity of the current risk landscape and the disciplinary siloing of risk concepts and the consequent inability of risk assessment methods to capture the relevant and necessary aspects of risk. The concept has two main dimensions; the first being the multiple perspectives on risk that exist and the need for an interdisciplinary conceptualisation of risk. The second dimension is that the desirable function (the risk to what) can vary (depending on perspectives and audiences), but where I argue that sustainability places limitations on what these can be. Together these two dimensions create the concept of sustainability risk. Below I discuss each dimension in more detail.

The first dimension captures the different perspectives that exist of risk and the need to develop a broadened definition of risk that is easier to communicate and work with across disciplinary boundaries and within inter- and transdisciplinary teams (Figure 2). An overview and integration of risk definitions is developed in the field of risk science (Aven 2020, Aven and Thekdi 2021). I contribute to this work by bringing a social-ecological and sustainability perspective and argue for better integration of risk science literature (and knowledge) into sustainability science (Paper I), as it is very seldom done (however, see e.g. Becker 2014, 2024). In their introductory book to risk science Aven and Thekdi (2021) bring up that to find an interdisciplinary definition of risk, it is important to separate the concept of risk from the way that it is assessed. What they are referring to, and what I bring up in my scope, is that although many fields define risk narrowly and in a way that is often connected to a method (e.g. risk as a probability), there are underlying components that these definitions have in common. In this book Aven and Thekdi (2021) argue that the concept of risk can be defined as "the consequences of an activity associated with uncertainty". However in earlier overviews of risk conceptualisations Aven has noted that most definitions share a common feature of risk as movement away from desirability or the potential for loss of something desirable (Aven and Renn 2009, Aven 2012), something argued by other scholars in the field as well (Kaplan 1997, Becker 2014). Therefore, the first dimension of my concept of sustainability risk is the definition of risk as movement away from desirability (top left, Figure 2).

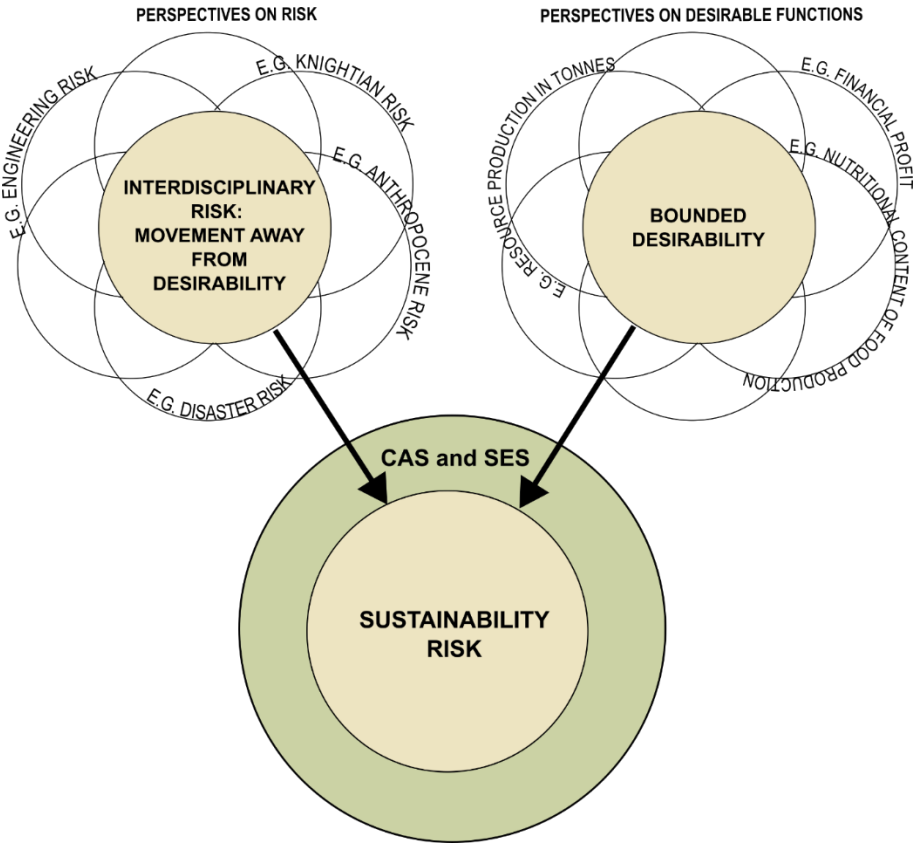


Figure 2. The two dimensions of the conceptual development that together make up the concept of sustainability risk. The first dimension is the interdisciplinary notion of risk as movement away from desirability (top left). The second dimension is the idea that different actors can have different perspective on what a desirable function is. Since these different perspectives are not fully compatible with each other or compatible with the limits of sustainability, I develop the idea of bounded desirability (top right) to encompass this. The concept of sustainability risk is made up of these two dimensions and developed using a complex adaptive (CAS) social-ecological systems (SES) lens (bottom middle).

The second dimension of the concept of sustainability risk, captures that sustainability can also be defined around desirability (top right, Figure 2). My thinking and the development of the sustainability risk concept is highly influenced by the definition I use of sustainability, even though I have not made this definition explicit in my papers. This is also why I have chosen to call the concept "sustainability" risk, rather than for example complex risk. Sustainability, or sustainable development is perhaps most famously defined by the Brundtland report (1987), to "meet the needs of the present without

compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development 1987). Although still widely used, the Brundtland definition has been criticized for its narrow focus on needs rather than encompassing wider notions of well-being. The argument has been that covering needs is not a sufficient goal (Clark and Harley 2019). Later definitions and uses have also highlighted the normative nature of sustainability. As Elmqvist et al. (2019) writes "Sustainability is a normative concept, representing the vision for society". This sustainability vision, and the normative aspect of it, highlights that sustainability is focused on desirable futures (Elmqvist et al. 2019). However, as with all normative concepts, the idea of what constitutes a desirable future likely varies from person to person and between different groups of actors or stakeholders. In this thesis, I combine the idea of sustainability as a desirable vision, together with the Brundtland definition of meeting the needs of the present as well as the needs of the future. I therefore define sustainability as "maintaining desirable functions long-term without diminishing the possibility to meet the needs of the present or the future". This definition is thus both intended to capture the idea that desirable functions are both grounded in needs, the need for food, water, and a stable environment, but also that depending on the actor, a wider scope of desirable functions that could be maintained (such as the continued operations of businesses, or for a particular type of food). The fact that it includes and allows for multiple perspectives on desirability, is part of the aim, making it versatile and applicable for a range of different disciplines, actors, and contexts. However, the definition also makes it explicit that this sustainable and desirable future cannot be obtained if it diminishes the possibility to meet the needs of the present or the future. In my thesis I discuss the different perspectives on desirable functions in several of my papers. For example, if the desirable function of the food system is the caloric content or a wider view of macro and micronutrient content (Paper II) or if the desirable functions addressed in corporate risk assessments should be financial returns or planetary stability (Paper III) or long-term natural resource production (Paper IV). I also discuss how shifting the focus of the desirable function from short-term financial returns to the long-term resource is also necessary due to the underlying resource needs of individuals and societies today and in the future (Paper IV). The definition of sustainability I use, of desirable functions coupled with needs of the present and the future, is another contribution of the thesis. I choose to call this "bounded desirability" (Figure 2) as it is based around desirable functions, in line with the idea of sustainability as a desirable vision (Elmqvist et al. 2019), but bounded by needs and the limitations by the planet to fulfil those needs. Using the wording of bounded, is a nod to the concept of "bounded rationality", that describes how rational choice is bounded by cognitive limitations, a concept coined and developed by Herbet Simon over his career (Jones 1999).

In one of his earliest discussions on the topic he wrote:

"Broadly stated, the task is to replace the global rationality of economic man with a kind of rational behaviour that is compatible with the access to information and the computational capacities that are actually possessed by an organism, including man, in the kinds of environments in which such an organism exists." (Simon 1955, p.99)

This idea, of placing back humans (man) "in the kinds of environments" in which we exist, is very similar to the notions of placing "back" humans into and as part of ecosystems and the biosphere (Folke 2010, Folke et al. 2021). Thus we are bounding desirability by the limitations of humans in the environment in which we exist, both the earth system limitations (Rockström et al. 2009, Steffen et al. 2015b, Richardson et al. 2023) and the social needs (Raworth 2012). This notion that desirability can or should be bound based on needs today and in the future is also a novel contribution of this concept in relation to risk and the field of risk science, which places no such limits on desirable function.

