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THE TRANSITION TO A BIO-BASED ECONOMY TOWARD AN INTEGRATED UNDERSTANDING

Thèse présentée et soutenue publiquement le 25 septembre 2020
pour l'obtention du titre de Docteur en Sciences Economiques

par

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L'université Clermont Auvergne n'entend donner aucune approbation ni improbation aux opinions émises dans cette thèse. Ces opinions doivent être considérées comme propres à l'auteur.

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Abstract

The bio-based economy has gained increasing attention in societal and academic debates over the past two decades, and is argued to hold solutions to several pressing sustainability challenges. However, it is not yet clear if the high-reaching aspirations of the bio-based economy can be realized. The bio-based economy discourse has been criticized for being promissory, vague, and single-sector focused, thereby overlooking larger systemic impacts, trade-offs, and unintended consequences that may result from pursuing the goals of the bio-based economy. Against this background, this thesis aims to advance an integrated and systemic understanding of the transition to a bio-based economy and what it implies for sustainability. Sweden is used as an empirical case, where specific bio-based economy goals, as well as their interactions and sustainability outcomes, are examined. The focus is primarily on developments in the forestry, agriculture, and energy sectors. The analysis also seeks to identify how goals related to the bio-based economy are interconnected with goals promoted by parallel sustainability initiatives, specifically the 2030 Agenda and the associated Sustainable Development Goals (SDGs). Integration is achieved by using systems analysis tools and methods. Further, the weak and strong sustainability paradigms, and the opposing definitions of sustainability they provide, are used to assess the contribution of the bio-based economy to sustainability.

The integrated analysis provides a detailed and operational conceptualization of transition pathways to a Swedish bio-based economy. The goals of the Swedish bio-based economy are divergent and broad-reaching, emphasizing that there is no general agreement on what the transition to a bio-based economy entails. The results point to multiple barriers that need to be addressed to realize the goals of the Swedish bio-based economy. Goal conflicts constitute one such barrier. These are found internal to as well as across the bio-based economy and the parallel 2030 Agenda. Additional hindrances include policy resistance, negative cross-sectoral spill-overs, and patterns of path dependency. However, the results also highlight several opportunities for supporting the transition process in a Swedish context. These opportunities include the identification of goals and interventions with synergetic potential, which offer a basis for developing efficient implementation strategies with high systemic impact. There is also large potential to support cross-sectoral collaboration and learning, based on shared interests and challenges. Finally, the results emphasize the importance of better understanding and addressing perceptions about risk, conflict, legitimacy, and trust in the transition process.

In terms of the overarching question of what the bio-based economy implies for sustainability, the results find that the bio-based economy has been contributing to developments that align primarily with weak sustainability. From the perspective of the strong sustainability paradigm, the prospects of the bio-based economy are less promising, potentially leading to outcomes that could worsen ongoing environmental and social issues. For the future, fundamental changes to the way the bio-based economy is conceptualized and implemented are needed for it to contribute to sustainability according to the notion of strong sustainability.

Keywords: bio-based economy, bio-economy, sustainability transitions, 2030 Agenda, Sustainable Development Goals, integrated sustainability assessment, systems analysis.

Svensk sammanfattning

Begreppet bio-baserad ekonomi har kommit att diskuteras alltmer i samhällliga och vetenskapliga debatter de senaste två årtiondena. Den bio-baserade ekonomin förväntas kunna bidra till ett mer hållbart samhälle, till exempel genom att fasa ut användningen av fossilbaserad råvara och erbjuda nya arbetstillfällen inom de gröna näringarna. Samtidigt kan en övergång till en bio-baserad ekonomi medföra nya risker och osäkerhetsfaktorer. En källa till osäkerhet är att tidigare studier och debatter kring en bio-baserad ekonomi till stor del fokuserat på enskilda frågor, sektorer eller användningsområden för biomassa. Övergripande frågor om vad en övergång till en bio-baserad ekonomi innebär för samhället i stort, samt potentiellt negativa miljömässiga och sociala konsekvenser, har däremot fått mindre uppmärksamhet.

Denna avhandling syftar till att skapa en integrerad analys av övergången till en bio-baserad ekonomi från ett system- och hållbarhetsperspektiv. Fokus är den svenska bio-baserade ekonomin, dess mål samt hur dessa mål samverkar eller skapar konflikter i en övergångsprocess. Basen för analysen är det svenska jord- och skogsbruket. Avhandlingen syftar även till att utvärdera hur mål från parallella hållbarhetsprocesser, såsom Agenda 2030, påverkar utvecklingen mot en bio-baserad ekonomi. En blandad metodansats ligger till grund för avhandlingen, vilken inkluderar semi-strukturerade intervjuer, systemdynamisk modellering samt nätverksanalys. Olika perspektiv på kopplingen mellan den bio-baserade ekonomin och hållbarhet ges av två konkurrerande ramverk, så kallad svag och stark hållbarhet.

Resultaten visar hur aktörerna i den svenska bio-baserade ekonomin arbetar mot divergerande mål. Barriärer för att uppnå dessa mål inkluderar målkonflikter, där vissa mål skapar motsättningar med andra mål. Dessa inneboende motsättningar återfinns inom olika bio-baserade sektorer, mellan sektorer, samt mellan den bio-baserade ekonomin och Agenda 2030. Ytterligare hinder som identifierats i denna avhandling inkluderar policymotstånd, brist på ledarskap samt inlåsnings effekter. Resultaten visar dock även på många möjligheter att stödja en övergång till en bio-baserad ekonomi i en svensk kontext. Dessa möjligheter inkluderar mål och förslag med potential att skapa synergieffekter, det vill säga situationer där måluppfyllnad inom ett område stödjer måluppfyllnad inom ett eller flera andra områden. Det finns även stort utrymme att arbeta sektoröverskridande för att adressera gemensamma svårigheter och mål. Resultaten visar även på vikten av att förstå och hantera aspekter såsom konflikt, polarisering och legitimitet, samt att stärka förtroendet mellan den bio-baserade ekonomins olika aktörer.

För den övergripande frågan vad övergången till en bio-baserad ekonomi innebär för hållbarhet finner denna avhandling att den bio-baserade ekonomin främst bidrar till så kallad svag hållbarhet. Från ett starkt hållbarhetsperspektiv är den bio-baserade ekonomins möjligheter att bidra till hållbarhet mindre lovande. En övergång till en bio-baserad ekonomi kan utifrån detta perspektiv i värsta fall leda till att sociala och ekologiska hållbarhetsproblem förvärras. En fundamental förändring i hur den bio-baserade ekonomin definieras och implementeras behövs för att den ska kunna bidra till hållbarhet som uppfyller kriterierna för stark hållbarhet.

Nyckelord: bio-baserad ekonomi, bio-ekonomi, hållbarhet, Agenda 2030, de globala hållbarhetsmålen, integrerad hållbarhetsanalys, systemanalys.

Thesis content

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

Paper I: Bennich, T., Belyazid, S., 2017. The Route to Sustainability – Prospects and Challenges of the Bio-Based Economy. *Sustainability* 9, 887.

<https://doi.org/10.3390/su9060887>

Paper II: Bennich, T., Belyazid, S., Kopainsky, B., Diemer, A., 2018. The Bio-Based Economy: Dynamics Governing Transition Pathways in the Swedish Forestry Sector. *Sustainability* 10, 976. <https://doi.org/10.3390/su10040976>

Paper III: Bennich, T., Belyazid, S., Kopainsky, B., Diemer, A., 2018. Understanding the Transition to a Bio-Based Economy: Exploring Dynamics Linked to the Agricultural Sector in Sweden. *Sustainability* 10, 1504. <https://doi.org/10.3390/su10051504>

Paper IV: Bennich, T., Weitz, N., Carlsen, H., 2020. Deciphering the scientific literature on SDG interactions: A review and reading guide. *Science of the Total Environment*. 728, 138405. <https://doi.org/10.1016/j.scitotenv.2020.138405>

Paper V: Bennich, T., Belyazid, S., Stjernquist, I., Diemer., A., Kalantari, Z. The bio-based economy, 2030 Agenda, and strong sustainability - a regional-scale assessment of sustainability goal interactions. *Journal of Cleaner Production* (in review).

Author contributions

Paper I: TB conceived the idea of the paper and conducted the literature review. SB supported the analysis, provided comments and feedback on early drafts, and contributed to writing the final version of the manuscript.

Papers II and III: TB designed the study. All authors supported the stakeholder mapping. TB conducted the interviews. TB and SB carried out the data analysis, and all authors contributed to writing the paper.

Paper IV: All authors initiated and shaped the original research idea. TB carried out the literature review and conducted an initial round of coding. All authors contributed to revising the coding scheme and to the subsequent rounds of coding. HC carried out the network analysis, and all authors contributed to writing the paper.

Paper V: TB designed the study. TB and SB jointly developed the modeling framework. TB, SB, IS, and AD carried out the cross-impact scoring and analysis, and all authors contributed to the writing process.

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1. Introduction

1.1 The bio-based economy as a response to societal challenges

The consequences of unsustainable patterns of economic activity have become evident and better understood in recent decades. An increasing body of scientific knowledge points to the links between resource exploitation and adverse environmental and social impacts (EEA, 2019; González de Molina and Toledo, 2014; Krausmann et al., 2009; Steffen et al., 2015). These negative consequences include climate change, biodiversity loss, growing inequality, resource depletion (e.g., fish stocks, forests, fossil-based energy, and minerals), and conflict over the resources that remain. The magnitude of these negative impacts and the perceived ability of human activity to alter biophysical systems have resulted in the idea that Earth has entered a new geological epoch, the Anthropocene (Crutzen and Stoermer, 2000; Steffen et al., 2007; Zalasiewicz et al., 2011).

The bio-based economy is one of many concepts that have emerged in response to these grand challenges. It captures the idea that biological resources are not only impacted by the adverse consequences of human activity, but that they also hold solutions to multiple sustainability challenges. It is a policy-driven concept, covering a broad range of societal sectors, as stated by the definition provided by the European Commission (2018; p. 4):

“The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services.”

Given the broad reach of the concept, the specific goals and characteristics of the bio-based economy vary between different national, regional, and sectoral contexts. The implementation of the bio-based economy therefore requires a contextualized understanding of the concept, and the strategies for goal attainment need to be adjusted to situation-specific opportunities and challenges (Global Bioeconomy Summit, 2015). Bio-based economy strategies are documents put forward by the actors engaged in the bio-based economy, detailing their visions and the resulting future uses of biological resources, and specifying how these uses may contribute to meeting societal objectives. To date, over 60 bio-based economy strategy documents have been published (BioSTEP, 2020). Their formulation reflects the political aims, resource endowments, capabilities, and financial means accessible to the actors in the decision-making context at hand (Dabbert et al., 2017; Staffas et al., 2013).

Goals commonly elaborated in these strategy documents include mitigating climate change, ensuring energy security, developing cleaner production processes, realizing improvements in human health, increasing competitiveness, and creating new business and employment opportunities. These goals are expected to be realized through an increasing provision of goods

derived from biological resources (e.g., renewable energy, food and feed, bio-based chemicals, materials, textiles, and building materials), as well as services (e.g., recreational opportunities, carbon storage, and biodiversity protection) (Formas, 2012; Langeveld et al., 2012; McCormick and Kautto, 2013; Pelli et al., 2017). The concept of a bio-based economy thus serves as an umbrella for ideas on how to value, manage, and use biological resources to meet a diverse set of goals.

It is not yet clear, however, if and how the high-reaching aspirations of the bio-based economy will be realized. The transition process is linked to uncertainty, and current academic and policy debates suggest growing controversy and polarization around the meaning of the concept and its sustainability implications (Mukhtarov et al., 2017). One source of uncertainty is the broad but interconnected nature of the concept. The definition of the bio-based economy provided by the European Commission stresses that the many systems and sectors relying on biological resources are interlinked (European Commission, 2018). This also implies that goals in one area of the bio-based economy interact with goals in other areas. Additionally, the bio-based economy is interconnected with other societal goals, promoted by parallel initiatives such as the United Nations (UN) 2030 Agenda (UN General Assembly, 2015), and national environmental strategies (e.g., Sweden's environmental objectives system (SEPA, 2020a)). These goal interactions, whether internal or external to the bio-based economy, may create synergetic effects when interventions or goals are well-aligned and mutually supporting (Pedercini et al., 2019). Conversely, in other situations, different actors may promote interventions or goals that are fundamentally conflicting, giving rise to trade-offs and a need for prioritization (ICSU, 2017). Failing to recognize interactions across goals, sectors, and scales – and incorporating them into implementation strategies – may impede the transition to a bio-based economy in several ways. First, it might lead to a loss of opportunity to leverage synergies, while critical trade-offs may be overlooked. Second, it could lead to policy resistance, i.e., situations where interventions fail due to the internal response of the system. Third, failing to account for interactions may lead to unintended environmental, social, economic, and ethical consequences of interventions, ultimately reducing the ability to efficiently address the grand challenges of our time (Sterman, 2009). There is therefore large scope for integrated approaches that consider different perspectives, identify synergies and trade-offs among goals, support the development of coherent strategies for goal attainment, and account for how the resulting benefits and risks are distributed in society.

Moving away from positivist and reductionist thinking toward integrated approaches, based in systems thinking, has been recognized as critical for sustainability transitions (Abson et al., 2017; Ben-Eli, 2018; Gasparatos et al., 2009; Köhler et al., 2019; Liu et al., 2015). Yet, the bio-based economy discourse has largely been dominated by industry and government perspectives, potentially overlooking the perceptions of the many other actors who could play critical roles in the transition process (e.g., farmers and the public) (Schmidt et al., 2012). Furthermore, the discourse has been characterized by a strong technology and engineering focus, centered on single sectors, issues, or biomass applications (de Besi and McCormick, 2015; Bugge et al., 2016; Dabbert et al., 2017; Kitchen and Marsden, 2011). There are exceptions, including discussion on the potential contribution of social science perspectives to the bio-based economy

discourse (Kleinschmit et al., 2014), and scenario modeling that spans bio-based economy sectors (Tsiropoulos et al., 2018). Generally, however, relatively little attention has been given to developing an integrated and systemic understanding of goal interactions that would enable rethinking broader social, economic, or ecological processes (Johnson, 2017; Lindahl et al., 2017; O'Brien et al., 2017; Staffas et al., 2013).

Against this background, this thesis seeks to contribute to an integrated systems understanding of the transition to a bio-based economy from a sustainability perspective. The transition is understood as the process of realizing the goals of the bio-based economy. Specific emphasis is placed on eliciting previously overlooked goals and perspectives. Sweden is used as an empirical case, as it is a country perceived to have favorable preconditions to facilitate a transition to a bio-based economy. This, in terms of resource endowments and traditional industries (Formas, 2012), is combined with an explicit political ambition for sustainability (Government Offices of Sweden, 2020; SEPA, 2019a). The forestry sector provides a point of departure for analysis due to its central role in the Swedish bio-based economy (Antikainen et al., 2017; Nordic Council of Ministers, 2017; Skånberg et al., 2016). However, goal interactions are also explored within and between other sectors of relevance to the bio-based economy, primarily agriculture and energy, as well across the parallel UN 2030 Agenda. Thereby, the analysis seeks to contribute to, and clarify, the debate around goal interactions and their sustainability implications, and is expected to support the development of integrated and coherent strategies to facilitate a transition process.