Together the development of these two dimensions, an interdisciplinary view of risk as movement away from desirability, and as desirability bounded by limitations and needs, make up my concept of sustainability risk and its updated (from Paper I) definition.

Updated Definition of Sustainability Risk: Risks that arise from events or actions that erodes the capacity of the system to maintain desirable functions in the long term, where desirable functions of today cannot be obtained if they diminish the possibility to meet the needs of the present or the future.

So why is having, an (arguably generic) definition of sustainability risk better than building on existing concepts of complex risks, such as systemic risk, or specifically in the case of SES and CAS systems Anthropocene risks? The concept of systemic (and thus Anthropocene risk) is premised around the notion that you cannot view or assess the risks to a component of the system in the complex systems of today but rather have to take a more holistic approach (Keys et al. 2019, Renn et al. 2022, Sillmann et al. 2022). In my concept of sustainability risk I do not argue with this notion, it is rather one of the key messages of Paper I (that risk assessments need to consider social-ecological and cross-scale dynamics). However, to operationalize these

concepts, and start to assess and thus mitigate some of the risks described, system boundaries need to be set. The contribution of the sustainability risk concept in phrasing it around desirable functions, allows for setting these boundaries, by asking the questions: risk of what? And risk to whom? Those familiar with the resilience scholarship will notice that these questions are borrowed from this body of literature, where the narrowing down of general resilience into specified resilience is facilitated by asking the questions of resilience of what and to whom (Carpenter et al. 2001, Folke 2010, Folke et al. 2016). By framing risk around desirable functions, and posing these questions, the boundaries around the system can be set (without having to delimit it to a single system component) and assessment metrics can be developed.

As a sustainability science scholar part of the endeavour is also to reclaim the term sustainability risk from the corporate risk management sphere, where it has become synonymous with risks stemming from natural systems and result in negative financial implications for the firm (often referred to as physical, regulatory, litigation or reputational risks)(Eccles et al. 2020, TCFD 2022, TNFD 2023). Along with some accounting scholars (Milne and Gray 2013), I argue that this narrow view of financial desirability as the only view on sustainability leads to misconceptions of how to improve sustainability and reduce these risks within corporations.

Navigating the space between uncertainty and risk: when to use the concept of sustainability risk

Uncertainty can be split up into two dimensions, aleatory and epistemic uncertainty, as Paper I lays out. Aleatory uncertainty is the uncertainty that arises due to natural variability or randomness of systems, whereas epistemic uncertainty stems from the uncertainty surrounding lack of knowledge (O'Hagan 2004, Fox and Ulkumen 2011, Maier et al. 2016). These two dimensions of uncertainty have allowed scholars and practitioners to talk about the known knowns, the known unknowns, and the unknown unknowns. These categories came to mainstream attention with former US Secretary of Defence, Donald Rumsfeld, in a speech in 2002 (Rumsfeld 2002). However, it had been used in academic settings much earlier, such as in Norman Myers discussion of the unknown unknown future implications on biodiversity and the need for the precautionary principle (Myers 1993). The first usage is however attributed to the development of the "Johari Window" by Luft and Ingham in 1955 (Oliver and Duncan 2019, Ale et al. 2020). The Johari window was initially designed to acknowledge the differences between what you know yourself and what is known to others, as a tool for self-awareness. However it can be used to delineate what is known and what can be known (Oliver and

Duncan 2019, Ale et al. 2020). In its usage as a tool for risk assessment it has also changed meaning to both be conceived as what is known to the risk assessor, versus what is known to the rest of the world (Taleb 2010). Taleb (2010) introduced his concept of "black swans", as events of extreme rarity and outside the realm of regular expectation, with severe impact, that are retrospectively (but not before the event) explicable and predictable. Taleb is clear in that the knowledge limitations of black swan risks lies with the assessor, or has he puts it "the result of collective and individual epistemic limitations" (Taleb 2010, p. xxiii), however many have used the term within risk scholarship to mean things that are completely unknown, and thus fall into the category of unknown unknowns (Aven 2013). This has spurred scholarly discussion on if Taleb's conception of black swan risks as only unknown to the assessors, is thus used as an excuse not to adequately mitigate known risks (Paté-Cornell 2012, Ale et al. 2020, Phan and Wood 2020). I argue, as I did in Paper I, that if we view black swans instead as complete unknown unknowns they fall into the space of both high epistemic and high aleatory uncertainty, and is a space beyond risk assessment, and rather the space for resilience thinking. I also argue that in situations where we know a lot about the risks at hand and where randomness is low (i.e. both aleatory and epistemic uncertainty is low), including knowing for example the probability at which they occur, traditional risk assessment methods are still useful. I argue here that it is in the space in between where sustainability risk finds its useful place.

To understand why I argue for this, it is also important to briefly discuss the role of resilience thinking. Resilience (as oppose to how I have defined risk, sustainability and thus sustainability risk) is not a normative concept, but rather a quality of the system (Anderies et al. 2013, Elmqvist et al. 2019). However, since we as humans and as sustainability scholars have preferences for certain trajectories, we can talk about desirable or undesirable resilience. Undesirable resilience is when the function that the system is maintaining is not the function we desire (Oliver et al. 2018). If resilience is undesirable, the desirable actions might be to break the resilience of the system and reform it around more desirable functions (Folke et al. 2016). If a system is organised around a desirable function, we may want to strengthen and build resilience to keep it that way. Regardless of the desire to shift or maintain a function, the resilience approach is a focus on the system itself, its components, the connections and feedback between components, and how these define the ability of the system to handle shocks and stresses. A recent study from risk science scholars argues, similarly to me, that risk and resilience approaches are compatible, however in it the authors describe resilience as a normative concept and that high resilience means a better ability to fulfil desirable functions (Logan et al. 2022). Based on my reading and understanding of the

resilience scholarship I do not agree with this conclusion but appreciate the work to bring resilience thinking and risk science scholarship closer.

Resilience thinking can be split into two concepts, general and specified resilience. General resilience is the system's ability to handle all types of shocks and stresses, even the unknown and unforeseen (Folke 2010, 2016). Specified resilience on the other hand is the system's ability to handle a particular stress or shock and maintain a specific function. Specified resilience is therefore often talked about as the resilience of what, to what (Carpenter et al. 2001, Folke 2010). By building general resilience in a system, we do not need to know or be able to predict what the future might hold. Instead we build the capacities of the system to deal with (true) uncertainty. Since general resilience is not targeting any particular shock or stressor, the actions we take to build general resilience are not as useful for quickly mitigating behaviour leading to undesirable outcomes. Specified resilience, is useful for building resilience of desirable systems to known shocks and stresses, to maintain particular desirable functions (Folke 2010). The weakness of specified resilience is that it has been argued to reduce general resilience and reduce the options for the wider system by focusing too narrowly on particular shocks, stresses and functions (Folke 2010). The link between specified resilience and risk is unclear, and with little research describing it. Risk mitigation strategies have been described as ways to build specified resilience (Carpenter et al. 2012). However resilience has also been argued to differ from risk mitigation in that resilience thinking, as opposed to risk thinking, views the system itself as ever-changing rather than stable, and that we will never be able to completely understand future outcomes (i.e. uncertainty is irreducible)(Adger et al. 2005, Berkes 2007). I view risk mitigation and specified resilience as separate due to the divide between focus on desirable function and focus on system, however more research would likely develop the gap or intersection between these concepts.

Therefore, the space I see the concept of sustainability risk filling is the space between the known knowns, where traditional risk approaches suffice, and the space of unknown unknowns and general resilience (Figure 3). It is the space where we know enough about the desirable functions and the different causal pathways (or hypothesised causal pathways) by which these functions can be affected, but where the complex and systemic nature of the risk landscape today has made traditional risk assessment methods incompatible.