1.2 Thesis aim and objectives

The aim of this thesis is to advance an integrated understanding of what the transition to a bio-based economy implies for sustainability, using Sweden as a case study. A systems thinking approach is used for integration. This is based on the assumptions that elements of a system act differently when isolated from other parts of the system, and that a systems view is necessary to better understand and facilitate system change in interconnected complex systems, such as those underpinning the transition to a bio-based economy. To meet the overarching research aim, the thesis addresses the following objectives:

Objective A – To theoretically and empirically investigate how the bio-based economy may contribute to sustainability, from the opposing perspectives provided by the weak and strong sustainability paradigms.

Objective B – To develop a contextualized and operational understanding of the transition to a bio-based economy in a Swedish setting, by identifying context-specific goals, goal interactions, leverage points, and interventions suggested to govern goal attainment.

Objective C – To identify potential trade-offs and synergies that may hinder or help goal attainment in a Swedish setting, based on goal interactions both internal to the bio-based economy and across goals promoted by parallel sustainability initiatives.

1.3 Overview of scientific publications included in the thesis

The results of the analysis are published in five scientific articles (Papers I–V). Table 1 gives an overview of how these scientific publications are linked to six guiding research questions and the research objectives. **Paper I** provides an initial understanding of the bio-based economy and its potential contribution to sustainability. The analysis is based on a review of the scientific and gray literature, as these different sources of information are important to gain insight into the bio-based economy discourse. Specifically, the thesis aims to be policy-relevant (although not prescriptive), hence an understanding of the gray literature is crucial. The literature review focused on the bio-based economy as a global concept, but did also seek to establish an initial understanding of the Swedish context. The weak and strong sustainability paradigms were used as lenses to clarify the debate around the potential contribution of the bio-based economy to sustainability.

Papers II and III present an operational conceptualization of the bio-based economy concept, by exploring transition dynamics in a Swedish decision-making context. Bio-based economy goals, and the dynamics governing goal attainment, were elicited based on the perceptions of a broad range of actors engaged in the Swedish bio-based economy (e.g., practitioners, green sector interest organizations, and policy-makers). The aim was to account for multiple framings of what a desirable future looks like. The perceptions of these actors were then integrated using conceptual system diagrams.

After having created an initial, conceptual, systems understanding of the transition to a bio-based economy, the next step was methodological in nature. **Paper IV** outlines the results from a review of the scientific literature on the UN 2030 Agenda and the associated SDGs. Specifically, the study presented in this paper provides an overview of the research landscape on SDG interactions, thereby contributing knowledge on how the interconnected nature of sustainability goals can be understood and analyzed. The study identified the policy challenges that the literature on SDG interactions responds to, and the various ways in which “interactions” have been conceptualized. Furthermore, the study mapped the data sources and methods used to underpin the presence of these interactions.

The final step of the research drew on the previous findings. Based on the understanding of the bio-based economy and sustainability provided in Paper I, the goals outlined in Papers II and III, and the insights from studying the 2030 Agenda and the methodological approaches to analyzing goal interactions as presented in Paper IV, an analytical framework was developed and applied to a regional-scale case. The aim was to advance the operational understanding of the bio-based economy by assessing goal interactions across the bio-based economy, the 2030 Agenda, and the strong sustainability paradigm. Specifically, this step focused on analyzing the coherency of goals covered by these different initiatives and agendas, to support goal priority setting. The results are presented in **Paper V**.

Table 1. Overview of research questions, the objectives they address, and related scientific publications

Research Question	Research Objective	Paper I	Paper II	Paper III	Paper IV	Paper V
RQ1: Does a transition to a bio-based economy provide a viable pathway to sustainability?	A. Bio-based economy and weak and strong sustainability B. Contextualization C. Trade-offs and synergies	X				
RQ2: What are the goals of the transition to a bio-based economy in Sweden?	B. Contextualization		X	X		
RQ3: What social-ecological dynamics currently govern goal attainment in Sweden?	B. Contextualization C. Trade-offs and synergies		X	X		
RQ4: Based on the conceptual understanding of transition dynamics, what potential leverage points and interventions could support a transition process?	B. Contextualization C. Trade-offs and synergies		X	X		
RQ5: How can interactions between sustainability goals be understood?	C. Trade-offs and synergies				X	X
RQ6: Are the goals of the bio-based economy coherent with the SDGs and strong sustainability?	A. Bio-based economy and weak and strong sustainability B. Contextualization C. Trade-offs and synergies					X

1.4 Thesis outline

Following Chapter 1, the introduction, the remainder of the thesis is organized into a further eight chapters. Chapter 2 provides a background, outlining the history and modern understanding of the bio-based economy, and linked policy initiatives such as the 2030 Agenda. The chapter also introduces key concepts and fields used as a basis for the analysis, including sustainability, systems thinking, dynamic complexity, as well as the challenges of integration in the context of governing sustainability transitions. Chapter 3 presents the research design and methods. Chapter 4 summarizes the results, while a synthesis is provided in Chapter 5. Chapter 6 offers a discussion of the results. Chapter 7 elaborates and reflects on the research approach. Chapter 8 outlines potential avenues for further research. Chapter 9 concludes and highlights the main findings.

2. Background

The following sections serve as a basis for exploring the transition to a bio-based economy and what it implies for sustainability. The history and current understanding of the bio-based economy concept are outlined, alongside parallel concepts and agendas. A definition of sustainability is provided, and systems thinking is introduced as a means to support integration. Specifically, key concepts in systems thinking are presented, showing how they can be used to understand sustainability goal interactions. These concepts include analytical dimensions such as feedback loops, delays, synergies, trade-offs, and leverage points. Moreover, some basic assumptions in the sustainability transitions literature are outlined, highlighting the normative aspects of sustainability, and the potential of research as a way of opening up rather than closing down alternative future pathways. Several normative governance challenges for sustainability are then presented. Finally, the Swedish case is introduced.

2.1 The history and current understanding of the bio-based economy

Biological resources are fundamental to human survival. From early hunter-gatherers to societies based on technologically complex forms of agriculture, a diversity of uses of biomass has provided humans with food and services, such as firewood for cooking and heating, or grass to feed domesticated animals. Still today, a large share of the human population depends directly on biomass as their primary energy source; it provides around 9.5% of the global primary energy supply (IEA, 2020). In this sense, the bio-based economy is not a new phenomenon, considering the essential role of biological resources in all human societies over time.

While acknowledging traditional uses of biological resources, the current understanding of the bio-based economy concept has emerged largely in relation to developments in the political domain over the past two decades. Sometimes, the labels “advanced” or “traditional” are applied to the bio-based economy to make that distinction clear. What separates the advanced from the traditional bio-based economy is a shift away from traditional uses of biomass, such as burning wood for cooking or heating. The advanced bio-based economy instead envisions entirely new ways of using biological resources, facilitated by social and technological innovation (Calvert et al., 2017). Developments of the bio-based economy are driven by actors such as the Organisation for Economic Co-operation and Development (OECD), the European Union (EU), nations, industries, research institutions, and civil society groups. The EU and the OECD were among the first actors to outline strategies on the bio-based economy (EU, 2005; OECD, 2009), and have been credited with the rise in publications of national bio-based economy agendas that followed. Strategy documents and agendas bring forward thinking around how changes in the management and uses of biological resources can respond to pressing societal challenges and increasingly deliver benefits to society. These are presented at transnational and national scales, as well as at the local or sector specific level (BioSTEP, 2020; Overbeek et al., 2016; Panchaksharam et al., 2019). In these strategy documents, clear differences can be distinguished, for example in terms of underlying political motivation and goals, meaning subscribed to the bio-based economy concept, ways of addressing policy coherence, political approaches employed, economic sector focus, as well as the political

intervention focus (German Bioeconomy Council, 2015a; Meyer, 2017). The definitions brought forward also vary in scope. As outlined by Skånberg et al. (2016), narrow definitions count only agriculture, food-producing sectors, fisheries, and aquaculture as part of the bio-based economy. Broader definitions also include forestry, bioenergy, the pharmaceutical industry, the chemical industry, nature tourism, waste management, the construction sector, and developments linked to water management. Another way to understand differences in scope between different definitions is to assess whether they focus on the biomass resource only, or if they also include or focus on applications and developments in the life sciences (Brunori, 2013; Staffas et al., 2013). For example, while the definition provided by the European Commission (2018) is broad, including all sectors directly and indirectly relevant to the biomass resource, it excludes biotechnology-related developments. Another aspect that adds to the complexity of grasping the meaning of the term is the variation in the naming of the concept. These variations include the bio-economy and the knowledge-based bio-economy (Urmetzer and Pyka, 2017). In some cases, these terms are used as synonyms (McCormick and Kautto, 2013). However, subtle differences between the terms have also been identified. For example, the term bio-economy is often used to refer to biotechnology and the life sciences in national strategy documents, while the bio-based economy is used when the focus is on the biomass resource (Staffas et al., 2013). Another difference is that the term bio-economy often refers to specific and quantifiable sectors of the economy. The term bio-based economy instead encompasses a process-oriented view (e.g., used to refer to the process of phasing out fossil-based resources), but does not specify any quantitative limits for when a country has reached a bio-based economy (ibid).

Strategies and agendas are fundamental in steering the way the transition to a bio-based economy unfolds in different contexts. Naturally, some dimensions have received more attention than others in these publications, while some issues have been overlooked altogether. What motivated the present thesis was a lack of integrated sustainability assessments of how the multiple goals of the bio-based economy, as promoted by different actors, interact in a transition process. Other areas where knowledge gaps and research needs have been identified include the service-based part of the bio-based economy (Pelli et al., 2017), farmer perspectives and public goods (Schmidt et al., 2012), citizen perspectives and participation (Mustalahti, 2018), social dimensions (Rafiaani et al., 2018), fairness and equity (Ramcilovic-Suominen and Pülzl, 2018), risk and ethics (Hilgartner, 2007), ecological and sociocultural diversity (Kitchen and Marsden, 2011), and lifestyle changes and non-material values (Vainio et al., 2019).

2.2 Visions of the bio-based economy

Many thoughts are collected under the umbrella of the term bio-based economy. Even though it may be understood as a relatively recent, policy-driven concept emerging in response to pressing sustainability challenges, these thoughts have long historical roots. Similar ideas, including the use of the terms bio-based economy and bio-economy, can be found, for example, in the school of economics and political movement of the Physiocrats in eighteenth-century France (Higgs, 1897), in the US notion of farm chemurgy in the 1920s and 1930s (Finlay, 2003), and later in the work on bio-economics by Romanian-born scholar Nicholas Georgescu-

Roegen (Georgescu-Roegen, 1977; Mayumi, 2009). In the more recent literature, attention has been directed toward finding patterns or more overarching clusters of thinking around the concept. Some of these studies have explored the relationship between the modern understanding of the bio-based economy and, for example, the work of Georgescu-Roegen, suggesting “an attempt of semantic hijacking of the original term” (Vivien et al., 2019; p.189). Others have aimed at mitigating the perceived confusion of the current meaning of the bio-based economy (Pavone and Goven, 2017).

By contrasting the work by Pavone and Goven (2017) with ideas presented by Bugge et al. (2016), Meyer (2017), Pülzl et al. (2014), and Stern et al. (2018), four distinct conceptualizations of the bio-based economy can be distinguished. These conceptualizations, or coinages, may be useful for understanding and comparing different views of the Swedish bio-based economy and its sustainability implications. They also demonstrate how future developments toward a bio-based economy may take fundamentally different directions.

First is what has been referred to as the biotechnology vision or the biotechnological-innovation economy. It is largely present in the visions and strategy documents provided by the OECD (OECD, 2009; Victoria, 2016). According to this coinage, the bio-based economy is an economy promoting the use of biotechnology in society. It highlights the ability of biotechnology to address problems such as climate change, pollution, disease threats, and resource scarcity. Simultaneously, biotechnology is assumed to bring competitiveness and increasing returns on capital. Thus, it is an industrial take on the bio-based economy, where technological change is central, promoting goals related to economic growth and productivity gains (Bugge et al., 2016; Pavone and Goven, 2017; Pülzl et al., 2014; Stern et al., 2018).

The second coinage is referred to as the bioresource vision or the biomass economy. This notion of the bio-based economy is prominent in an EU context (BECOTEPS, 2011; EU, 2012). Here, the focus is on the biomass resource itself, rather than on the technologies applied to it. This vision promotes the creation of new value chains, and the goal of substituting fossil-based resources for biomass. Based on the phasing out of fossil-based resources, sustainability claims are made (Bugge et al., 2016; Pavone and Goven, 2017). It is argued that the biotechnology vision and the bioresource vision promote specific and similar policies. These include increased public investment in science and the surrounding infrastructure, so that innovation and commercialization of knowledge are stimulated. They also promote the establishment of public-private partnerships to build public support for the actions carried out by commercial actors. Another policy avenue links to the adaptation of regulation so that it meets the needs of those carrying out the research and subsequently bringing it to the market. Environmental management metrics are developed, driven by private initiatives, and carried out by consumer choice. Lastly, there is a push for governmental support for new markets to materialize, and active governmental support for public acceptance of bio-economy related activities (Pavone and Goven, 2017).

Contrasting the biotechnology and bioresource visions is a third coinage, the so-called bioecology vision. This is also closely linked to what has been referred to as the agroecology or

alternative agriculture vision, the eco-economy, or the socio-ecological approach to the bio-based economy (Meyer, 2017). This vision promotes biodiversity, conservation of ecosystems, local knowledge and capabilities, optimized use of energy and nutrients, circular modes of production, and democratic deliberation (Bugge et al., 2016; Vivien et al., 2019). Aspects of regional environmentalism can also be recognized in this understanding of the bio-based economy (Stern et al., 2018).

The fourth coinage understands the bio-economy as a novel form of capitalism and a political project. This coinage has roots in literature exploring links between life sciences and capitalism. In this understanding, the focus areas are science, the state, and industry, and how these are reconfigured to promote goals of commercialization and competitiveness (Pavone and Goven, 2017).

2.3 Parallel concepts

The bio-based economy is not the only emerging initiative proposing new solutions to current sustainability challenges. This compounds the difficulty in reaching agreement on its meaning and scope. Adding to the complex issues of realizing policy coherency is that the bio-based economy is one of many sustainability-related agendas. For example, the bio-based economy emerges next to the 2030 Agenda and the related 17 SDGs (UN General Assembly, 2015). The 2030 Agenda offers a vision and roadmap to address environmental and social challenges globally. It is unique in that it is supposed to be treated as an indivisible whole, stressing the need for integration based on systems thinking. The ongoing implementation process may thus offer perspectives on how to address the integration of multiple sustainability goals, which is an issue of relevance also for decision-makers and policy-makers alike in the context of the emerging bio-based economy. Another guiding principle of the 2030 Agenda is that it is supposed to be universal, meaning that all nations are expected to contribute to the implementation and that no-one should be left behind. The bio-based economy has been suggested to be interlinked with the 2030 Agenda, seen as a pathway that may either hinder or promote the attainment of the SDGs (El-Chichakli et al., 2016; Heimann, 2018).

Other parallel concepts and initiatives include the green economy (Georgeson et al., 2017; UNEP, 2020), the circular economy (MacArthur Foundation, 2020; 2015), the sharing economy (Frenken and Schor, 2017; Richardson, 2015), and the eco-economy (Kitchen and Marsden, 2011; Marsden and Farioli, 2015). These concepts and proposed sustainability avenues have different roots, focus, and strategies linked to their respective implementation processes. Yet, it is possible to find overlaps as well as hierarchies among them. D'Amato et al. (2017) suggest that the green economy serves as an umbrella concept, drawing on elements from both the bio-based and circular economy. However, it also adds additional dimensions, such as a larger focus on social dynamics and the dependency of the economy on ecological processes. Loiseau et al. (2016) argue along similar lines, conceptualizing the bio-based economy as a notion with roots in environmental economics and part of the broader green economy concept. In terms of the circular economy, it is a concept that is often linked to the bio-based economy, having developed in parallel in an EU context. The bio-based economy agenda was initially driven by

an innovation strategy, while the circular economy agenda was more informed by resource scarcity and environmental concerns (EEA, 2018a). There are policy documents dealing with the circularity aspects of the bio-based economy, specifically regarding the end-of-life of bio-based products and the sustainability of natural resource use (ibid). Finally, the bio-based economy has been compared with the eco-economy. It has been argued that in contrast to the bio-based economy, the eco-economy promotes developments that re-embed social dimensions in the ecological sphere, thereby acting to integrate the social and the natural (Pavone and Goven, 2017).

2.4 Defining sustainability

Overall, it is not evident under what conditions the bio-based economy can realize hoped-for sustainability outcomes, if at all (Juan et al., 2019; Kleinschmit et al., 2017; O'Brien et al., 2017; Pfau et al., 2014; Ramcilovic-Suominen and Pülzl, 2018; Staffas et al., 2013). However, to better understand the relationship between the bio-based economy and sustainability, it is first necessary to establish an understanding of the term sustainability itself.

Thoughts around “progress” and concerns about what today would be understood as sustainability issues date back to pre-historic times. However, the term sustainability may first have been used in 1713, coined in relation to the sustainable management of forests (Du Pisani, 2006). Later, toward the end of the 1980s, the concept of sustainable development started to become popularized. This was a result of the World Commission on the Environment and Development (WCED) issuing the report *Our Common Future* (also referred to as the *Brundtland Report*) (WCED, 1987). An often-cited definition of sustainable development offered in the *Brundtland Report* stipulates that sustainable development is a development that meets the needs of the present, with a specific focus on the needs of the world’s poor, without compromising the ability of future generations to meet their needs (ibid). Since then, several alternative definitions have been proposed, and different forms of criticism of the Brundtland definition brought forward, such as it being too vague and unable to guide practice (Beckerman, 1994; Beckerman and Pasek, 2001; Norgaard, 1994; Williams and Millington, 2004).

Generally, the understanding of sustainability has been described as constantly evolving and reinterpreted (Jordan, 2008), where the lack of agreement on the definition might give rise to ambiguity, controversy, and confusion (Leach et al., 2010; Redclift, 1993). Sustainability-related terms are numerous and interconnected, and mapping them constitutes a significant challenge (Glavič and Lukman, 2007; Roostaie et al., 2019). On the other hand, it has been argued that the search for a singular and unified definition should be abandoned altogether, and that progress should be sought, despite the lack of common terminological ground (Owens, 2003).

Since the release of the *Brundtland Report*, sustainability has also been described as explicitly normative. It often refers to a broad and unspecified set of values, aiming to secure context-dependent and potentially contested standards in terms of social equity, the environment, and economic activity (Meadowcroft, 2007). Thus, the importance of distinguishing between

different normative views of sustainability has been stressed, acknowledging that there may be many sustainabilities, which need to be precisely defined for different problems and groups (Leach et al., 2010).

To understand how the bio-based economy may contribute to sustainability, the present thesis uses the frames of the weak and strong sustainability paradigms. These opposing sustainability definitions offer a way to contrast different underlying assumptions of what sustainability entails. A shared feature of these paradigms is, however, that they depart from a capital approach. In the weak sustainability paradigm, different forms of capital (i.e., natural, human, and manufactured) are considered substitutable (Dietz and Neumayer, 2007). Hence, if natural capital (e.g., forests, soils, or water) is degraded, the loss can be compensated for by an increase in other forms of capital, such as manufactured capital (e.g., building or machines). Sustainability is achieved when the total capital stock is maintained, or increasing, over time. When the capital stock remains intact, the utility derived thereof does not decline, responding to the intergenerational consideration in the Brundtland definition of sustainability, warranting that future generations can also satisfy their own needs. Tools perceived as important to ensure the efficient allocation of resources between different capital stocks include market-based solutions (e.g., monetary valuation of ecosystem services). Moreover, as different capital stocks are substitutional, there are no biophysical limits to growth in human economic activity. Instead, economic growth is seen as an enabling factor in achieving sustainability, for example as it supports increasing investments in cleaner technologies (Neumayer, 2003). Generally, technological change has an important role in the weak sustainability paradigm, assumed to generate solutions to environmental problems (Ang and Passel, 2012).

According to the strong sustainability paradigm, on the other hand, substitution of different forms of capital is seen as limited or not at all possible (Neumayer, 2003). Natural capital is perceived as holding qualitatively different characteristics and life-supporting functions compared to other forms of capital. Thus, it is not possible to compensate, for example, a loss of forests for more buildings, or clean air for fertile soils (Ekins et al., 2003; Ott, 2003). The notion of “critical” natural capital is sometimes used to refer to those aspects of natural capital that generate functions that are essential human survival and wellbeing (Pelenc and Ballet, 2015). Sustainability, then, becomes a matter of securing this critical natural capital. Moreover, the strong and weak sustainability paradigms hold different assumptions about the role of economic growth. The strong sustainability paradigm emphasizes that the economic system is dependent on the biophysical world, resulting in an understanding of sustainability that is embedded (van den Bergh, 2001; Ekins et al., 2003). This perspective stresses that all economic activity is ultimately constrained by the natural processes, and that attention therefore needs to be paid to limits of input resources (“source” constraints) as well as to the limited ability of the environment to assimilate waste and pollution (“sink” constraints) (Neumayer, 2003). Furthermore, the notion of strong sustainability questions the role of technological change in achieving sustainability. From this perspective, technologies might temporarily and locally mitigate adverse impacts of growth in economic human activity, but may not be adequate or sufficient to address the root causes of unsustainable patterns of resource use (Ang and Passel, 2012; Neumayer, 2003; Parker, 2014). The policy implications of adhering to the strong

sustainability paradigm include taking a precautionary approach and actively conserving and investing in natural capital (Ott, 2003). More specific examples of suggested actions and principles in support of strong sustainability include (i) limiting the harvest of renewable resources so that the harvest rate does not exceed the regeneration rate, (ii) lowering greenhouse gas emissions, (iii) reusing wastes as production inputs in other processes, and (iv) protecting biodiversity (Ekins et al., 2003; Oliveira Neto et al., 2018). Hence, decision-making in support of strong sustainability sets a different direction compared to the policies usually proposed under the weak sustainability paradigm.

2.5 Systems thinking and analysis

Systems thinking and analysis are fields of inquiry that lend themselves to integrated analysis. Practices and theories related to systems thinking and analysis provide useful knowledge, analytical concepts, and tools for uncovering how the goals of the bio-based economy interact, while recognizing complexity and context. A system can be broadly defined as “a set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its ‘function’ or ‘purpose’” (Meadows, 2008, p. 188). This definition stresses that systems are made up of interacting entities, distinct from interactions with other entities, with a common purpose. This understanding of systems also raises questions about how to define “purpose,” highlighting that systems, to a certain extent, are defined by the worldviews of those who perceive them (Abson et al., 2017). Systems thinking may be defined as the process of uncovering how the elements or parts of a system interact, or formally “the mental effort to uncover endogenous sources of system behavior” (Richardson, 2011, p. 241).

Reaching the goals of the bio-based economy entails changes in several interconnected systems. These include, for example, ecosystems (such as fields and forests), man-made material systems (such as infrastructure for biomass processing and transport), and intangible systems (such as trade and transfer of knowledge in the life sciences). While the specific functioning of these systems differs, they share characteristics with the types of systems usually being subject to investigation in the fields of systems thinking. They are dynamic and complex, they adapt and self-organize, and they can create emergent and non-linear patterns of behavior (Freeman et al., 2014). They also include tipping points, by which actions may result in fundamentally irreversible outcomes (Milkoreit et al., 2018). Due to these characteristics complex system behaviors may often seem counterintuitive at first sight (Forrester, 1971). Attention may be drawn to symptoms rather than root causes, and limited time and resources might result in the adoption of a linear and static world view, ultimately reducing the ability to understand and effectively address the issues at hand (Fischer et al., 2015; Ostrom, 2007; Sterman, 2009).

Systems thinking makes us pay attention to the sources of dynamic complexity. A key assumption is that there is a need to study both system structures and their resulting behaviors. System structures refer to the ways relationships between variables are organized; the behavior is the outcome of these configurations. Dynamic complexity arises when these variables interact over time (Sterman, 2009). A concept that is argued to be important for understanding these

interactions is feedback (Forrester, 1969). Feedback loops are circular connections of variables and can be either reinforcing or balancing. A reinforcing feedback loop (sometimes also referred to as a positive feedback loop) describes a self-reinforcing process, amplifying initial change in a system. A balancing feedback loop (also referred to as a negative feedback loop) describes a self-correcting process (Sterman, 2009). In terms of sustainability goal interactions, the way these feedback loops operate in relation to each other can contribute to progress, spiral a system away from a desired state, or create lock-in effects that make it difficult to change a currently dominant development path (Klitkou et al., 2015; Liu et al., 2015; Sydow et al., 2009).

Systems thinking also recognizes delays as important in understanding how systems behave. Delays can cause oscillating behavioral patterns, as well as trade-offs between short- and long-term goal attainment. The latter as the long-run effect of an intervention is sometimes different from the short-term impact. Some policies might generate short-term worse-before-better behavior. Conversely, short-term improvements might be offset by a long-term worsening of conditions. Additionally, delays are sources of system inertia and path dependency. Materials and information accumulate in systems over time, which gives rise to developments that take time and effort to reverse (Sterman, 2009).

Based on an understanding of system structures and functioning, systems thinking can also help in identifying synergies and trade-offs. In the context of sustainability goal interactions, these can be found in all stages of implementation (OECD, 2016). For example, a synergy can be understood as a situation where the achievement of one goal promotes progress on other goals. Conversely, a trade-off occurs when progress on one goal produces effects that inhibit or reverse progress on other goals, creating goal conflicts (Blanchard et al., 2017; Matsumoto et al., 2018; Nilsson et al., 2016; 2018). Another example is when synergies and trade-offs are identified across production inputs, infrastructure needs, and risks and benefits for ecosystem service provision linked to different goals (Fader et al., 2018). A concept related to synergies is “leverage points.” These are the places in complex systems where a small intervention can have large-scale impacts, creating long-lasting improvement (Meadows, 1997; Senge, 2006). In recent research on sustainability transitions, leverage points have been used as a heuristic framework to identify and classify interventions in a diversity of systems relevant to the bio-based economy, including food and energy systems (Dorninger et al., 2020; Fischer and Riechers, 2019).

Systems thinking also allows for the study of alternative system framings. Framings can be defined as “the different ways of understanding or representing a social, technological or natural *system* and its relevant *environment*. Among other aspects, this includes the ways system elements are bounded, characterized and prioritized, and meanings and *normative* values attached to each” (Leach et al., 2010; p. xiii). Individuals and groups hold different framings based on their knowledge and experiences. Attending to these framings has been argued to advance sustainability debates (ibid).

In the present thesis, the goals of the bio-based economy are understood as framings. Based on how actors perceive the systems in the bio-based economy, and their ideas on what constitutes a desired or unwanted outcome, multiple and contested goals emerge.

2.6 Integration across what?

Generating and using integrated knowledge on goal interactions to facilitate sustainability outcomes come with various governance challenges. That cross-cutting issues are not efficiently handled by institutions and organizations that operate in siloed and compartmentalized ways has long been recognized, stressing the need to develop the capacity to integrate environmental, economic, and social issues (Dernbach, 2003; WCED, 1987; UNCED, 1992). Consequently, it has been suggested that good governance for sustainability requires an agenda for reforming existing governance and administrative configurations (Steurer, 2009). Niestroy (2014) sets out five dimensions across which integration is needed: policy areas, spatial scales, actors, knowledge domains, and time. Each of these dimensions come with specific challenges, which decision-makers and policy-makers involved in the transition to the bio-based economy will also have to recognize.

First, policy belonging to environmental, social, and economic sectors interact. The governance challenge lies in achieving integration and coherence across different policy sectors and areas through horizontal coordination, based on an understanding of these interactions (Meijers and Stead, 2004). Thus, policy coherence can be understood as “an attribute of policy that systematically reduces conflicts and promotes synergies between and within different policy areas to achieve the outcomes associated with jointly agreed policy objectives” (Nilsson et al., 2012, p. 396). In a bio-based economy context, these requirements translate into a need to integrate policy related to natural resource management, energy and climate change, waste management, health, education, social equity, employment, and rural development, among other domains.

Second, governance occurs at different policy-making and spatial scales. Accounting for cross-scale interactions is often referred to as vertical integration. Related governance challenges include coordinating and collaborating across all levels of government and administration, from the local to the super-national (Steurer and Martinuzzi, 2005). For the bio-based economy, vertical integration entails bridging, for example, national policy programs with processes taking place within international governance institutions such as the EU, as well as with highly decentralized and local bio-based economy initiatives.

Third, a related dimension is integration across actor and stakeholder groups, ruled by the principle of participation. The challenge lies in creating space and processes where actors can actively participate in discussions and decision-making. These actors may be from the government, business, or civil society (Steurer, 2009).

Fourth, another challenge resides in the integration of knowledge from various sources in society, guided by a principle of reflexivity. This is a process of learning, reflecting on, and

evaluating decisions and policy instruments. By integrating different knowledge sources, for example across science and local knowledge, better decision-making in situations where issues are complex and uncertain is sought after (Liu et al., 2008; Reed, 2008). Additionally, when aiming to understand change in dynamically complex systems, it has been emphasized that data comes in diverse forms, where typically only a small fraction is numerical or written. Instead, a large share of the knowledge about dynamically complex systems resides in the minds of the actors engaged with these systems (Forrester, 1992). “Mental models” is a term used to refer to this knowledge and perceptions about the functioning of complex systems. While having some ambiguity in its use (Doyle and Ford, 1998), this term further stresses the importance of tacit knowledge as a data source.

The last dimension is integration across time, following the principle of intra- and intergenerational equity. What needs to be integrated is long- and short-term thinking, where the challenge lies in generating long-term thinking despite political cycles that are short term (Niestroy, 2014).

The view of the world as complex and dynamic differs from interventions and institutions that view the world as static and changing in linear ways, where factors such as risk and uncertainty can be fully predicted and controlled. Interventions based on a static world view run the risk of inefficiently addressing change in dynamically complex systems, as their assumptions fail to acknowledge sources of policy resistance, unintended consequences, and trade-offs. Such interventions may also risk overlooking leverage points and synergetic effects. Thus, a systems thinking approach warns against “magic bullet” solutions, or relying fully on large-scale, top-down managerial policies. It also assumes that looking at goal interactions across policy areas, spatial scales, and time, and including the perceptions of the people active in the systems under study, are necessary conditions to find effective interventions and approaches to goal attainment from a sustainability perspective.