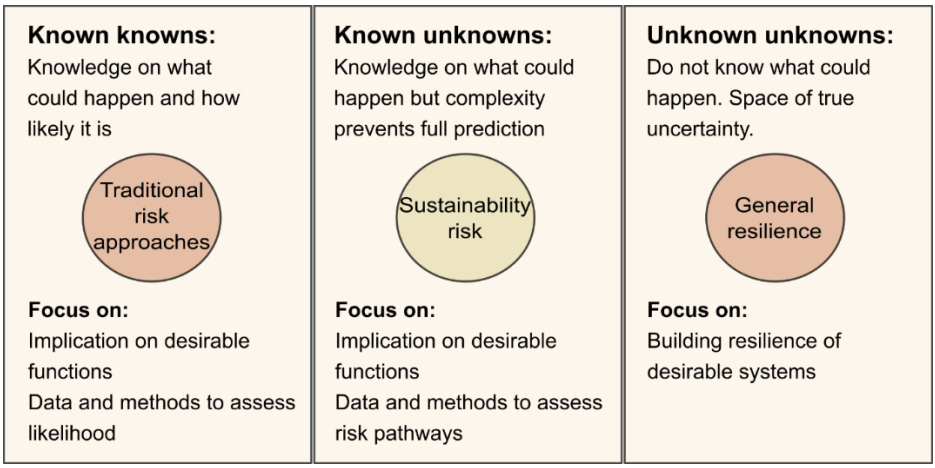


Figure 3. The space for sustainability risk, between traditional risk assessments and resilience thinking.

Operationalising sustainability risk: Contributions to different fields

Throughout papers II-IV I have applied the thinking on sustainability risk to particular desirable functions (risk of what) and to particular audiences (risk to whom). This has meant, that my thesis work has also contributed to two main fields, risks to national food production and supply and corporate sustainability risks.

Paper II specifically looks at connecting the findings of ecological or resilience studies with the studies on human health and nutritional demand. Bringing these two perspectives together highlights how both social and environmental risks combine to create the full risk to the desirable function, i.e. the sustainability risk. One pathway of risk is that what is produced is not nutritionally adequate, covering only a few nutrients or with too few calories – these are the social risks. The other pathway of risk is that the production system itself is too simplified (low diversity) that it risks large losses to production in times of production shocks (such as drought or pest outbreaks). The widened focus on sustainability risk in Paper II is also targeted at a national level, or national risk assessors, who arguably have the responsibility assess risks to food supply for the population (rather than the risks to individual consumers, food producers or companies). The thinking developed in this case could be similarly transferred to other situations of national resource supply risks. A striking example is the case that emerged a few years ago with the closing of the limestone quarry in Slite on Gotland (island in Sweden). The quarry has been in use for a long time and was reaching its end-

of-life. The intention to close the mine in 2021, was partly due to the risks of saltwater intrusion in the groundwater if mining was continued. However, when the intention of closing the quarry became public, there was a large outcry from particularly the building sector as it became apparent that most of Swedish cement is dependent on this single source, and thus underpins the entire sector (Silfwerbrand and Löfsjögård 2021). The decision was then made to extend the licence to mine in Slite (Ekberg 2022). The case of the Slite quarry clearly shows the varying risk dynamics with a low diversity (few mines supporting cement production) as well as production risks (saltwater intrusion). Taking the wider definition of sustainability risk developed in this thesis, and Paper II, to the case of Slite, would advocate that adequate risk mitigation in this case would rather have been to diversify chalk production/supply to maintain both the desirable function of cement production and the desirable function of secured groundwater supply. Interestingly, a government-initiated investigation into this type of broader risk perspective was later done and concluded that there was in fact, low diversity creating supply risks and that mitigation measures were going to be slow and expensive (Tillväxtanalys 2022).

Paper III and IV contribute to the field of sustainable accounting and corporate risk assessment. There is currently a large push within EU and International standard setting bodies to standardise corporate reporting (EFRAG 2022, IFRS 2023, TNFD 2024). Through engaging with this ongoing debate and undertaking the work of Paper III to bring a scientific perspective (including the perspectives of all participating experts), hopefully some of the insights gained will reach and influence this ongoing discussion and standardisation process. Through using the planetary boundaries framework to categorise impacts from corporate activities in Paper III, the scientific contribution of the paper also speaks to the work of operationalising the planetary boundaries (Häyhä et al. 2016, 2018, Bai et al. 2024). Paper IV contributes to the same field of corporate risk analysis, but to risk assessments specifically, contributing to the early developments of nature-related financial risk (Rudgley and Seega 2021, NGFS 2023, TNFD 2023).

Gaps remaining

Further applications of sustainability risk

As discussed, a key contribution of the thesis is the development of the concept of sustainability risk, with additional contributions being made with the application of this to different desirable functions (risks to what) and different audiences (risks to whom). This means that there is a large space of further application of this concept to different functions and audiences. Just as the cases included in the thesis has shone light on how different functions need to be limited or bounded (e.g. the limitations on practices due to the long-term need of the resource – explored in Paper IV), so will likely coming studies. A clear next step is of course to look at different desirable functions that fall into social sustainability. For example the social floor of the safe and just space, contains desirable functions such as health, education and jobs (Raworth 2012). Similarly, looking at food self-sufficiency (topic of Paper II) another desirable function is low price volatility in order to secure access (Clapp 2017), which is greatly driven by the increased influence of large corporate actors and financialised incentives in food production (Clapp and Isakson 2018a, 2018b). By addressing other types of desirable functions and tracing the causal risk pathways by which they are impacted, it is likely that other desirable functions (such as the modus operandi of corporations today) will likely have to be further bounded.

From idea to practice

The work in this thesis intends both to further scientific discussion, but also to contribute to changes in risk assessment in practice. This is perhaps most evident in Paper III and Paper IV targeting corporate sustainability reporting and risk assessment, as the papers are also calls for changing current practices and provides concrete variables and tools to do so. A gap remaining, or a next step, would be to engage with practitioners in the corporate and financial sectors to test the reporting variables (EEIVs in Paper III) and the risk assessment tool (developed in Paper IV). During my thesis I have been involved in providing feedback to the Task-force on Nature-related Financial Disclosures (TNFD) on their reporting framework (made possible due to Stockholm Resilience Centre being a knowledge partner to the TNFD). Although it is always difficult to know the effect of these types of engagements on outcomes, we (the author team of Paper III) have been happy to see (at least) the incorporation of location and site-specific reporting requirements from the early drafts to the current drafts of the framework. I will continue to be engaged in the TNFD through their newly developed working groups. In addition to engaging with TNFD, I have presented the findings of Paper III to the heads of Sustainability at a large Danish (Danske Bank) and a large Swedish bank (SEB). I have also helped develop a "Science in Brief" document (https://www.gedb.se/upl/files/197492/planetary-

materiality-final.pdf?t=763646700) of the findings in Paper III aimed at a corporate and investor audience. This brief has been circulated to the alumni of the Stockholm Resilience Centre Executive programme, a group that encompasses the CEOs of over 50 large Swedish corporations.

Hopefully, these initiatives that aim to bridge the science-practice divide will open opportunities for testing, feedback, and further development of these tools.

Concluding remarks

The current global risk landscape is complex, networked, and with risks emanating from both social and ecological feedbacks, requiring multifaceted and inter- and transdisciplinary solutions. However, current definitions of risk and thus current risk assessment tools are siloed into different disciplines, and the work to bridge these differences and come up with an interdisciplinary notion of risk (within the risk science field) do not take the fact that we live in complex adaptive, social-ecological systems into account. Thus, this thesis set out to answer two research questions. Firstly, how is risk conceptualised in different fields and how well suited are these concepts to deal with sustainability risk in the complex world of today? Secondly, what types of data and methods are used in different fields to assess risks, and are they suitable for assessing sustainability risk? I answer these questions by providing both an overview of disciplinary risk conceptualisations (Paper I) and a view on how risks are viewed and assessed in two different fields, food systems (Paper II) and corporate sustainability (Papers III and IV). I answer the research questions by arguing that current conceptualisations and methods are not well suited and provide initial suggestions for how to make them more suited. As part of this, I develop the concept of sustainability risk and define it as "Risks that arise from events or actions that erodes the capacity of the system to maintain desirable functions in the long term, where desirable functions of today cannot be obtained if it diminishes the possibility to meet the needs of the present or the future." I show how this definition and concept has come out of the diverse perspectives on risk, but also the diverse perspectives on what constitutes a desirable function (and how there may be trade-offs between them). I operationalise the concept through the application to two distinct fields and audiences (risks to national food production and supply and corporate sustainability risks) and have developed both a novel dataset for assessment of national food production, a framework for corporate sustainability reporting (as a tool to generate appropriate data) and an assessment framework of corporate sustainability risk.