2.7 Case study area: Sweden

This thesis identifies and analyzes goal interactions in the national and regional decision-making contexts of Sweden, to demonstrate the operational contextualization of the global bio-based economy concept. On a national scale, the analysis focuses primarily on goal interactions within and across forestry and agriculture. The regional-scale case study encompasses interactions across forestry, energy provision, and waste management, exploring the interplay of goals belonging to the bio-based economy, the 2030 Agenda, and the strong sustainability paradigm in these sectors. The analyses support integration both at the national and regional scales, primarily in terms of sectors (horizontal integration), across knowledge sources, and over time (Section 2.6).

Located in the Northern Hemisphere, Sweden covers a land area of approximately 41 million hectares, dominated by forest and fells in the North and plains in the South (SCB, 2019a). The total population is just above 10 million people (SCB, 2019b), of which 87% live in urban areas and the remaining 13% in rural areas (SCB, 2019c). In terms of sustainability, Sweden has

high-reaching political ambitions to become a carbon-neutral welfare state. The aim is to achieve zero net greenhouse gas emissions by 2045, and net negative emissions thereafter (SEPA, 2019b). Additionally, Sweden aspires to be a leader in the implementation of the 2030 Agenda and sustainability globally (Government Offices of Sweden, 2020; SEPA, 2019a). Support for such ambitions is considered high among the Swedish population (Gullers, 2018; Insight Intelligence, 2019; Svensk Handel, 2018).

2.7.1 The bio-based economy in Sweden

The bio-based economy has started to play a more prominent role in Sweden's work in sustainability over the past few years. A Swedish bio-economy strategy was published by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) in 2012, with a clear research and innovation focus. In this strategy, the bio-based economy is defined as an economy based on:

“A sustainable production of biomass to enable increased use within a number of different sectors of society. The objective is to reduce climate effects and the use of fossil- based raw materials” (Formas, 2012, p. 9).

Another aim according to the strategy is to achieve:

“An increased added value for biomass materials, concomitant with a reduction in energy consumption and recovery of nutrients and energy as additional end products. The objective is to optimize the value and contribution of ecosystem services to the economy” (Formas, 2012, p. 9).

The Formas strategy is one of few documents that provide insight into the goals of the Swedish bio-based economy. It encompasses aspects of both the bioresource and bio-ecology coinages of the bio-based economy (Section 2.2), centered on the biomass resource and its sustainable use. However, as it is a dedicated research and innovation agenda, with a distinct sector and industry focus, the Swedish strategy is considered less holistic relative to other country strategies (OECD, 2019).

What is the evidence of a transition to a bio-based economy occurring? Following the Formas publication, several initiatives emerged. For example, the bio-based economy was one of five innovation partnership programs launched by the Swedish government in 2016, to “mobilize initiatives to ensure that the proportion of the bio-based economy grows, and promotes circular solutions” (Government Offices of Sweden, 2016). Additionally, Sweden is engaged in Nordic collaboration programs in support of the bio-based economy, with a clear focus on industry, rural development, and innovation (Nordic Council of Ministers, 2018). Other initiatives include the innovation program BioInnovation, with the overarching vision of Sweden transitioning to a bio-based economy by the year 2050 (BioInnovation, 2019; Reime et al., 2016), and the Biorefinery of the Future program that aspires to create higher value streams from forest resources (Processum, 2019).

Additionally, Statistics Sweden has started to develop regional statistics on bio-based economy related industries. The statistics focus on those industries that produce goods or services linked to the biomass resource, based on the Formas definition of a bio-based economy. According to their findings, the contribution of the bio-based economy to the Swedish economy has been increasing over time, accounting for 6% of GDP in 2015 (value added) (SCB, 2018a). Further, the sectors included in their analysis employ around 330 000 persons, representing 7% of the total employment in Sweden (ibid). However, when categorizing and ranking different types of employment, agriculture, gardening, forestry, and fishery belong to the least common occupation types in Sweden (SCB, 2018b).

2.7.2 The Swedish forestry sector

When looking at individual sectors, the forestry sector plays a prominent role in the bio-based economy in Sweden (Antikainen et al., 2017; Government Offices of Sweden, 2018; Reime et al., 2016). Sweden holds a rich forest resource, which has shaped the Swedish economy and society over time. Out of Sweden's total land area of 40.8 million hectares, 28.0 million hectares are forest land, out of which 23.6 million hectares are in productive use (SLU, 2019). In terms of protected lands (e.g., national parks and nature reserves), 9% of the total forest land is formally protected, while 4% is made up by voluntary set-aside (i.e., forest areas that forest owners voluntarily protect to preserve specifically high natural or social values) (SCB, 2019d).

The Swedish forestry sector is highly industrial, technological, and knowledge intensive, and the forest management model is dominated by even-aged forestry and clear-cuts (KSLA, 2015, 2009). The forestry sector employs around 70 000 people, is export oriented, and constitutes the world's third largest exporter of pulp, paper, and sawn wood. In 2018, the export value amounted to 145 billion SEK (Swedish Forest Industries, 2020). Forest stands have been increasing over time (213% over the past 90 years) (SLU, 2019). Currently, the total biomass is 3533 cubic meter standing volume (2655 million tones dry weight). The most common tree species are pine and spruce, as almost the entire country is in the boreal region. Until the 1970s, the volume of spruce was mainly growing, but thereafter the share of pine and broad-leaved trees also increased (ibid).

The forest resource is governed by the interplay of forest ownership and regulation. Of the total productive forest land, 48% is privately owned, 24% is owned by private limited liability companies, and 13% by public limited liability companies. The remaining productive forest land is owned either by the state (7%) or by "other" owners (8%). The latter category includes actors such as the Swedish Church. The diversity in ownership structure has remained stable over time (Swedish Forest Agency, 2018a). The priorities and goals of the forest owners greatly influence how forest management evolves in practice. However, forest management is also governed by regulation in accordance with the Swedish Forestry Act (SFS (1979:429)), first established in 1903. Initially, the regulation was introduced to ensure continuous regeneration of the raw material base for the Swedish state and industries. In 1993, changes were made so that not only productive goals (i.e., high yields for industrial purposes) but also environmental

values needed to be promoted. Ultimately, under what has been referred to as freedom with responsibility, the forest owner, regardless of ownership category, is supposed to balance productive and environmental management goals (KSLA, 2015; Swedish Forest Agency, 2020). The Swedish forest also plays an important role in recreation, tourism, and culture. The right of public access exists in parallel to the Swedish Forestry Act, and allows people to pursue outdoor recreational activities, pick berries and mushrooms, and camp in the Swedish countryside, also on privately owned forest land (SEPA, 2020b).

There are different views on the way Swedish forest management has evolved in practice, specifically in terms of sustainability. Oftentimes the fact that the standing volume of biomass is increasing, and that the forest is a source of innovation and climate benefits, are highlighted (KSLA, 2015). On the other hand, critics argue that the long tradition of industrial use of Swedish forests has left a legacy, making the productive goal a priority, and thereby favoring industrial interests over environmental concerns (Lindahl et al., 2017). Additionally, existing management practices have been criticized for not sufficiently recognizing and promoting social or cultural forest values (Björstig and Kvastegård, 2016; Schlyter et al., 2009; Sténs et al., 2016; Swedish Forest Agency, 2018b).

2.7.3 Agriculture in Sweden

The role of the agricultural sector in the Swedish bio-based economy is not as prominent as the role of forestry. In the densely forested country, there are just above 3 million hectares of agricultural land in Sweden, of which 15% is pasture (SCB, 2019e). Despite the northern location, the Swedish climate is considered favorable for agriculture. There are, however, considerable differences in the north and south; the growing season in the south can be up to 100 days longer (Swedish Board of Agriculture, 2009). Animal husbandry is the main line of production of Swedish agriculture. In terms of crops, cereals and leys dominate production (Swedish Board of Agriculture and SCB, 2019). Agricultural trade has been increasing over time; the largest export products are cereals and cereal products. The EU is the biggest export market for Swedish agricultural products, and specifically other Nordic countries. Agricultural imports stem mostly from Denmark, Germany, and the Netherlands (Swedish Board of Agriculture, 2009).

Like elsewhere in the world, agricultural preconditions and practices in Sweden have changed over time, shaped by the interplay of biophysical and social factors. In the past 50 years, structural change has caused a decline in the number of farms, while the average farm size has grown. Specialization has increased, enabled by large investments in machinery (Welinder et al., 2004). In 2016, there were 63 000 agricultural holdings in Sweden, with an average area of 41 hectares of arable land (Swedish Board of Agriculture and SCB, 2019). Despite the increase in farm size, the total amount of agricultural land decreased between 1951 and 2015 by 29% (a loss of around one million hectares). Factors contributing to this loss are the expansion of built-up areas and infrastructure (SCB, 2019e).

Around 91% of the agricultural land is individually owned, where 52% of owners have management units consisting of more than 30 hectares. The average age of farmers is high with 58% of the agricultural land owned by those over 55 years of age. The largest share of the agricultural land is owned by men (73%) (Swedish Board of Agriculture, 2015). Agriculture makes up around 2% of total employment in Sweden, and the number of people working in the sector is steadily declining. In addition, labor requirements per farm are oftentimes small (Swedish Board of Agriculture and SCB, 2019), thus making it common to combine farming with other income-generating activities (e.g., forestry or tourism) (Swedish Board of Agriculture, 2009).

Agricultural supply and demand are governed by free market dynamics, complemented by agricultural regulation and policy. Agricultural politics have shifted in both Sweden and the EU, from a system built around import tariffs and support for exports, to offering direct payments to the agricultural sector (SCB, 2012). The political aims for the Swedish agricultural system include realizing food production that is socially, financially, and environmentally sustainable and that meets consumer demand (Prop. 2016/17:104; Prop. 2019/20:1). Additionally, agricultural production should not cause environmental or health problems outside Sweden's borders (Prop. 2009/10:155; Steinbach, 2018). Sweden has been an EU member since 1995, hence adhering to the EU's Common Agricultural Policy (CAP). CAP aims to enhance agricultural productivity, ensure stability and affordability of food, safeguard that EU farmers make a reasonable living, and maintain rural areas and landscapes within the union (European Commission, 2020).

In terms of sustainability, Swedish agriculture is expected to contribute multiple benefits (e.g., food self-sufficiency, renewable energy production, biodiversity protection, and employment opportunities) (Government Offices of Sweden, 2017; SCB, 2012). Past efforts to address sustainability issues, such as the implementation of advisory programs or financial support for rural development, have been considered successful. They have contributed to water quality improvements, protection of pastures and meadowlands, and to making companies in rural areas more competitive (SEPA, 2019a). Furthermore, organic farming has been increasing over time, with 17.8% of the total farmland converted. This can be compared to 2005, when the converted area was 6.2% of the total agricultural land (Swedish Board of Agriculture and SCB, 2019). At the same time, substantial sustainability challenges remain. Agriculture holdings have become fewer, larger, and more efficient, but the prospects for biodiversity protection and the preservation of cultural heritage environments have worsened. Furthermore, fossil fuels have received government subsidies in the agricultural sector, halting the transition to fossil-fuel-free agricultural production, and it is not yet clear how to account for ecosystem services in land-use planning (SEPA, 2019a).

2.7.4 The Norrköping case

The regional-scale case study area is Norrköping, situated in the Östergötland county in the East Middle part of Sweden (Figure 1). It covers an area of 1495 km², has a population of around 140 000 inhabitants, and counts as the ninth largest municipality in Sweden (Norrköping Municipality, 2020).



Figure 1. Sweden is a country dominated by forests. The regional-scale case study area Norrköping is located in the East Middle part of Sweden. Data source: The Corine Land Cover inventory (EEA, 2020).

Norrköping was chosen as a case study as it has been presented as an example of the bio-based economy emerging in practice (LiU, 2020) in the form of a growing industrial symbiosis network, centered on biomass resources, energy use, and waste management (Figure 2). Both the forestry and agricultural sectors play a role in this symbiosis, as well as local energy providers and the municipality (ibid). Additionally, there are high-reaching sustainability ambitions in the region, reflecting national priorities on climate change mitigation and progress on the 2030 Agenda (Norrköping Rådhus AB, 2019). The analysis focused specifically on goal interactions across forestry, energy, and waste management, thereby allowing for an in-depth exploration of a sub-set of the total industrial symbiosis network. The choice to include goals from the 2030 Agenda was motivated by its relatively broad scope and explicit focus on integration in the implementation stage (Sánchez Gassen et al., 2019), compared to for example the Swedish environmental quality objectives (Edvardsson, 2004). Furthermore, goals specifically related to strong sustainability were included in the analysis, as this dimension of sustainability is not evidently addressed by the 2030 Agenda, or the bio-based economy (Loiseau et al., 2016; Spangenberg, 2017).

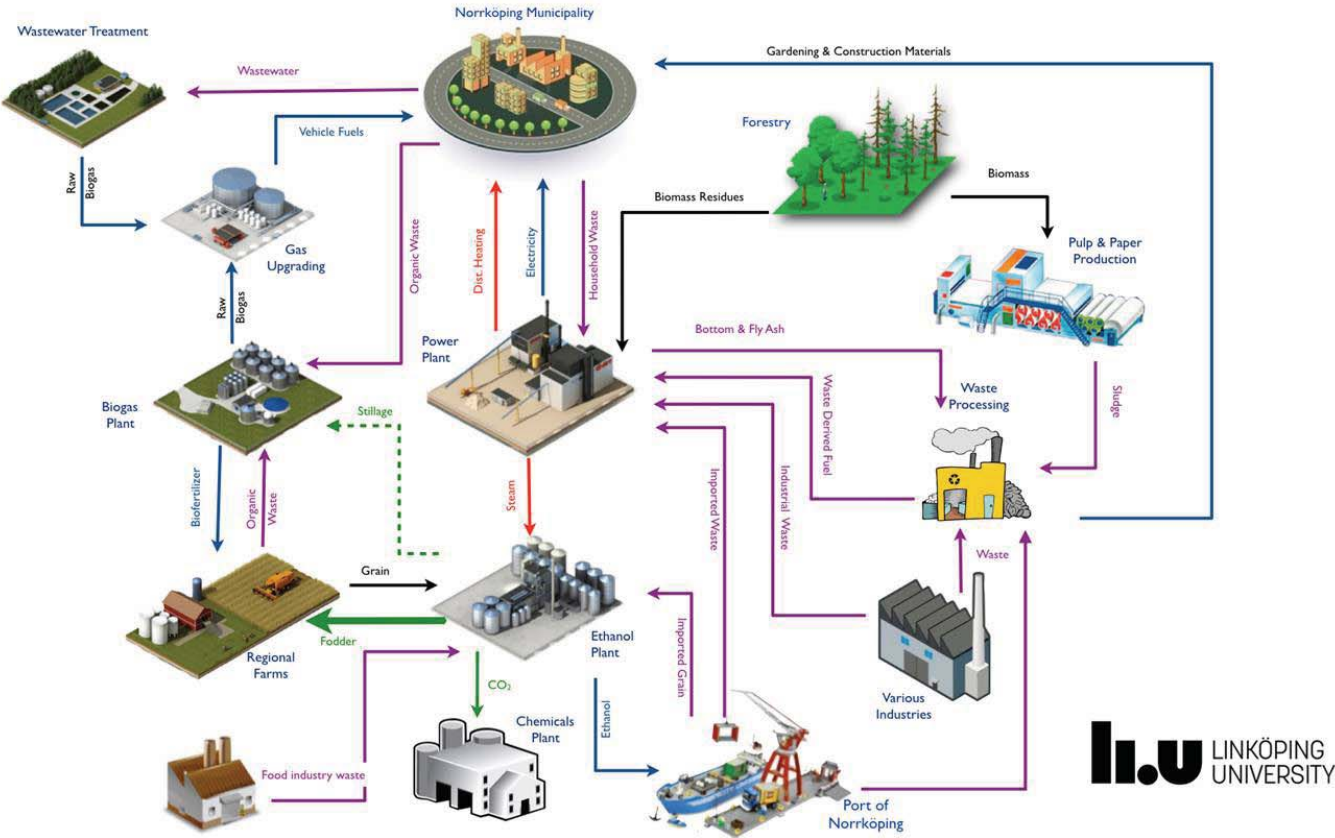


Figure 2. The Händelö industrial symbiosis network. Source: LiU (2020).