Thus, this thesis contributes to aligning the mismatch between the complexity of the risk landscape in the world today and the concepts and tools we have to tackle it. Hopefully it will be a starting point for interesting future research and discussions, by myself and others.

Positionality statement

A positionality statement is one where the researcher reflects on who she or he is and what perspectives and worldviews that are brought into the research because of this individual background. This reflexivity acknowledges that there is no truly objective research but that what questions are asked, which approaches are taken and henceforth which research is conducted is highly dependent on who the researcher is (Darwin Holmes 2020). To understand how this thesis came to contain these four papers it is important to understand my background.

I am a white woman, born in Sweden to Swedish parents. During both my childhood and my early adult years I have lived in multiple countries outside of Sweden (China, Thailand, Indonesia, Australia, and Scotland), for longer or shorter durations (6 months to 4 years). Both abroad and in Sweden I attended international school during some of my school-aged years. My experiences both of international school and from living abroad shaped my thinking to be open to new perspectives and ways of thinking. I believe these experiences underpin my belief that there are no black or white, right or wrong dualities in relation to complex problems, but rather that our actions and decisions are shaped by the context in which they were formed. This belief manifests itself in that I would classify myself as a pragmatist. Pragmatism is defined by its focus on the practical consequences of decisions, rather than if they are the "true" or "real" explanation of reality (Cherryholmes 1992). Pragmatists therefore also choose the methods and approaches that best help understand these practical consequences (Cherryholmes 1992). Although it interests me to discuss how the world could be different, and potentially better, if it was driven by different underlying principles, the pragmatist in me focuses my research on tackling problems based on the world that is. This results perhaps that my research is not as critical of the status quo as it potentially could be.

I entered my academic career through an undergraduate degree in Marine Biology and consider myself still today to have a natural science or ecological underpinning in my thinking. I continued with a Masters degree in "Social-Ecological Systems for Sustainable Development". My transition to sustainability was largely driven by my need to understand how humans and human actions fit into the ecological systems I had been studying, but also to participate in figuring out solutions to the grand challenges these systems are facing. Both prior to my PhD (in my years as a research assistant) and during my PhD I have continued to expand the boundaries of the systems I have been investigating to further understand what the drivers of unsustainable behaviour and practices are. My background, particularly my undergraduate and Masters degree, has instilled the core belief in the complexity of our world, and the complexity of diverse ecosystems. This belief has led to the

assumption that we do not, and likely will never, fully understand all the ways that human societies interact with ecosystems and how they shape our needs and wellbeing. Due to this complexity, and our inability to fully understand it, I am a "biophile" rather than a "technophile" in that I believe that technical (man-made and designed) solutions will never fully capture all the complexity of the natural "solutions" that have evolved and co-developed over millennia.

Although I have a keen interest in knowledge, and in being a life-long learner, my research focus and interest has always been shaped by the question of; why is this interesting? How does this knowledge help us solve the problems we face today? If this interest came about from studying the "problem-focused" discipline of sustainability science, or if my decision to study sustainability arose from this interest is impossible to say. They have likely acted as a reinforcing feedback loop, increasing my interest in this over time. This interest has shaped the types of papers I have written, and thus included in the thesis.

Acknowledgements

This thesis was funded by the Global Economic Dynamics and the Biosphere programme at the Royal Swedish Academy of Sciences, funded by the Erling-Persson Foundation. The PhD was undertaken as part of the PhD programme at the Stockholm Resilience Centre at Stockholm University.

References

Adger, W. N., T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström. 2005. Social-Ecological Resilience to Coastal Disasters. *Science* 309(5737):1036–1039.

Albert, J. 2022. A Course in Exploratory Data Analysis. https://bayesball.github.io/EDA/.

Ale, B. J. M., D. N. D. Hartford, and D. H. Slater. 2020. Dragons, black swans and decisions. *Environmental Research* 183:109127.

Al-Saidi, M. 2023. Caught off guard and beaten: The Ukraine war and food security in the Middle East. *Frontiers in Nutrition* 10.

Althaus, C. E. 2005. A Disciplinary Perspective on the Epistemological Status of Risk. *Risk Analysis* 25(3):567–588.

Anderies, J. M., C. Folke, B. Walker, and E. Ostrom. 2013. Aligning Key Concepts for Global Change Policy: Robustness, Resilience, and Sustainability. *Ecology and Society* 18(2):art8.

Armstrong McKay, D. I., A. Staal, J. F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S. E. Cornell, J. Rockström, and T. M. Lenton. 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377(6611):eabn7950.

Aven, T. 2012. The risk concept—historical and recent development trends. *Reliability Engineering & System Safety* 99(0951):33–44.

Aven, T. 2013. On the meaning of a black swan in a risk context. *Safety Science* 57:44–51.

Aven, T. 2020. Risk Science Contributions: Three Illustrating Examples. *Risk Analysis* 40(10):1889–1899.

Aven, T., and O. Renn. 2009. On risk defined as an event where the outcome is uncertain. *Journal of Risk Research* 12(1):1–11.

Aven, T., and S. Thekdi. 2021. *Risk Science: An Introduction*. Routledge.

Ayyub, B. M. 2003. *Risk Analysis in Engineering and Economics*. Page *Risk Analysis in Engineering and Economics*. Chapman and Hall/CRC.

Bai, X., S. Hasan, L. S. Andersen, A. Bjørn, Ş. Kilkiş, D. Ospina, J. Liu, S. E. Cornell, O. Sabag Muñoz, A. de Bremond, B. Crona, F. DeClerck, J. Gupta, H. Hoff, N. Nakicenovic, D. Obura, G. Whiteman, W. Broadgate, S. J. Lade, J. Rocha, J. Rockström, B. Stewart-Koster, D. van Vuuren, and C. Zimm. 2024. Translating Earth system boundaries for cities and businesses. *Nature Sustainability* 7(2):108–119.

Bebbington, J., C. Larrinaga, B. O'Dwyer, and I. Thomson. 2021. *Routledge Handbook of Environmental Accounting*. Page (J. Bebbington, C. Larrinaga, B. O'Dwyer, and I. Thomson, editors). First edition. Routledge, Milton Park, Abingdon, Oxon; New York, NY: Routledge, 2021.

Becker, P. 2014. *Sustainability Science: Managing Risk and Resilience for Sustainable Development*. Page (Elsevier, editor). 1st edition. Oxford, UK.

Becker, P. 2024. *Sustainability Science: Managing Risk and Resilience for Sustainable Development*. 2nd edition. Elsevier.

Beltran-Peña, A., L. Rosa, and P. D'Odorico. 2020. Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. *Environmental Research Letters* 15(9):095004.

Berg, F., J. F. Kölbel, and R. Rigobon. 2022. Aggregate Confusion: The Divergence of ESG Ratings. *Review of Finance* 26(6):1315–1344.

Berkes, F. 2007. Understanding uncertainty and reducing vulnerability: Lessons from resilience thinking. *Natural Hazards* 41(2):283–295.

Bernstein, P. L. 1996. *Against the gods: The remarkable story of risk*. John Wiley & Sons, Inc, New York, NY.

Bettencourt, L. M. A., and J. Kaur. 2011. Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences* 108(49):19540–19545.

Biesbroek, R., J. Dupuis, and A. Wellstead. 2017. Explaining through causal mechanisms: resilience and governance of social–ecological systems. *Current Opinion in Environmental Sustainability* 28:64–70.

Biggs, R., S. R. Carpenter, and W. A. Brock. 2009. Turning back from the brink: detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences of the United States of America* 106(3):826–31.

Biggs, R., H. Clements, A. de Vos, C. Folke, A. Manyani, K. Maciejewski, B. Martín-López, R. Preiser, O. Selomane, and M. Schlüter. 2021. What are social-ecological systems and social-ecological systems research? Page *The Routledge Handbook of Research Methods for Social-Ecological Systems*. Routledge.

Biggs, R., M. Schlüter, and M. L. Schoon. 2015. *Principles for Building Resilience*. Page (R. Biggs, M. Schluter, and M. L. Schoon, editors) *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems*. Cambridge University Press, Cambridge.

Brandt, P., A. Ernst, F. Gralla, C. Luederitz, D. J. Lang, J. Newig, F. Reinert, D. J. Abson, and H. Von Wehrden. 2013. A review of transdisciplinary research in sustainability science. *Ecological Economics* 92:1–15.

Cabell, J. F., and M. Oelofse. 2012. An Indicator Framework for Assessing Agroecosystem Resilience. *Ecology and Society* 17(1):art18.

Calvin, K., D. Dasgupta, G. Krinner, A. Mukherji, P. W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W. W. L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F. E. L. Otto, M. Pathak, A. Pirani, E.

Poloczanska, H.-O. Pörtner, A. Revi, D. C. Roberts, J. Roy, A. C. Ruane, J. Skea, P. R. Shukla, R. Slade, A. Slangen, Y. Sokona, A. A. Sörensson, M. Tignor, D. Van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F. X. Johnson, S. Pachauri, N. P. Simpson, C. Singh, A. Thomas, E. Totin, P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. Van Der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D. J. A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J. S. Fuglestvedt, G. Hansen, C. Ludden, V. Masson-Delmotte, J. B. R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, and C. Péan. 2023. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* First. Intergovernmental Panel on Climate Change (IPCC).

Carpenter, S. R., K. J. Arrow, S. Barrett, R. Biggs, W. A. Brock, A. S. Crépin, G. Engström, C. Folke, T. P. Hughes, N. Kautsky, C. Z. Li, G. Mccarney, K. Meng, K. G. Mäler, S. Polasky, M. Scheffer, J. Shogren, T. Sterner, J. R. Vincent, B. Walker, A. Xepapadeas, and A. de Zeeuw. 2012. General resilience to cope with extreme events. *Sustainability* 4(12):3248–3259.

Carpenter, S., B. Walker, J. M. Anderies, and N. Abel. 2001. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* 4(8):765–781.

Centeno, M. A., M. Nag, T. S. Patterson, A. Shaver, and A. J. Windawi. 2015. The Emergence of Global Systemic Risk. *Annual Review of Sociology* 41(1):65–85.

Chatterji, A. K., R. Durand, D. I. Levine, and S. Touboul. 2016. Do ratings of firms converge? Implications for managers, investors and strategy researchers. *Strategic Management Journal* 37(8):1597–1614.

de Chazal, J., and M. D. A. Rounsevell. 2009. Land-use and climate change within assessments of biodiversity change: A review. *Global Environmental Change* 19(2):306–315.

Cherryholmes, C. H. 1992. Notes on Pragmatism and Scientific Realism. *Educational Researcher*(August-September).

Chrysafi, A., V. Virkki, M. Jalava, V. Sandström, J. Piipponen, M. Porkka, S. J. Lade, K. La Mere, L. Wang-Erlandsson, L. Scherer, L. S.

Andersen, E. Bennett, K. A. Brauman, G. S. Cooper, A. De Palma, P. Döll, A. S. Downing, T. C. DuBois, I. Fetzer, E. A. Fulton, D. Gerten, H. Jaafar, J. Jägermeyr, F. Jaramillo, M. Jung, H. Kahiluoto, L. Lassaletta, A. W. Mackay, D. Mason-D'Croz, M. M. Mekonnen, K. L. Nash, A. V. Pastor, N. Ramankutty, B. Ridoutt, S. Siebert, B. I. Simmons, A. Staal, Z. Sun, A. Tobian, A. Usubiaga-Liaño, R. J. van der Ent, A. van Soesbergen, P. H. Verburg, Y. Wada, S. Zipper, and M. Kummu. 2022. Quantifying Earth system interactions for sustainable food production via expert elicitation. *Nature Sustainability* 5(10):830–842.

Clapp, J. 2017. Food self-sufficiency: Making sense of it, and when it makes sense. *Food Policy* 66:88–96.

Clapp, J., and S. R. Isakson. 2018a. *Speculative Harvests*. Practical Action Publishing, Fernwood Publishing.

Clapp, J., and S. R. Isakson. 2018b. Risky Returns: The Implications of Financialization in the Food System. *Development and Change* 49(2):437–460.

Clark, W. C., and A. G. Harley. 2019. Sustainability Science: Towards a Synthesis.

Cook, D. A. 2019. Systematic and Nonsystematic Reviews: Choosing an Approach. Pages 55–60 *in* D. Nestel, J. Hui, K. Kunkler, M. W. Scerbo, and A. W. Calhoun, editors. *Healthcare Simulation Research: A Practical Guide*. Springer International Publishing, Cham.

Cortes, G. M., and E. Forsythe. 2023. Heterogeneous Labor Market Impacts of the COVID-19 Pandemic. *ILR Review* 76(1):30–55.

Cottrell, R. S., K. L. Nash, B. S. Halpern, T. A. Remenyi, S. P. Corney, A. Fleming, E. A. Fulton, S. Hornborg, A. Johne, R. A. Watson, and J. L. Blanchard. 2019. Food production shocks across land and sea. *Nature Sustainability* 2(2):130–137.

Crona, B. I., E. Wassénius, M. Jonell, J. Z. Koehn, R. Short, M. Tigchelaar, T. M. Daw, C. D. Golden, J. A. Gephart, E. H. Allison, S. R. Bush, L. Cao, W. W. L. Cheung, F. DeClerck, J. Fanzo, S. Gelcich, A. Kishore, B. S. Halpern, C. C. Hicks, J. P. Leape, D. C. Little, F. Micheli, R. L. Naylor, M. Phillips, E. R. Selig, M. Springmann, U. R. Sumaila, M. Troell, S. H. Thilsted, and C. C. C. Wabnitz. 2023. Four ways blue foods can help achieve food system ambitions across nations. *Nature* 616(7955):104–112.

Crona, B., and E. Sundström. 2021. *Sweet Spots or Dark Corners? An environmental sustainability examination of Big Data and AI in ESG*. SSRN.

Crona, B., E. Wassénius, K. Lillepold, R. A. Watson, E. R. Selig, C. Hicks, H. Österblom, C. Folke, J.-B. Jouffray, and R. Blasiak. 2021. Sharing the seas: a review and analysis of ocean sector interactions. *Environmental Research Letters* 16(6):063005.

Crona, B., E. Wassénius, M. Troell, K. Barclay, T. Mallory, M. Fabinyi, W. Zhang, V. W. Y. Lam, L. Cao, P. J. G. Henriksson, and H. Eriksson. 2020. China at a Crossroads: An Analysis of China's Changing Seafood Production and Consumption. *One Earth* 3(1):32–44.

Darwin Holmes, A. G. 2020. Researcher Positionality - A Consideration of Its Influence and Place in Qualitative Research - A New Researcher Guide. *Shanlax International Journal of Education* 8(4):1–10.

Dilley, M., R. S. Chen, U. Deichmann, A. Lerner-Lam, M. Arnold, J. Agwe, P. Buys, O. Kjekstad, B. Lyon, and G. Yetman. 2005. *Natural disaster hotspots: A global risk analysis*. Pages 1–132 *World Bank Disaster Risk Management Series*.

Dobbins, T. 2020, June 24. COVID illuminates global inequalities in workers' rights and working conditions. https://www.birmingham.ac.uk/research/perspective/covid-illuminates-global-inequalities-in-workers-rights.aspx.

Dobbins, T., S. Johnstone, M. Kahancová, J. R. Lamare, and A. Wilkinson. 2023. Comparative impacts of the COVID-19 pandemic on work and employment—Why industrial relations institutions matter. *Industrial Relations: A Journal of Economy and Society* 62(2):115–125.