3. Research design – a mixed-methods approach

The research design was based on an interdisciplinary mixed-methods approach. It combined qualitative and quantitative methods for data collection and analysis, and used systems thinking as a framing for integration. Table 2 presents an overview of data sources, methods for data collection and analysis, and procedures for ensuring validity and reliability for each publication, explained in further detail in Sections 3.1–3.3.

Table 2. Overview of data sources and research methods

Publication	Scale of analysis	Data sources	Methods for data collection	Methods for data analysis	Ways of addressing validity and reliability
Paper I	Global/national	Scientific and gray literature	Literature search	Document analysis	Triangulation
Paper II	National	Scientific and gray literature Expert knowledge	Stakeholder mapping Snowball sampling Literature search Semi-structured interviews	Causal loop diagrams Workbooks	Use of interview guide Interviews recorded and transcribed Process of translating interview data into causal loop diagrams documented Triangulation
Paper III	National	Scientific and gray literature Expert knowledge	Stakeholder mapping Snowball sampling Literature search Semi-structured interviews	Causal loop diagrams Workbooks	Use of interview guide Interviews recorded and transcribed Process of translating interview data into causal loop diagrams documented Triangulation
Paper IV	Global	Scientific literature	Literature search	Document analysis and coding Network analysis	Use of qualitative data analysis software to document coding process Triangulation
Paper V	Regional (sub-national)	Scientific and gray literature Expert knowledge Official databases	Stakeholder mapping Literature search Semi-structured interviews Database searches	Cross-impact scoring Network diagramming Key variable selection and conceptual modeling Numerical system dynamics modeling	Formal procedures for validation of system dynamics models, including structural and behavioral tests Triangulation

3.1 Data sources and methods for data collection

Papers I and IV rely on the scientific and gray literature as sources of data, collected by the means of literature searches in databases such as SCOPUS and Google Scholar. Gray literature can be understood as scientific information that is not formally published as articles in scientific journals; it includes, for example, reports, dissertations, and guidelines published by governments, non-governmental organizations (NGOs), companies, and universities (Schöpfel, 2011). In Paper I, gray literature constituted an important data source, as policy documents and reports are key to understanding what the bio-based economy is and how it is expected to contribute to sustainability. In Paper IV, the basis for the analysis was a sample of 70 peer-reviewed articles. Gray literature was used to substantiate the discussion, and to provide a better understanding of what in the present thesis is referred to as the SDG interactions field, but was not formally included in the analytical steps in the study (i.e., coding and network analysis). Both the literature on the bio-based economy and SDG interactions cover a broad range of disciplines, spanning fields such as engineering, chemistry, economics, agronomy, forestry, and policy research.

The primary data source in the study presented in Papers II and III was expert knowledge. An expert in the context of this study was understood as someone who has substantive and in-depth knowledge of Swedish agriculture and/or forestry. This knowledge could have been obtained through formal training, research, and profession, but also through personal experience (Bogner et al., 2009; Burgman et al., 2011; Martin et al., 2012). The process of identifying and selecting experts was guided by work on stakeholder analysis for transdisciplinary research projects (i.e., projects aiming to engage and both academic and non-academic actors in all stages of the research process). The process included defining system boundaries, identifying the actors within these boundaries, specifying the issue to be studied, finding the actors relevant to the specific issue at hand, selecting whom to engage in the research, and finally deciding on the nature of engagement in the research process (Lelea et al., 2014). The expert identification was carried out based on reviews of the scientific and gray literature but also made use of a snowball sampling approach. Snowball sampling can be described as an approach where the interviewees are asked to identify other potential interviewees they believe fit the selection criteria of the study (Ritchie et al., 2014). The selection criteria employed in this specific case included (i) the real-world experience from the chosen systems (agriculture and forestry), (ii) the ability of the participants to represent the views and perspectives of larger actor groups, and (iii) their ability to provide diverse standpoints. The experts' ability to provide diverse standpoints was assessed in the initial stakeholder identification stage, but also during the snowball sampling, as some questions were directly aimed at eliciting views on which actors currently lack a voice in the Swedish bio-based economy debate. In total, 14 experts representing the Swedish government, farmers associations, NGOs, forest owner associations, practitioners engaged in the green sectors, and the research community were interviewed for the study. For an overview of the participants, see Paper II, Appendix B. The data were collected through semi-structured interviews, based on an interview guide. The interviews took place in person or digitally.

Paper V combined scientific and gray literature, expert knowledge, and official databases as data sources. Four semi-structured interviews were carried out early in the process for scoping purposes, to sharpen the research questions, and to set research boundaries. The interviewees were representatives from the Norrköping municipality, energy experts, and researchers engaged in the industrial symbiosis network. Expert knowledge was also used to provide preliminary insights on sustainability goal interactions. Four of the co-authors were engaged in this process, making an expert judgment of the scoring of interactions based on prior knowledge and experience as well as a reading of the literature. The scoring was carried out through the distribution of an online matrix in combination with workshops. The numerical data, used for model calibration, were collected through searching online databases, and by reviewing scientific publications and official documents from the regional municipality and local energy provider. For an overview of the model data and sources, see Paper V, Appendix B.

3.2 Data analysis methods

3.2.1 Document analysis

In Papers I and IV, the output from the literature search was structured through document analysis (Bowen, 2009) and elements of open and axial coding (Strauss and Corbin, 2008). In Paper I, the literature was first analyzed for data describing the relationship between the bio-based economy and sustainability. Both relevant pieces of text and numerical data were identified. Then analysis was performed to find patterns and relationships within the data, uncovering emerging themes such as potential contributions of the bio-based economy to sustainability, challenges, and risk factors. In Paper IV, the initial coding scheme was based on several guiding questions (Paper IV, p. 4). The questions belonged to different overarching themes (such as the expected contribution of a study to policy-making, the methods used, and the strengths and weaknesses of that method). In the subsequent step, several key themes were selected. Under each theme, sets of sub-codes were elicited, grouped, and refined. Based on the overarching themes and sub-codes, additional rounds of literature screening and coding were carried out (Figure 3).

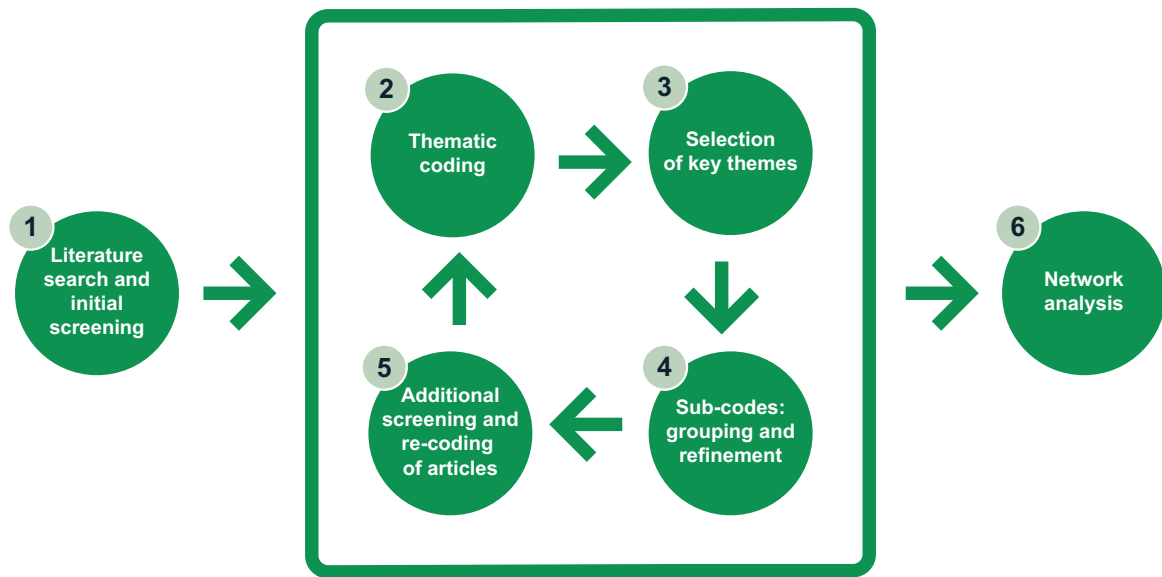


Figure 3. The iterative steps of the research process employed when mapping the literature on SDG interactions. Source: Paper IV.

3.2.2 Conceptual systems modeling – causal loop diagrams

In Papers II and III, elements of grounded theory served as a basis for translating interview data into causal loop diagrams (CLDs), following the principle outlined by Kim and Andersen (2012). CLDs are diagramming tools, developed within the fields of system analysis, providing a broad representation of the feedback structure of a system (Sedlacko et al., 2014; Sterman, 2009). They consist of variables and hypothesized causal relationships between these variables, indicated in the diagrams by arrows. Each link is assigned a polarity, showcasing if change in the independent variable causes the dependent variable to move in the same or opposite direction, as denoted by a plus or minus sign (Lane, 2008). In Papers II and III, CLDs were used to integrate the views of the interviewed experts, and as a tool for exploring transition pathways to a Swedish bio-based economy. The CLD diagramming method was also used in Paper V. In this paper, the purpose of the CLD developed was to serve as an intermediary step between system conceptualization and numerical modeling, and to communicate key feedback loops. Hence, the CLD developed in Paper V was less detailed as compared to those developed for Papers II and III. In the three papers using CLDs as a method, the Vensim¹ software was used to construct the diagrams. For a detailed description of the CLD connotation and use, see Paper II, Appendix A.

3.2.3 Network diagramming and analysis

Network analysis is a method that emerged from graph theory, used to represent and analyze relationships between system components (Newman et al., 2006). Network analysis begins by defining a finite set of elements, commonly referred to as nodes. The nodes represent single

¹ Available online at <https://www.vensim.com>

entities and may potentially be interrelated in the context of the study. The relationships are represented by edges and may be either undirected or directed. The total network is represented by a graph, made up of the set of nodes and the pairwise interactions among them (Butts, 2009). In Paper IV, network analysis techniques were used to analyze the co-occurrence of themes found in the SDG interactions literature. The co-occurrence network was divided into clusters, using a modularity-based approach to clustering (Newman, 2006; Newman and Girvan, 2004). The software VOSviewer² was used to carry out the modularity-based approach and clustering, as well as for visualization purposes. Network diagramming was also used in Paper V. The network diagrams presented in Paper V depict how the sustainability goals (nodes) interact, specifying connectivity, trade-offs, synergies, and strength of interactions. Due to the limited set of goals under study, the analysis was based on network diagramming rather than quantitative network analysis.

3.2.4 Cross-impact analysis

In Paper V, one of the methods used was cross-impact scoring and analysis. Cross-impact analyses are considered scenario technique tools, offering a structured process for exploring plausible future developments based on expert judgment about interactions between system elements (Weimer-Jehle, 2006). In previous research on sustainability goal interactions, a typology of SDG interactions and pairwise scoring was used in combination to assess the occurrence of links between the SDGs in various contexts (Allen et al., 2018; ICSU, 2017; Weitz et al., 2017). In this thesis, the typology and cross-impact analysis were adapted and used primarily to provide an initial understanding of interactions between goals from the bio-based economy, the SGDs, and the strong sustainability paradigm.

3.2.5 System dynamics modeling

Paper V utilized numerical system dynamics modeling to assess goal interactions and potential future scenarios, using the STELLA architect software³ to carry out the analysis. Numerical system dynamics modeling deals with causal interactions between system components, providing a tool to numerically assess how these interactions give rise to a system's behavior over time (Ford, 1999; Richardson, 2011; Wolstenholme, 1999). System dynamics is interdisciplinary at its core. It has its origins in control theory and cybernetics, hence drawing on fields such as engineering, mathematics, and physics. It does, however, concern change in social systems, therefore also relying on social sciences such as psychology, sociology, and economics (Sterman, 2009). A core concept in a system dynamics model is that the system state is self-modifying through feedback processes. This can be displayed through formal visual language, as depicted in Figure 4.

² Can be accessed online at <https://www.vosviewer.com>

³ Provided by the software developer isee systems, available at <https://www.iseesystems.com>

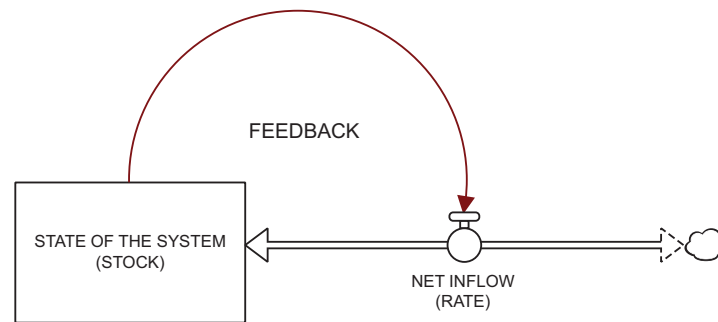


Figure 4. The formal visualization language of system dynamics is used to illustrate elements of systems and their interactions. Key components include stocks (state variables), flows (rates), and feedback.

The box in Figure 4 represents a stock (or state variable), which is a quantity of interest in the system under study. Stocks are subject to accumulation, regulated by the net inflow to the stock denoted by the arrow with the valve symbol. Mathematically, system dynamics models are effectively integral equation models (Yearworth, 2014). System dynamics facilitates learning about complex systems, partly as a tool that elicits and represents “mental models” held about the functioning of the system under study, and moreover as a tool that can test and improve these mental models through computer simulation, in an expert or participatory setting (Ford and Sterman, 1998). System dynamics models are therefore often developed in collaboration with problem owners (Andersen et al., 2007; Lane, 2000; Vennix, 1999).

3.3 Validity and reliability

For this thesis, triangulation has played an important role in ensuring validity and reliability. Four different types of triangulation can be distinguished. **Data triangulation** refers to using multiple data sources in one single study. **Investigator triangulation** is the use of several researchers in a study of a certain phenomenon. **Theory triangulation** is the use of multiple theoretical perspectives to design a study or to interpret the results. Finally, **methodological triangulation** is the use of multiple methods to carry out a study (Denzin, 1970). As a basis for gaining confidence in the credibility of the results, all four types of triangulation were used in this thesis. Data from primary and secondary sources were collected and contrasted. Investigator triangulation was used particularly in the analysis of results, where researchers from the core research team, external experts, as well as actors from the sectors of the bio-based economy were engaged. Theory triangulation was used as a basis for the research design and for the interpretation of the results, drawing on literature from multiple fields from both social and natural sciences. Methodological triangulation was at the core of the research design, realized through combining qualitative and quantitative methods and tools. In addition to these overarching considerations, each method employed comes with a specific philosophical basis and principles for understanding and addressing the issues of validity and reliability. The remainder of this section outlines some of these principles and measures taken in the data collection and analysis steps.