D'Odorico, P., J. A. Carr, F. Laio, L. Ridolfi, and S. Vandoni. 2014. Feeding humanity through global food trade. *Earth's Future* 2(9):458–469.

Eccles, R. G., L.-E. Lee, and J. C. Stroehle. 2020. The Social Origins of ESG: An Analysis of Innovest and KLD. *Organization & Environment* 33(4):575–596.

EFRAG. 2022. European Sustainability Reporting Standards - First Draft. https://www.efrag.org/lab6.

EFRAG. 2023. *Draft EFRAG IG 1 Materiality Assessment*.

Ekberg, H. 2022, December 13. Cementa får fortsätta bryta kalk i Slite. https://www.byggvarlden.se/cementa-far-fortsatta-bryta-kalk-i-slite/.

Elmqvist, T., E. Andersson, N. Frantzeskaki, T. McPhearson, P. Olsson, O. Gaffney, K. Takeuchi, and C. Folke. 2019. Sustainability and resilience for transformation in the urban century. *Nature Sustainability* 2(4):267–273.

Escrig-Olmedo, E., M. Á. Fernández-Izquierdo, I. Ferrero-Ferrero, J. M. Rivera-Lirio, and M. J. Muñoz-Torres. 2019. Rating the Raters: Evaluating how ESG Rating Agencies Integrate Sustainability Principles. *Sustainability* 11(3):915.

FASB. 2022. Standards. https://fasb.org/standards.

Folke, C. 2010. Resilience Thinking: Integrating Resilience, Adaptability and Transformability. *Ecology and Society* 15(4).

Folke, C. 2016. Resilience. Page *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press.

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., H. Österblom, J. B. Jouffray, E. F. Lambin, W. N. Adger, M. Scheffer, B. I. Crona, M. Nyström, S. A. Levin, S. R. Carpenter, J. M. Anderies, S. Chapin, A. S. Crépin, A. Dauriach, V. Galaz, L. J. Gordon, N. Kautsky, B. H. Walker, J. R. Watson, J. Wilen, and A. de Zeeuw. 2019. Transnational corporations and the challenge of biosphere stewardship. *Nature Ecology and Evolution* 3(10):1396–1403.

Folke, C., S. Polasky, J. Rockström, V. Galaz, F. Westley, M. Lamont, M. Scheffer, H. Österblom, S. R. Carpenter, F. S. Chapin, K. C. Seto, E. U. Weber, B. I. Crona, G. C. Daily, P. Dasgupta, O. Gaffney, L. J. Gordon, H. Hoff, S. A. Levin, J. Lubchenco, W. Steffen, and B. H. Walker. 2021. Our future in the Anthropocene biosphere. *Ambio* 50(4):834–869.

Fox, C. R., and G. Ulkumen. 2011. Distinguishing two dimensions of uncertainty. Pages 21–35 *in* W. Brun, G. Keren, G. Kirkebøen, and H. Montgomery, editors. *Perspectives on Thinking, Judging, and Decision Making*. Universitetsforlaget.

Gottdenker, N. L., D. G. Streicker, C. L. Faust, and C. R. Carroll. 2014. Anthropogenic Land Use Change and Infectious Diseases: A Review of the Evidence. *EcoHealth* 11(4):619–632.

Gray, R., and J. Bebbington. 2000. Environmental accounting, managerialism and sustainability: Is the planet safe in the hands of business and accounting? Pages 1–44 *Advances in Environmental Accounting & Management*. Emerald Group Publishing Limited.

Gray, R., and M. Milne. 2002. Sustainability reporting: who's kidding whom? *Chartered Accountants Journal of New Zealand* 81(6):66–70.

GRI. 2022. Global Reporting Initiative Standards. https://www.globalreporting.org/how-to-use-the-gri-standards/gri-standards-english-language/.

Haddad, L., C. Hawkes, P. Webb, S. Thomas, J. Beddington, J. Waage, and D. Flynn. 2016. A new global research agenda for food. *Nature* 540(7631):30–32.

Hasan, S. S., L. Zhen, Md. G. Miah, T. Ahamed, and A. Samie. 2020. Impact of land use change on ecosystem services: A review. *Environmental Development* 34:100527.

Häyhä, T., S. E. Cornell, H. Hoff, P. Lucas, and D. van Vuuren. 2018. *Operationalizing the concept of a safe operating space at the EU level-first steps and explorations*.

Häyhä, T., P. L. Lucas, D. P. van Vuuren, S. E. Cornell, and H. Hoff. 2016. From Planetary Boundaries to national fair shares of the global safe

operating space — How can the scales be bridged? *Global Environmental Change* 40:60–72.
Helbing, D. 2013. Globally networked risks and how to respond. *Nature* 497(7447):51–59.
Hemming, V., M. A. Burgman, A. M. Hanea, M. F. McBride, and B. C. Wintle. 2018. A practical guide to structured expert elicitation using the IDEA protocol. *Methods in Ecology and Evolution* 9(1):169–180.
Herrero, M., P. K. Thornton, B. Power, J. R. Bogard, R. Remans, S. Fritz, J. S. Gerber, G. Nelson, L. See, K. Waha, R. A. Watson, P. C. West, L. H. Samberg, J. van de Steeg, E. Stephenson, M. van Wijk, and P. Havlík. 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *The Lancet Planetary Health* 1(1):e33–e42.
Hicks, C. C., P. J. Cohen, N. A. J. Graham, K. L. Nash, E. H. Allison, C. D'Lima, D. J. Mills, M. Roscher, S. H. Thilsted, A. L. Thorne-Lyman, and M. A. MacNeil. 2019. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* 574(7776):95–98.
Hodbod, J., and H. Eakin. 2015. Adapting a social-ecological resilience framework for food systems. *Journal of Environmental Studies and Sciences* 5(3):474–484.
Holling, C. S. 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics* 4(1):1–23.
Holling, C. S., editor. 1978. *Adaptive environmental assessment and management*. International Institute for Applied Systems Analysis ; Wiley, [Laxenburg, Austria] : Chichester ; New York.
Huelin, R., I. Iheanacho, K. Payne, and K. Sandman. 2015. *What's in a Name? Systematic and Non-Systematic Literature Reviews, and Why the Distinction Matters*. Evidera.
IFRS. 2023. *ISSB issues inaugural global sustainability disclosure standards.*
Jacobi, J., S. Mukhovi, A. Llanque, H. Augstburger, F. Käser, C. Pozo, M. Ngutu Peter, J. M. F. Delgado, B. P. Kiteme, S. Rist, and C. Ifejika Speranza. 2018. Operationalizing food system resilience: An indicator-based assessment in agroindustrial, smallholder farming, and agroecological contexts in Bolivia and Kenya. *Land Use Policy* 79(September):433–446.
Jebb, A. T., S. Parrigon, and S. E. Woo. 2017. Exploratory data analysis as a foundation of inductive research. *Human Resource Management Review* 27(2):265–276.
Jesson, J., L. Matheson, and F. M. Lacey. 2011. *Doing Your Literature Review: Traditional and Systematic Techniques*. SAGE.
Jones, B. D. 1999. BOUNDED RATIONALITY. *Annual Review of Political Science* 2(1):297–321.
Kaplan, S. 1997. The Words of Risk Analysis. *Risk Analysis* 17(4):407–417.

Kashuba, R., C. Menzie, and L. Martin. 2021. Risk of cardiovascular disease is driven by different combinations of environmental, medical and behavioral factors: Building a conceptual model for cumulative risk assessment. *Human and Ecological Risk Assessment: An International Journal* 27(7):1902–1925.

Keys, P. W., V. Galaz, M. Dyer, N. Matthews, C. Folke, M. Nyström, and S. E. Cornell. 2019. Anthropocene risk. *Nature Sustainability* 2(8):667–673.

Knight, F. 1964. *Risk, Uncertainty and Profit*. Sentry Press, New York, NY.

Laborde, D., W. Martin, J. Swinnen, and R. Vos. 2020. COVID-19 risks to global food security. *Science* 369(6503):500–502.

Lade, S. J., J. M. Anderies, P. Currie, and J. C. Rocha. 2021. Dynamical systems modelling. Pages 359–370 *The Routledge Handbook of Research Methods for Social-Ecological Systems*. First edition. Routledge, London.