3.3.1 Validity and reliability in data collection

In stakeholder identification and engagement (Papers II, III, and V), a challenge lies in what has been described as self-exclusion, i.e., actors might not recognize the need to engage with the issue at hand (Lelea et al., 2014). The bio-based economy concept is not well-known to a broad audience and there is no general agreement on the meaning of the term, two factors that may have exacerbated the issue of self-exclusion in the present study. Another challenge, specifically related to the use of snowball sampling, is that the sample could be biased by the social networks of the initial choice of interviewees (Reed et al., 2009). To address these issues, a broad approach to stakeholder identification was taken. The sample included participants from multiple disciplines and sectors. Their expertise ranged from being highly specialized (such as for the practitioners) to being more broad-reaching (e.g., in terms of the policy-makers working with the bio-based economy concept). When reaching out to potential interviewees, no definition of the bio-based economy was provided, but the context of the term was outlined. Furthermore, the rationale behind inviting each interviewee was provided, explaining how their specific expertise could contribute to the study.

In respect to semi-structured interviews (Papers II, III, and V), the work by Barriball and While, (1994) provided guiding principles to ensure validity and reliability. Specific measures employed include the use of an interview guide, developed to test the interview questions before the actual meetings. This was to ensure that the questions were effective, clearly formulated, and non-steering. Additionally, the interviews were recorded and transcribed.

When using secondary data sources (Papers I–V), such as the scientific literature or official databases, a number of principles were followed to ensure the applicability and credibility of the data, following the guidelines in Saunders and Lewis (2012). Each data source was examined, looking to identify the original purpose of data collection, the methods and instruments employed to collect the data, and potentially also the theoretical framework used. Additionally, the data were examined to determine the relevance for the research questions in the present thesis.

3.3.2 Validity and reliability in data analysis

In using document analysis (Papers I–V), the guiding principles were objectivity and sensitivity, the former referring to the aim of representing the data fairly, and the latter to responding to differences in the meaning of the data (Bowen, 2009). For the CLDs developed in Papers II and III, validity and reliability were to a large extent based on the iterative procedure of engaging multiple researchers as well as the respondents in the data-analysis step. A shared document was used to reflect on the research process and outcomes (a so-called workbook (Vennix, 1996, p. 128)). It was sent out to the respondents, offering several opportunities to provide written and oral feedback and clarification. The CLDs were then revised based on their input. Moreover, using elements of grounded theory to establish clear links between the data and the final CLDs made the interpretative process transparent, a critical step in building confidence in CLDs (Kim and Andersen, 2012).

With respect to network analysis and diagramming (Paper IV), the Maxqda software⁴ was used to keep the codes intact in relation to the original piece of text. This provided a transparent account of the coding scheme serving as the basis for the network analysis. Moreover, each paper was coded by multiple analysts. This made it possible to compare and discuss how the codes had been assigned, and to refine the final distribution of codes. In terms of the cross-impact analysis (Paper V), the interaction scores were assigned by experts, and therefore the results are subjective to the level of expertise and accuracy of their knowledge. To build validity in this context, the process was based on iterative rounds of discussion allowing for clarification or justification among the experts. Claims were also backed up by the relevant scientific literature, and where there was prevailing disagreement on the interaction scores, this was indicated in the results as a source of uncertainty. Additionally, the method was used in conjunction with other methods. This enabled both data and methodological triangulation, which helped build confidence in the results.

System dynamics models (Paper V) belong to a family of a descriptive, so-called white-box models. In a way, a system dynamics model holds a theory about how a system functions, and model validation is to a large extent a matter of assessing the validity of the model's internal structure, as well as its behavioral output. It has been argued that system dynamics agree with a relativist, holistic philosophy of science, and that consequently, validation cannot rely on entirely formal or objective procedures (Barlas and Carpenter, 1990). A model is seen as one of many ways to represent a system. No model can claim absolute objectivity, and cannot be judged to be true or false, but rather found to be placed on a continuum of usefulness. Thus, validation of the internal structure of the model depends both on formal, objective, and quantitative procedures, as well as qualitative elements (ibid). Several guidelines and tests exist to increase confidence in a model as a useful representation of a real-world system. In the present thesis, the validation of the system dynamics model was an iterative process following the steps outlined by Barlas (1996). The tests performed include both structural and behavioral tests.

⁴ Available for download at <https://www.maxqda.com>

4. Summary of results

4.1 Paper I: The bio-based economy and sustainability – an initial understanding

The literature review conducted in Paper I was guided by the overarching question of whether the bio-based economy can provide a viable pathway to sustainability (RQ1). The relationship between the bio-based economy and sustainability was analyzed using the frames of weak and strong sustainability.

The results suggest that when taking the perspective of the weak sustainability paradigm, the prospects for the bio-based economy are promising. Bio-based resources hold the potential to replace fossil- and mineral-based resources and might thereby contribute to climate change mitigation and cleaner production processes. Thus, increasing the use of renewable, bio-based resources may be a way to overcome potential limits to growth in economic activity, both on the source side and the sink side of the economy. The bio-based economy is also expected to contribute to social sustainability. At the core is the possibility to place biomass processing closer to primary production. This decentralized mode of production can create new employment opportunities and growth in economic activity, primarily in rural areas. Additional economic benefits may be created through specialization. When nations, regions, or sectors specialize to exploit the economic potential in natural resource endowments, or knowledge on biomass processing, their market competitiveness is expected to increase. Innovation and novel technologies (e.g., biorefineries) are perceived as key to the transition process. Aside from the direct positive outcomes brought by the generation of new knowledge in the sectors of the bio-based economy, a strong innovation focus is also suggested to bring indirect benefits. Research and development may create spill-over effects that could help to realize sustainability goals in sectors not directly linked to the bio-based economy. Finally, the literature on the role of biotechnology in the bio-based economy highlights several hoped-for sustainability outcomes. These include improvements in human health, enhanced global governance of biological resources (e.g., through genetic barcoding), and the development of novel crops that are resistant to adverse climate change impacts.

From the strong sustainability perspective, on the other hand, the contribution of the bio-based economy is perceived as less promising. The bio-based economy is largely understood as a business-as-usual scenario, an attempt to overcome the limits to growth of the fossil-based economy, but not a fundamental and much needed shift to sustainability. Instead, the discourse surrounding the concept has been recognized as promissory, carrying with it a “something-for-all” rhetoric. At the same time, the core meaning of the term bio-based economy has remained unclear, and sources of uncertainty, potential trade-offs, and the limits also to the use of bio-based resources have been overlooked. The debate has also been criticized for being dominated by an industrial perspective, overlooking the concerns of primary producers and the views of the public. According to the strong sustainability paradigm, in a worst-case scenario, a transition process may accelerate already existing ecological and social sustainability issues. For example, growing claims on biological resources may increase their exploitation, resulting in further loss of fertile soils, degradation of water sources, deforestation, and threats to biodiversity. Growing and competing claims for biological resources may also lead to

accelerating conflicts over the rights to these same resources, displacing local communities and endangering livelihoods. And finally, if the premises of the bio-based economy are not realized, public support for the concept might be lost. Thereby, the promissory discourse runs the risk of creating boom-and-bust cycles similar to those in financial markets.

While the main focus of the literature review was to provide a basis for understanding the relationship between the bio-based economy and sustainability, Paper I also introduces the Swedish case. The literature highlights favorable preconditions that may support a transition process in Sweden (e.g., resource endowments, a highly skilled labor force, and a favorable business environment), but also indicates that the transition process is linked to considerable ecological and socio-economic uncertainty. The underlying reasons include the risks associated with investing in novel technologies, such as biorefineries, and uncertainty linked to how the policy landscape for the bio-based economy will change in the future. From a sustainability viewpoint, existing bio-based economy initiatives in a Swedish context seem to fit well within the weak sustainability paradigm (e.g., through their strong industrial, economic, and research and innovation focus). However, these initiatives remain limited in challenging business-as-usual developments in bio-based sectors (e.g., by questioning the further exploitation of biological resources or by addressing potential biophysical or social limits to this exploitation), and are thereby less likely to contribute to strong sustainability.

4.2 Papers II and III: Bio-based economy goals and transition dynamics in Sweden

The study serving as the basis for Papers II and III was guided by research questions RQ2–4. The results introduce eight overarching goals of the bio-based economy in Sweden (Table 3), as elicited during the semi-structured interviews providing the empirical basis for both papers. The eight goals represent diverse views on the hoped-for outcomes of a transition to a bio-based economy in Sweden, detailing what the global bio-based economy concept could potentially mean in this specific national context. The goals are primarily linked to the forestry and agricultural sectors but also include one goal specifically related to the political dimension of the bio-based economy.

Table 3. Suggested goals of the Swedish bio-based economy

Overarching goal	Sector focus
The diversification goal: achieve greater diversity in Swedish forestry (e.g., in terms of species, forest management practices, and in the provision of forest values).	Forestry
The advancement goal [*] : enhance profitability, resource-use efficiency, and innovation capacity within the existing configuration of the forestry industry.	Forestry
The high-value-added production goal: achieve a fundamental shift away from existing configurations in the forestry industry to an industrial structure that is centered on high-value-added production.	Forestry
The goal of ensuring a viable agricultural sector: maintain or expand farming activities in Sweden.	Agriculture
The goal related to the sustainability of conventional agriculture: facilitate the use of more environmentally friendly practices in conventional agriculture production.	Agriculture
The goal of securing biomass supplies: ensure biomass availability for both food and non-food applications.	Agriculture
The regenerative production goal: achieve a fundamental shift in how agriculture is carried out, from conventional modes of production to regenerative production. Value in regenerative production is based on ecological improvement, thus placing ecosystem functioning at the core of the agricultural practice.	Agriculture
The political bio-based economy goal: build political support for the bio-based economy, which to a large extent is dependent on public support for the concept.	Political dimension of the bio-based economy

^{*} This goal was not explicitly included in the set of desired change processes presented in Paper II as it was described as a goal promoted by other actors, but not as a desired change process according to the interviewees. Nevertheless, it is included here as it was described in detail during the interviews and represents one potential, and debated, future development trajectory for the forestry industry under the bio-based economy umbrella.

In addition to the goals presented in Table 3, Papers II and III provide a mapping and systemic analysis of how the eight goals interact, thereby integrating different actor views. The interactions are made up of causal chains, but also by feedback loops. Most of these feedback loops were found to be reinforcing, which indicates that initial changes in these systems may easily be amplified. Furthermore, based on the mapping of how the goals of the bio-based economy interact, a total of 37 leverage points for action were identified. These point to places to intervene to facilitate goal progress. The leverage points cover a broad range of themes, such as attitudes and values, governance and collaboration, ecological factors, education and knowledge generation, economic factors, and changes in resource use. Some leverage points stand out as belonging to what has been referred to as higher-order leverage points (Abson et al., 2017), for example those targeting shifts in underlying beliefs, motivations, and values among the actors engaged in the bio-based economy.

Related to the leverage points are 15 specific interventions, with the potential to initiate and facilitate a transition process. The interventions differ in nature. Some are linked to the generation of new knowledge, for example the proposals to invest in national plant breeding

programs or research on plant interactions. Others aspire to spread knowledge, such as the proposal to invest in training and education programs for forest owners. Yet another category of proposals is linked to infrastructure and technology investments. The proposals include both top-down (e.g., a green tax shift) and bottom-up (e.g., communication of successful examples of regenerative production) interventions. However, most of the proposed interventions require some support from local, regional, or national government institutions. Finally, the proposed interventions are unevenly distributed over the goals of the bio-based economy. For example, seven interventions target the shift to regenerative agricultural production. In contrast, only two interventions aim to realize the attainment of the goal to employ more environmentally friendly practices in conventional agriculture.

Taken together, the goals, the feedback processes governing goal attainment, the leverage points, and the specific interventions presented in Papers II and III form potential transition pathways to a Swedish bio-based economy.

4.3 Paper IV: Approaches for identifying and understanding goal interactions

The study serving as a basis for Paper IV contributes mainly to RQ5. The paper presents the results from a literature review, coding, and network analysis carried out to understand how interactions between sustainability goals can be identified and analyzed. The basis for the analysis was a sample of articles that study interactions between the SDGs.

The results identified and mapped four central themes in the sample: (i) the policy challenges addressed, (ii) the ways “interactions” have been conceptualized, (iii) the data sources used, and (iv) the methods of analysis employed. Under each theme, several sub-codes were derived, serving as a basis for a reading guide. The reading guide was developed to code future studies, and to support decision-makers in singling out appropriate studies or methods to address a certain policy challenge.

The results also include a network diagram, showcasing how the sub-codes under each theme co-occur in three clusters. The first cluster encompasses quantitative modeling research, seeking to analyze interactions across SDG indicators. It responds to policy challenges such as prioritization of actions and outcomes, contextualization, and policy innovation. Generally, this cluster stresses that (globally) generalized statements about SDG interactions and goal progress should be treated with caution, and instead prompts the development of detailed and empirically grounded models. The second cluster represents qualitative approaches and scenario building, relying on the literature as a data source. It responds primarily to the policy challenge of strengthening policy integration and coherence. Naturally, this cluster focuses on interactions across the 2030 Agenda and external entities, including the studies that connect to the wider policy landscape external to the 2030 Agenda. Conversely, the third cluster focuses on the interactions within the 2030 Agenda, encompassing research on goal-goal or target-target interactions. Commonly used tools and techniques include network analysis and participatory methods. The cluster also uses expert and stakeholder knowledge as a key data source. This

cluster has the weakest link to the policy challenges, meaning that it is not evident what policy challenge it responds to.

Furthermore, research gaps were highlighted. These include a need to better address interactions across indicators in the SDG framework, geographic spill-overs, actor interactions, and integrated monitoring and evaluation. There is also a need to be more specific in terms of what policy challenge a given study seeks to address and to employ more participatory modes of research. The analysis in Paper IV suggests that by addressing these research gaps, the literature will be better able to support integration of the SDGs in policy-relevant ways.

4.4 Paper V: Goal interactions in a regional context – the Norrköping case

The study presented in Paper V responds primarily to RQ5 and RQ6. In this study, an analytical framework was developed and applied to study goal interactions internal to the bio-based economy, as well as across the 2030 Agenda and the strong sustainability paradigm. These interactions were assessed in the regional context of Norrköping, Sweden. The following sections provide more detail on the steps of the analysis, on the types of goal interactions identified, and what they imply for goal priority setting. The first section focuses primarily on how the goals interact in terms of structures, and the second on the resulting behavior over time.