Leggett, T. 2021. Egypt's Suez Canal blocked by huge container ship - BBC News. https://www.bbc.com/news/world-middle-east-56505413.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105(6):1786–1793.

Logan, T. M., T. Aven, S. D. Guikema, and R. Flage. 2022. Risk science offers an integrated approach to resilience. *Nature Sustainability* 5(9):741–748.

Maier, H. R., J. H. A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and J. H. Kwakkel. 2016. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software* 81:154–164.

Maniatakou, S., B. Crona, I. Jean-Charles, M. Ohlsson, K. Lillepold, and A. Causevic. 2024. A science-based heuristic to guide sector-level SDG investment strategy. *Journal of Sustainable Finance & Investment* 14(2):258–282.

Mena, C., A. Karatzas, and C. Hansen. 2022. International trade resilience and the Covid-19 pandemic. *Journal of Business Research* 138:77–91.

Meuwissen, M. P. M., P. H. Feindt, A. Spiegel, C. J. A. M. Termeer, E. Mathijs, Y. D. Mey, R. Finger, A. Balmann, E. Wauters, J. Urquhart, M. Vigani, K. Zawalińska, H. Herrera, P. Nicholas-Davies, H. Hansson, W. Paas, T. Slijper, I. Coopmans, W. Vroege, A. Ciechomska, F. Accatino, B. Kopainsky, P. M. Poortvliet, J. J. L. Candel, D. Maye, S. Severini, S. Senni, B. Soriano, C.-J. Lagerkvist, M. Peneva, C. Gavrilescu, and P. Reidsma. 2019. A framework to assess the resilience of farming systems. *Agricultural Systems* 176:102656.

Milne, M. J., and R. Gray. 2013. W(h)ither Ecology? The Triple Bottom Line, the Global Reporting Initiative, and Corporate Sustainability Reporting. *Journal of Business Ethics* 118(1):13–29.
Morgenthaler, S. 2009. Exploratory data analysis. *WIREs Computational Statistics* 1(1):33–44.
Myers, N. 1993. Biodiversity and the Precautionary Principle. *Ambio* 22(2/3):74–79.
Natural Capital Finance Alliance. 2022. ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure). https://encore.naturalcapital.finance/en.
NGFS. 2023. *Nature-related Financial Risks: a Conceptual Framework to guide Action by Central Banks and Supervisors*. Network for Greening the Financial System.
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* 3(3):182–190.
Nyström, M., J.-B. Jouffray, A. V. Norström, B. Crona, P. Søgaard Jørgensen, S. R. Carpenter, Ö. Bodin, V. Galaz, and C. Folke. 2019. Anatomy and resilience of the global production ecosystem. *Nature* 575(7781):98–108.
Oakley, J. E., and A. O'Hagan. 2019. *SHELF: the Sheffield Elicitation Framework (version 4).* School of Mathematics and Statistics, University of Sheffield, UK.
O'Hagan, A. 2019. Expert Knowledge Elicitation: Subjective but Scientific. *The American Statistician* 73(sup1):69–81.
O'Hagan, T. 2004. Dicing with the unknown. *Significance* 1(3):132–133.
Oliver, S., and S. Duncan. 2019. Editorial: Looking through the Johari window. *Research for All* 3(1).
Oliver, T. H., E. Boyd, K. Balcombe, T. G. Benton, J. M. Bullock, D. Donovan, G. Feola, M. Heard, G. M. Mace, S. R. Mortimer, R. J. Nunes, R. F. Pywell, and D. Zaum. 2018. Overcoming undesirable resilience in the global food system. *Global Sustainability* 1:e9.
Paté-Cornell, E. 2012. On "Black Swans" and "Perfect Storms": Risk Analysis and Management When Statistics Are Not Enough. *Risk Analysis* 32(11):1823–1833.
Phan, P. H., and G. Wood. 2020. Doomsday Scenarios (or the Black Swan Excuse for Unpreparedness). *Academy of Management Perspectives* 34(4):425–433.

Plowright, R. K., J. K. Reaser, H. Locke, S. J. Woodley, J. A. Patz, D. J. Becker, G. Oppler, P. J. Hudson, and G. M. Tabor. 2021. Land use-induced spillover: a call to action to safeguard environmental, animal, and human health. *The Lancet Planetary Health* 5196(21).

Porkka, M., M. Kummu, S. Siebert, and O. Varis. 2013. From Food Insufficiency towards Trade Dependency: A Historical Analysis of Global Food Availability. *PLoS ONE* 8(12):e82714.

Preiser, R., R. Biggs, A. De Vos, and C. Folke. 2018. Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. *Ecology and Society* 23(4):art46.

Puma, M. J., S. Bose, S. Y. Chon, and B. I. Cook. 2015. Assessing the evolving fragility of the global food system. *Environmental Research Letters* 10(2):024007.

Raworth, K. 2012. *A Safe and Just Space for Humanity: Can we live within the doughnut?* Oxfam.

Renn, O., M. Laubichler, K. Lucas, W. Kröger, J. Schanze, R. W. Scholz, and P.-J. Schweizer. 2022. Systemic Risks from Different Perspectives. *Risk Analysis* 42(9):1902–1920.

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(1):267–289.

Richardson, K., W. Steffen, W. Lucht, J. Bendtsen, S. E. Cornell, J. F. Donges, M. Drüke, I. Fetzer, G. Bala, W. Von Bloh, G. Feulner, S. Fiedler, D. Gerten, T. Gleeson, M. Hofmann, W. Huiskamp, M. Kummu, C. Mohan, D. Nogués-Bravo, S. Petri, M. Porkka, S. Rahmstorf, S. Schaphoff, K. Thonicke, A. Tobian, V. Virkki, L. Wang-Erlandsson, L. Weber, and J. Rockström. 2023. Earth beyond six of nine planetary boundaries. *Science Advances* 9(37):eadh2458.

Robinson, S. 2004. *Simulation: the practice of model development and use*. Wiley, Chichester.

Robinson, S., editor. 2011. *Conceptual modeling for discrete-event simulation*. CRC Press, Boca Raton.

Rocha, J. C., G. D. Peterson, and R. Biggs. 2015. Regime Shifts in the Anthropocene: Drivers, Risks, and Resilience. *PLOS ONE* 10(8):e0134639.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. 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. 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. Foley. 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* 14(2).

Rudgley, G., and N. Seega. 2021. *Handbook for Nature-related Financial Risks: Key concepts and a framework for identification*. University of Cambridge Institute for Sustainable Leadership.

Rumsfeld, D. 2002. NATO Speech: Press Conference US SoD - NATO HQ, Brussels - 6 June 2002. https://www.nato.int/docu/speech/2002/s020606g.htm.

Schlüter, M., G. Caniglia, K. Orach, Ö. Bodin, N. Magliocca, P. Meyfroidt, and B. Reyers. 2022. Why care about theories? Innovative ways of theorizing in sustainability science. *Current Opinion in Environmental Sustainability* 54:101154.

Schramski, J. R., C. B. Woodson, G. Steck, D. Munn, and J. H. Brown. 2019. Declining Country-Level Food Self-Sufficiency Suggests Future Food Insecurities. *BioPhysical Economics and Resource Quality* 4(3):12.

Seekell, D., J. Carr, J. Dell'Angelo, P. D'Odorico, M. Fader, J. Gephart, M. Kummu, N. Magliocca, M. Porkka, M. Puma, Z. Ratajczak, M. C. Rulli, S. Suweis, and A. Tavoni. 2017. Resilience in the global food system. *Environmental Research Letters* 12(2):025010.

Silfwerbrand, J., and M. Löfsjögård. 2021, November 19. Cementkrisen och dess konsekvenser för svenskt betongbyggande. https://byggteknikforlaget.se/cementkrisen-och-dess-konsekvenser-for-svenskt-betongbyggande/.

Sillmann, J., I. Christensen, S. Hochrainer-Stigler, J.-T. Huang-Lachmann, S. Juhola, K. Kornhuber, M. D. Mahecha, R. Mechler, M. Reichstein, A. C. Ruane, P.-J. Schweizer, and S. Williams. 2022. *ISC-UNDRR-RISKKAN Briefing note on systemic risk*. International Science Council, Paris, France.

Simon, H. A. 1955. A Behavioral Model of Rational Choice. *The Quarterly Journal of Economics* 69(1):99–118.

Sjåfjell, B. 2018. Beyond Climate Risk: Integrating Sustainability into the Duties of the Corporate Board. *Deakin Law Review* 23:41–62.

Smith, G. S., F. Ascui, A. P. O'Grady, and E. Pinkard. 2024. Indicators for measuring and reporting corporate nature-related impacts, dependencies, and risks. *Environmental and Sustainability Indicators* 22:100351.

Spangenberg, J. H. 2011. Sustainability science: a review, an analysis and some empirical lessons. *Environmental Conservation* 38(3):275–287.

Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney, and C. Ludwig. 2015a. The trajectory of the anthropocene: The great acceleration. *Anthropocene Review* 2(1):81–98.

Steffen, W., K. Richardson, J. Rockstrom, 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. Sorlin. 2015b. Planetary boundaries: Guiding human development on a changing planet. *Science*.
Suter, G. W. 1999. Developing Conceptual Models for Complex Ecological Risk Assessments. *Human and Ecological Risk Assessment: An International Journal* 5(2):375–396.
Suter, G. W. 2007. *Ecological risk assessment*. 2nd ed. CRC Press/Taylor & Francis, Boca Raton.
Suter, G. W., Ii. 1996. *Guide for developing conceptual models for ecological risk assessments*. Page ES/ER/TM--186, 237427.
Taleb, N. N. 2010. *The Black Swan: The Impact of the Highly Improbable*. Random House, New York, NY.
Tatem, A. J., D. J. Rogers, and S. I. Hay. 2006. Global Transport Networks and Infectious Disease Spread. *Advances in Parasitology* 62:293–343.
TCFD. 2022. *Taskforce on Climate-related Financial Disclosures: 2022 Status Report*.
Tendall, D. M., J. Joerin, B. Kopainsky, P. Edwards, A. Shreck, Q. B. Le, P. Kruetli, M. Grant, and J. Six. 2015. Food system resilience: Defining the concept. *Global Food Security* 6:17–23.
The Economist. 2016. *The rise of the superstars*.
Tillväxtanalys. 2022. *Förutsättningar för en alternativ försörjning av cement i Sverige*. Myndigheten för tillvbästpolitiska utvärderingar och analyser.
TNFD. 2023. *Guidance on the identification and assessment of nature-related issues: The LEAP approach Version 1.1*. Taskforce for Nature-related Financial Disclosures.
TNFD. 2024. Taskforce of Nature-related Financial Disclosures Publications. https://tnfd.global/tnfd-publications/.
Tuite, A. R., D. Bhatia, R. Moineddin, I. I. Bogoch, A. G. Watts, and K. Khan. 2020. Global trends in air travel: implications for connectivity and resilience to infectious disease threats. *Journal of Travel Medicine* 27(4):taaa070.
Tukey, J. W. 1977. *Exploratory data analysis*. Addison-Wesley Pub. Co, Reading, Mass.
Turzo, T., G. Marzi, C. Favino, and S. Terzani. 2022. Non-financial reporting research and practice: Lessons from the last decade. *Journal of Cleaner Production* 345:131154.
UN/ISDR. 2004. *Living with risk: a global review of disaster reduction initiatives*. Page (United Nations ISDR, editor) *UN Publications*. New York and Geneva.
Verschuur, J., E. E. Koks, and J. W. Hall. 2021. Observed impacts of the COVID-19 pandemic on global trade. *Nature Human Behaviour* 5(3):305–307.
Wassénius, E., and B. I. Crona. 2022. Adapting risk assessments for a complex future. *One Earth* 5(1):35–43.

White, R. J., and O. Razgour. 2020. Emerging zoonotic diseases originating in mammals: a systematic review of effects of anthropogenic land-use change. *Mammal Review* 50(4):336–352.

Wickham, H., M. Çetinkaya-Rundel, and G. Grolemund. 2023. *R for Data Science (2e)*. 2nd edition.

Wood, A., C. Queiroz, L. Deutsch, B. González-Mon, M. Jonell, L. Pereira, H. Sinare, U. Svedin, and E. Wassénius. 2023. Reframing the local–global food systems debate through a resilience lens. *Nature Food* 4(1):22–29.

World Commission on Environment and Development, editor. 1987. *Our common future*. Oxford University Press, Oxford ; New York.

Young, W., and F. Tilley. 2006. Can businesses move beyond efficiency? The shift toward effectiveness and equity in the corporate sustainability debate. *Business Strategy and the Environment* 15(6):402–415.

Zhang, Z., M. J. Abdullah, G. Xu, K. Matsubae, and X. Zeng. 2023. Countries' vulnerability to food supply disruptions caused by the Russia–Ukraine war from a trade dependency perspective. *Scientific Reports* 13(1):16591.

Thank you

First and foremost, I would like to thank you, Bea. I have worked with you now for more than eight years and you have been an amazing; supervisor, boss, mentor, co-author, and colleague. You are incredibly intelligent and kind, with a keen eye for the "next big thing" in research, and a drive and passion for not only doing great science but contributing to solve the pressing problems of today. I have learned so much from you. You have pushed my thinking, and immensely improved my writing skills (and turned writing from something I dreaded to something I enjoy). One of the things I have appreciated the most, is that you have always, from day one, believed in my capabilities and my ideas. I know that your belief in me is a large contributing factor to my endeavours and successes so far, by allowing me to dare to dive into the big messy topics and issues. The ones that don't have easy methods, or answers, or audiences, and make for difficult papers to write. Thank you, Bea. I look forward to continuing our work together.

Thank you to all my co-authors. To Miina for all our great conversations and technical and moral support. To Peter, for all you have taught me about pests, pathogens, and the importance of remembering that evolution is still ongoing. To Magnus, for being a co-author, but importantly a constant rock of support during all these years. To Sasha, thank you for diving deep into corporate reporting and expert elicitations with me, it wouldn't have been possible to write the paper we did without you.

To GEDB and Beijer, past and present. Wow, what a workplace this is! You are all so incredibly kind, humble, and funny. To my old "roomies" Daniel, Sofia, and Alice – thank you for being part of my journey and for making the day to day so much fun – what an era it was! To Caroline, it has meant, and still means, so much to me to have you as a friend, a colleague and support during these PhD years. To Anne-Sophie for all the laughs. To Therese for all the banter. To Patrik for all the fun sock and half-fruit discussions. To Max for the support – one day we will write our salmon paper. To Agneta, for dance discussions, Askö trips, and of course all help with communications. To Sofia-Kristin for making sure I have had a contract – really the most important person to thank! To Marie, my morning-time buddy. To the silent duo, Johan and Gustaf. To my new "roomies", Malin and Louis, thank you for making this last stretch so fun. To all the RAs past and present – you are a driving force in GEDB and it has been great to get to know and learn from all of you. To Calle, I hope I grow up to be like you, so brilliant yet so kind!

To all the people at SRC. I have spent nine years at SRC and have too many people to thank to mention all by name. Thank you, Miriam, for selecting me for the Masters programme in the first place, and for suggesting me to Bea – you started this whole thing off. Thank you, Albert, for the internal review for

my PhD and for my Lic and for being part of the journey from the start (the literal start – the first person at SRC I ever spoke to). I have grown as an academic from your feedback. Thank you, JB, for the internal review, but also for so much more. For pushing my thinking, for improving my figures, for being a reminder that some people really read all the supplementary materials. For the academic and personal support and friendship. To the PhD cohort past and present – you are all shining examples of how we can change academia to a more fun and friendly place without compromising excellent research. To Patty, for the dancing, boxing, and general friendship. To Anna, you got to keep hold of the good ones, even if it starts with a short visit. I'm not letting go of you!

And lastly, thank you to my family. Till mamma och pappa – tack för att ni alltid stöttat mig till att göra det jag vill och för erat fantatiska stöd än idag. Tack Lucas – du är bästa barnet. Tack till Christoffer och Waldemar – jag är lyckligt lottad att ha en så underbar familj.