4.4.1 A structural hypothesis about goal interactions

The first step of the study presented in Paper V consisted of identifying what initiatives and goals to consider. This “goal screening” exercise resulted in a final list of seven goals to explore in further depth. Two of the goals were chosen based on the analysis in Paper II: to achieve diversity in the forestry sector, and to make the existing forestry industry more advanced, innovative, and resource-use efficient. Further, three SDG targets from the 2030 Agenda were chosen: SDG 7.2 (increases in renewable energy use), SDG 7.3 (gains in energy efficiency), and SDG 12.5 (reductions in waste generation). Finally, two overarching goals related to strong sustainability were included in the analysis: to maintain critical natural capital and to create closed-loop production systems. The goals were chosen based on their relevance to current sustainability challenges and developments in the emerging bio-based economy cluster in Norrköping, focusing specifically on the forestry sector, energy dynamics, and waste management. The set of goals does not cover all aspects of sustainability relevant to Norrköping but constitutes a starting point for analyzing goal interactions in this context.

The results include a mapping of how the goals interact directly (through cross-impact scoring), and indirectly in broader causal structures (as represented in a CLD and numerical system dynamics model). The results from the cross-impact scoring and analysis suggest that, generally, the relationships between the goals included in the analysis are synergetic. However, these synergies are relatively weak. This means, for example, that progress the goals included in the analysis could create beneficial conditions or aid the attainment of other goals. However, few goals were found to be indivisibly linked to other goals. The two goals related to strong sustainability, to maintain critical natural capital and to build closed-loop production systems, stood out as having the largest synergetic effects with other goals. Also, SDG 12.5 (substantially

reduce waste generation) was found to promote goal progress in other areas through synergetic effects. Thus, if prioritizing goals based on their ability to generate synergies, these goals would merit high priority in the decision-making context of Norrköping. SDGs 7.2 and 7.3 ranked in the middle, while the two bio-based economy goals performed the worst based on the initial cross-impact scoring (i.e., were the least synergetic). Additionally, the analysis identified trade-offs between the two goals from the bio-based economy, emphasizing that sustainability initiatives may be both internally and externally conflicting.

Building on the cross-impact scoring, network diagramming was used to provide a visual and more detailed account of the distribution of trade-offs and synergies. These diagrams highlight how trade-offs and synergies may arise both in the implementation stage and at the stage where progress on various sustainability goals is made. The diagrams show, for example, how the implementation of the bio-based economy and SDG 7.2 may create competition for input resources. However, the network diagrams also revealed new synergies linked to the implementation of the goal to achieve higher diversity in the forestry sector, thereby slightly altering its low initial priority suggested by the cross-impact analysis.

In the next step, indicators representing each overarching goal were identified, and their interactions mapped through a CLD and a numerical system dynamics model (the so-called BBE-SDG model). Several key feedback loops were identified in this process, many of them balancing. The large share of balancing feedback loops may indicate a relatively stable system, but also calls for finding the drivers of change, potentially overlooked in the initial CLD and BBE-SDG model. To get a better understanding of the structure of the BBE-SDG model, Figure 5 provides a simplified overview in the form of a stock and flow diagram. The model is divided into three main modules: energy supply (gray), dynamics of energy demand and waste management in the municipality (yellow), and forest biomass growth and regeneration (green).

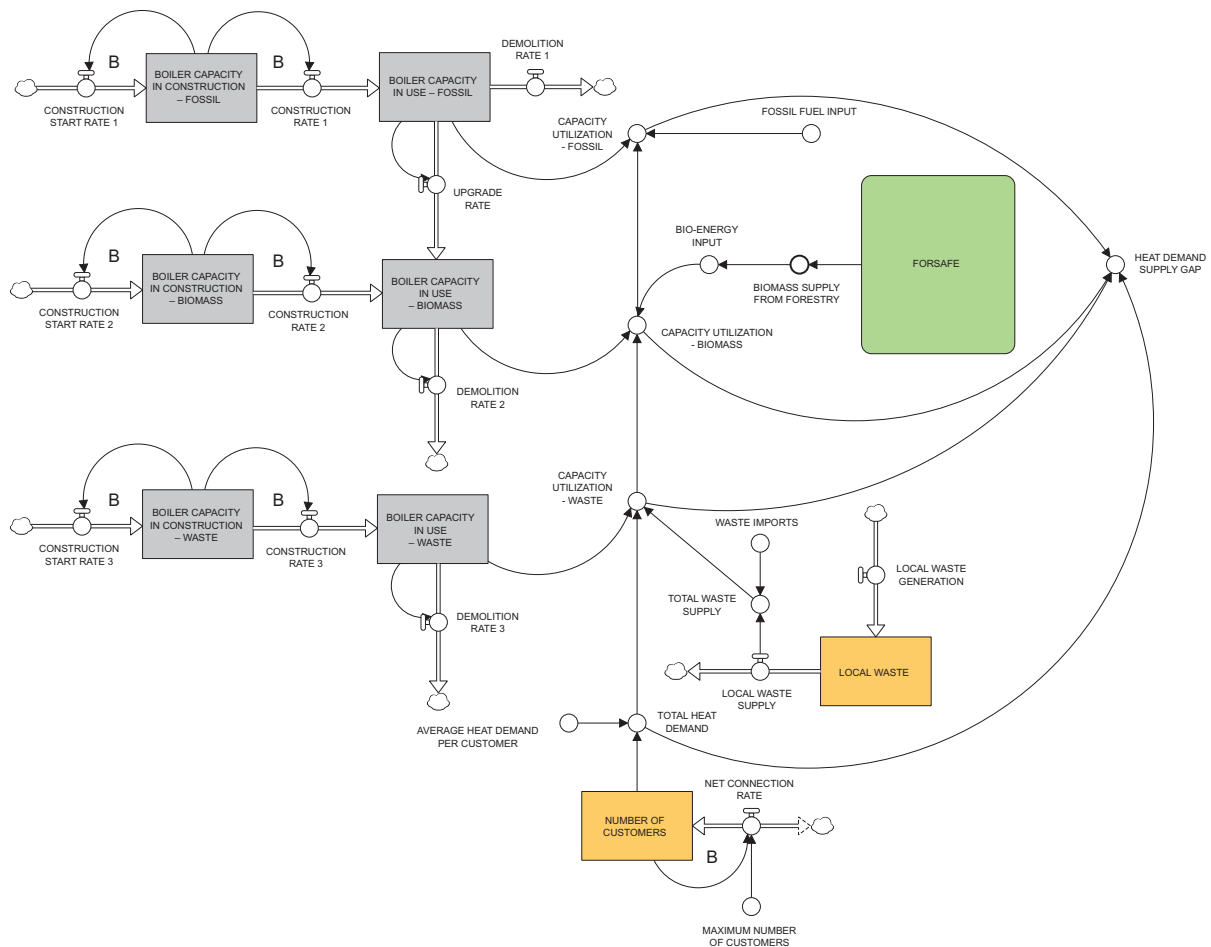


Figure 5. Stock and flow diagram providing an overview of the components of the BBE-SDG model. The model structure encompasses variables linked to the sustainability goals included in the analysis and specifies how they interact.

There are several key stocks (or state variables) in the model. In Figure 5, six of them are linked to the energy supply, representing the boiler capacity of a local combined heat and power (CHP) plant. The balancing feedback loops (denoted B) represent the process of adjusting the production capacity of the CHP plant to the desired level. The total boiler capacity is one of the factors that determines how much heat is produced and supplied to the municipality. Another determining factor is the total heat demand, which is dependent on the stock variable tracing the number of customers connected to the district heating system, times the average heat demand per customer. The total heat produced is also dependent on the fuel input. Waste is one source of fuel input. The local waste supply is a stock, that together with waste imports makes up the total waste supply. Biomass for energy provision is derived from the ForSAFE model, coupled as depicted in Figure 5. The fossil fuel input is exogenous to the model. The total capacity utilization determines how much heat is produced and affects the so-called heat demand supply gap. This gap is zero under normal operation, as the heat demand is supposed to be met at all times. However, if the heat produced does not cover demand, the heat demand supply gap becomes positive. For further details on the model specification, see Paper V, Appendix B.

The variables in the BBE-SDG model are linked to the sustainability goals as follows. Progress on the goals of the bio-based economy is traced in the ForSAFE model and is related to decisions about forest management practices. Progress on the SDGs is related to the variable fossil fuel input (progress on SDG 7.2 means a lower use of fossil fuels), average heat demand per customer (progress on SDG 7.3 entails higher energy efficiency and thus a lower heat demand per customer), and the local waste generation rate (where progress on SDG 12.5 means lower waste generation). Progress on the goals related to strong sustainability is indicated by changes to the variables C/N ratio and soil organic carbon (representing strong sustainability in terms of maintaining critical natural capital). Progress on strong sustainability is also traced by changes to the heat demand supply gap, waste imports, and net CO₂-emissions (representing strong sustainability in terms of achieving closed-loop production systems). The C/N ratio and soil organic carbon are endogenous to ForSAFE. How the net CO₂-emissions develop over time is determined by changes to the soil organic carbon in ForSAFE, and fuel consumption in the CHP plant.

4.4.2 Simulated results

Three scenarios (Sc1–3) were simulated using the BBE-SDG model. The scenarios were developed to explore how synergies and trade-offs arise over time. In Sc1, goal progress was maximized on the goal to make the existing industrial composition in the forestry sector more resource-use efficient and innovative (the advancement goal). In the model, this goal was translated into an intensive management scenario, to maximize biomass output to be used for energy provision. In Sc2, goal progress was instead maximized on the bio-based economy goal of making Swedish forestry more diverse (the diversification goal). The assumption was that no forest would be in productive use. While not realistic, running this scenario showed what minimum inference to the forest resource would entail for progress on other goals, in a sense making Sc2 a reference scenario. Finally, Sc3 explored goal interactions when progress was maximized on multiple goals simultaneously. The forest management was the same as in Sc2, but progress was also made in terms of lower use of fossil-based fuel inputs (SDG 7.2), higher energy efficiency (SDG 7.3), reductions in local waste generation (SDG12.5), and restrictions to waste imports (to achieve closed-loop production systems).

The results of the simulation-based analysis found two clusters of coherent goals, but with trade-offs in between. One cluster includes the goals to make the existing industrial mode of forestry production more resource-use efficient and innovative, to increase renewable energy provision, and to achieve closed-loop production systems. The other cluster includes the goal to enable greater diversity in the Swedish forestry sector and the goal to maintain critical natural capital. These results can be compared to the outputs from the previous steps in the analysis. First, the simulation-based analysis uncovered previously silent trade-offs, such as between the diversified forestry goal and the attainment of lower use of fossil fuels and closed-loop production systems. Second, the goals related to the bio-based economy emerged as critical to the attainment of other goals, despite having low synergy scores in the cross-impact scoring. Third, the potential of energy efficiency gains in mediating trade-offs was highlighted, stressing the importance of SDG 7.3 in facilitating overall goal progress.

Finally, the cross-impact scoring indicated that all goals, in theory, could adhere to the principles of the strong sustainability paradigm, but the final simulation-based analysis came to challenge this assessment. None of the scenarios explored in the BBE-SDG model resulted in simultaneously fulfilling the goals of strong sustainability, due to the presence of, potentially counterintuitive, goal trade-offs.

5. Synthesis: Cross-cutting themes

The synthesis draws on Papers I–V and focuses specifically on cross-cutting themes. The thesis aims to inform decision-making and policy-making in the implementation of the bio-based economy. Therefore, the synthesis section places specific emphasis on several opportunities and challenges linked to realizing the goals of the bio-based economy. Specific attention is also devoted to trade-offs and synergies, identified within bio-based economy sectors, between sectors, and across parallel sustainability agendas and paradigms. Finally, each paper included in the thesis contributes either directly or indirectly to assessing what the bio-based economy implies for sustainability. The last section of the synthesis brings together these different contributions.

5.1 Opportunities for realizing the goals of the bio-based economy

Papers I–V provide detailed analyses of ways to support goal attainment (e.g., through the leverage points and proposed interventions), but it is also possible to identify some more overarching and cross-cutting opportunities. First, an explicit aim of many of the goals and leverage points is to build resilience and viability in the sectors related to the bio-based economy. For example, strengthening forest-owners' self-motivation and confidence is ultimately expected to result in more resilient forests, able to withstand climate change impacts such as forest fires, storms, and pests. Similarly, achieving successful generation shifts is a precondition for ensuring the long-term viability of the agricultural sector, as well as for realizing bio-based economy goals in the future. Further, diversity has been a re-occurring theme, both in relation to forestry and agriculture. The underlying assumption is that greater diversity (e.g., in management practices, species, values, and markets) would lead to long-term resilience. Also, the goal to make conventional agriculture more sustainable, and the aim to boost innovation potential in the forestry sector, would help build viability and resilience. None of these goals are prescriptive but reflect an overarching aspiration to cope with change in an uncertain future (Papers II and III). Second, the multiple (and diverse) goals of the bio-based economy have some similar features. Working across sectors to learn from these similarities constitutes a key opportunity. For example, the different strategies for achieving a price premium for promoting environmental values in agricultural production could be explored in further depth. The results suggest that these strategies are quite different across conventional and regenerative agricultural production, offering an opportunity for cross-sectoral learning (Paper III). Another example that may merit further attention is the different ways in which developments in the agricultural and forestry sector could contribute to the public and political support for the bio-based economy (Paper II). Including the views of different actors, such as the public, in the formulation of bio-based economy strategies may offer a way to increase the perceived legitimacy and support for the transition process as a whole.

Finally, the soft aspects of realizing the goals of the bio-based economy are worthy of consideration. A strong technological, engineering, and research and innovation focus has been a distinguishing feature of the bio-based economy discourse to date. Conversely, discussions on the soft aspects of a transition have been largely missing, as highlighted in Chapter 2. However, and perhaps unexpectedly, the results from Papers II and III show that many of the

proposed leverage points and the feedback loops suggested to govern goal attainment are not related to technological change, but rather to shifts in values, beliefs, preferences, and mindsets. They are also linked to perceptions about conflict, risk, and trust. Specifically, the results stress the importance of acknowledging and addressing:

- The perceived level of conflict regarding the sustainability and viability of different forestry management options.
- The perceived level of polarization in the bio-based economy discourse.
- Farmers' willingness to engage in innovation processes.
- Forest owners' self-motivation and confidence to take on an active management role.
- Potential new generations of farmers and their views on agriculture as a desirable career choice.
- Consumer views on novel biomass applications.
- Community support for regenerative agricultural production.
- Public perceptions of the green sectors and to what extent they deliver desired values.

Better understanding and addressing these underlying beliefs and value systems may be essential to support the transition to a bio-based economy.

5.2 Potential hindrances for realizing the goals of the bio-based economy

There are multiple sources of uncertainty and barriers linked to the implementation of the Swedish bio-based economy. These include patterns of path dependency and lock-in, risk, negative spill-over effects across bio-based economy sectors, and a suggested lack of coherent leadership.

Papers II and III present several feedback loops that may create lock-in effects, being of both a social and a physical nature. Some of these are reinforcing, but the CLDs also stress the role of balancing feedback loops in contributing to lock-in effects. In the forestry sector, one example is the perceived conflict about forest management practices, generating increasingly high levels of polarization through a reinforcing feedback loop. This polarization hampers goal attainment both with respect to the shift to diversified forestry and the shift to high-value-added production. Another lock-in is the result of past investments in infrastructure and human capital in the forestry sector, making it difficult to change the direction of the currently dominant industrial structure. A set of social dynamics may reinforce these investment-related lock-ins, linked to a lack of organizational innovation ability, strong support for the existing forestry management model as long as it remains profitable, and actor mobilization that protects industrial interests.

Furthermore, a lock-in on the biomass processing side may hinder structural change on the primary production side and vice versa. For example, high-value-added production is reliant on the use of forest biomass with certain qualitative characteristics. This raw material is currently not provided by Swedish primary producers at an industrial scale. The lack of biomass raw material with the right characteristics stalls the shift to high-value-added production. At the same time, the lack of industrial demand for this raw material means that there are few

incentives for primary producers to start providing this type of biomass. Together, these dynamics are suggested to create a lock-in in existing modes of production.

Path dependence and lock-in are present also in the agricultural sector. In terms of the goal to employ more environmentally friendly practices in conventional agriculture, biophysical and technological lock-ins are interlinked. Production systems based on economies of scale support the development of technologies for large-scale production systems. Technological development makes these systems increasingly efficient and contributes to developments toward monocultures and extensive use of chemical fertilizers and pesticides. This type of production has adverse impacts on ecosystem service provision, which reinforces the dependency on the intensive use of production inputs. Thereby, a biophysical lock-in is created, making it increasingly difficult to shift to other modes of farming (e.g., regenerative production) (Paper III).

Finally, reinforcing feedback loops linked to polarization have been identified as problematic in relation to the support for the bio-based economy as a whole. The polarized debate makes it difficult to create a shared definition and understanding of the bio-based economy concept, thereby reducing political support. This ultimately contributes to the status quo, halting goal progress in all sectors linked to the bio-based economy (Paper II).

Risk, be it real or perceived, is another factor that may inhibit goal attainment in the transition to a bio-based economy. The eight goals are subject to different types of risk, unequally distributed across the actors responsible for their implementation. The literature review in Paper I pointed to financial risk constituting a barrier to the transition process, due to past investments failing and future market prospects being uncertain. The nature of this financial risk was elaborated on by some of the experts in Papers II and III. For example, a need to redirect investments from R&D to commercialization when seeking to facilitate high-value-added production in the forestry sector was highlighted. Moving from theoretical potential to bringing a product to the market is perceived as challenging (Paper II). In regenerative agricultural production, risk arises when trying to scale up production and expand beyond local markets. The direct connection between producer and consumer is lost in this process, while at the same time competition grows, making this step a risk-filled undertaking (Paper III).

Moreover, the interconnected nature of the bio-based economy sectors may be seen as an opportunity but might just as well constitute a risk. One example is linked to the build-up of public and political support (Figure 6). Public support for the bio-based economy is important as it affects political will, and the support mechanisms that the political will generates (e.g., new funding streams and the establishment of formal platforms for collaboration). The expert interviews suggested that public support is influenced by the perceived legitimacy of developments in the green sectors. The interviews further suggested that the legitimacy in the agricultural and forestry sectors have different origins. In agriculture, it may be based on the role of the sector as a provider of food, as it thereby fulfills a basic human need. In the forestry sector, legitimacy is built on the ability of forestry-related actors to meet diverse societal objectives, including recreation, climate change mitigation, and rural employment. If a

transition to a bio-based economy changes the view of the agricultural sector as a provider of food and feed, it might erode legitimacy. Similarly, if a transition process in the forestry sector entails change that does not align with public priorities, it might reduce the perceived legitimacy of this sector. If the legitimacy in any of these sectors is eroded, it will lower public support, thereby reducing political support, and ultimately having negative ripple effects halting the overall transition process.

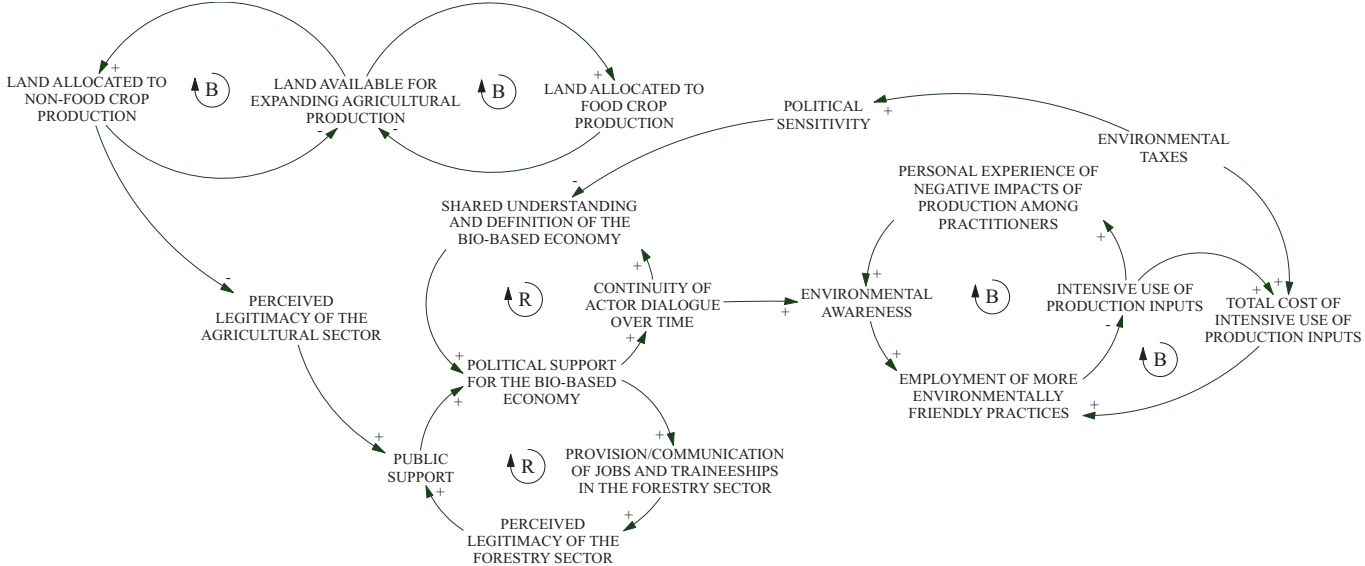


Figure 6. The CLD exemplifies how feedback loops found in the forestry and agricultural sectors are connected through cross-sectoral linkages.

Specific interventions could also be a source of negative spill-over effects and policy resistance. For example, environmental taxes are suggested as a way to support the employment of more environmentally friendly practices in conventional agriculture. However, introducing such taxes might be politically sensitive. If their use is associated with the bio-based economy concept, it may negatively affect the ability to align stakeholders' views on the transition process. Again, ripple effects may be created, having (potentially adverse) impacts on goal attainment in both the agriculture and forestry sectors.

The uncertainty linked to what actors will take the lead in the transition process is another potential barrier to realizing the goals of the bio-based economy. A general lack of leadership has been recognized, as well as the limited ability of some of the incumbent actors in the green sectors to take on that role, particularly so for goals that envision change of more transformative character (Papers II and III). In the Norrköping case, effective leadership from the municipality was one of the enabling factors in creating the emerging industrial symbiosis network (Mikkola et al., 2016) (Paper V). Generally, leadership in various forms has been identified as a critical factor to facilitate change toward sustainability (Olsson et al., 2006).

5.3 Trade-offs and synergies

Papers II and III present national-scale trade-offs and synergies based on the perceptions of the experts interviewed. The study presented in Paper V instead uncovered regional-scale trade-offs and synergies, based on the application of the analytical framework.

5.3.1 Trade-offs and synergies within the forestry sector

In the forestry sector, an important trade-off that surfaced is the need to choose between promoting diversified forestry or an advancement of the current industrial structure, as these two are seemingly incompatible. This is conceptualized in the CLDs (Paper II) and re-emphasized in the quantitative assessment (Paper V). Further, some trade-offs become apparent only over time. One such trade-off results from having to balance striving to maximize biomass output in the short term (based on an intensive forest management model), and maintaining the long-term viability of the forest ecosystem and productive capacity (which would benefit from a less intensive forest management model) (Paper II).

In terms of synergies, strengthening forest owners' self-motivation and confidence contributes to realizing diversified forestry, while simultaneously supporting the structural shift in the forestry industry toward high-value-added production (primarily as the raw material base becomes more diverse). At the same time, a more diverse set of productive, cultural, recreational, and ecological forest values are promoted. This development could, in turn, contribute to strengthening the public's view on the legitimacy of the forestry sector. Another synergy comes from investing in emerging technologies, where spill-over effects may support innovation also within existing modes of production. And at the same time, the more successful (i.e., profitable) the current configuration of the forestry industry, the more resources become available to invest in emerging technologies (Paper II).

5.3.2 Trade-offs and synergies within the agricultural sector

Multiple trade-offs were identified in the agricultural sector, to a large extent arising due to the limited nature of resources (e.g., land and capital). For example, trade-offs exist in investing in a highly efficient production system, tuned toward monocultures and economies of scale, versus employing more environmentally friendly practices in conventional agriculture. The trade-off arises due to the tendency of highly industrial and efficient production systems to rely heavily on the intensive use of production inputs, such as mineral fertilizers and chemical pesticides. Moreover, the limited access to productive agricultural land is creating trade-offs, for example in the choice between allocating land to regenerative or conventional agriculture. Finally, in research and innovation, a choice between investing in technology development for diversified agricultural systems or technology development for conventional agricultural systems was highlighted.

When it comes to synergy potential, investing in national plant breeding programs might be one way to promote synergetic effects. Such programs may contribute to securing biomass for both

food and non-food purposes. Further, successful generation shifts may bring significant synergetic effects. First, with successful generation shifts a larger share of agricultural land remains in production, thus contributing to the goal of maintaining (or expanding) farming activities in Sweden. Thereby, also the ability to secure biomass supplies for both food and non-food applications would be strengthened. Second, successful generation shifts make it possible to avoid a development where agricultural land accumulates in the hands of a few owners. Avoiding this development, in turn, could enable the employment of more environmentally friendly means of production in conventional agriculture, as it counters a development toward increasingly large and industrial production units. Lastly, successful generation shifts may bring with them a change in attitudes and mindsets, offering an opportunity to do things differently. This is perceived as a way to support goal attainment in terms of converting farmland to regenerative production.

5.3.3 Trade-offs and synergies across bio-based economy sectors

Several synergies and trade-offs may result from interactions across the forestry and agricultural sector. In general, land was recognized as a connecting variable, where the expansion of forest or agricultural land, in theory, could entail compromising the potential to maintain or expand land-use in interlinked sectors. Interestingly, the connection was solely brought up in relation to goal attainment in the agricultural sector, but not in relation to the forestry sector. This might indicate different perceptions among the experts belonging to these different sectors (Papers II and III). Trade-offs may also result from promoting more controversial transition pathways in the bio-based economy. Such transition pathways might negatively affect public and political support, and hence reduce the potential for goal attainment in other areas of the bio-based economy. One such, potentially controversial, pathway is to promote the production and use of crops for non-food biomass applications in the agricultural sector, which is subject to ongoing and unresolved debate (Fischer et al., 2009; Kline et al., 2017). Moreover, interventions aiming to reach specific goals might bring with them trade-offs, stressing the importance of assessing trade-offs in the implementation stage (as a complement to analyzing the trade-offs arising from goal progress). One example, as previously mentioned, is the use of environmental taxes (or other policy instruments that are politically sensitive). With environmental taxes (e.g., making the intensive use of fossil-based and mineral resources relatively more expensive), the bio-based economy concept might become increasingly sensitive, ultimately creating a barrier to the formation of a shared understanding of the concept. In terms of investments in evaluation and follow-up, there is a perceived trade-off in ensuring proper monitoring and evaluation of bio-based economy developments on the one hand, and support for and investment in innovation for the bio-based economy on the other. The administrative burden that comes with evaluation measures is suggested to inhibit the ability and willingness of actors to innovate in the bio-based economy (Papers II and III).

One example of synergetic effects across sectors is related to developments that build legitimacy. If actions promoted by the forestry sector under the bio-based economy umbrella are seen as legitimate by the public, this could lead to stronger political support for the concept. Political support, in turn, may enable continuous actor dialogues around the concept. The bio-

based economy was described as a neutral ground for actors to come together and discuss environmental issues in the agricultural domain. Thus, these actor dialogues may not only result in greater consensus on the ultimate goals of the bio-based economy, but also in greater environmental awareness in the agricultural sector (Paper III). In this way, actions in the forestry sector might indirectly support the goal of achieving more environmentally friendly practices within conventional agriculture.

Paper V presents the result of identifying and analyzing trade-offs and synergies across sustainability goals promoted by different sustainability initiatives, as outlined in Chapter 4. Indirectly, this analysis demonstrates how trade-offs and synergies play out across sectors relevant to the bio-based economy (in this case linked to the energy, waste management, and forestry sectors). In addition, some more general lessons can be learned from the analysis. For example, Paper V emphasizes that disaggregation and long-term time horizons are crucial for uncovering synergies and trade-offs across sectors and warns against generic inferences about goal interactions. The results also indicate that it may be difficult to find all-encompassing and coherent policy strategies that span multiple sectors. This is due to internal and external goal conflicts seemingly inherent in the formulation of different sustainability initiatives.

5.4 Does the bio-based economy provide a viable pathway to sustainability?

Papers I, II, III, and V provide diverse perspectives on what the bio-based economy implies for sustainability and highlight that this relationship is dependent on the implementation process and local conditions. Generally, however, it seems that in a bio-based economy business-as-usual scenario, the bio-based economy results in sustainability outcomes that align with the weak sustainability paradigm. According to the notion of strong sustainability, such developments could, in the worst case, be detrimental to sustainability as they accelerate root causes of sustainability issues (e.g., patterns of unsustainable exploitation of biological resources) (Paper I).

Are there alternative ways of thinking around the bio-based economy, questioning the business-as-usual logic? The results suggest that the bio-based economy could, theoretically, develop in a way that promotes goals, strategies, and outcomes in line with strong sustainability (Papers II, III, and V). Even though the frames of the weak and strong sustainability paradigm were not formally employed to analyze the CLDs in Papers II and III, some goals stand out as being more closely linked to the principles of strong sustainability. These goals include the aspiration to achieve greater diversity in the forestry sector, and the goal to facilitate a shift to regenerative production in the agricultural sector. These goals align with strong sustainability on the basis that they promote ecological and social values, and place ecosystem functioning at the core of the management of biological resources, thereby challenging dominant industrial modes of production (Papers II and III). In the regional-scale case study, the potential of the bio-based economy to contribute to strong sustainability in terms of promoting closed-loop production systems and protecting critical natural capital was highlighted (Paper V). At the same time, the results from the numerical modeling carried out in Paper V suggest that simultaneously realizing multiple goals belonging to strong sustainability may be difficult. Building closed-

loop production systems might require changes that negatively affect the ability to maintain critical natural capital and vice versa. Hence, the bio-based economy is not self-evidently sustainable, and the prospects of finding coherent pathways that promote strong sustainability are specifically uncertain and in need of further exploration.

6. Discussion

6.1 Theoretical perspectives

The following sections place the results in a wider theoretical context, building on the overarching objectives of the thesis. The first section focuses on the objective of providing a contextual and operational understanding of the Swedish bio-based economy. The subsequent section puts the identified trade-offs and synergies into a broader research context. Finally, the results related to the relationship between the bio-based economy and sustainability are contrasted with previous research findings.

6.1.1 Characteristics of the Swedish bio-based economy

The way the bio-based economy is conceptualized, understood, and operationalized is context-dependent, as highlighted in scientific articles (McCormick and Kautto, 2013; Mukhtarov et al., 2017; Staffas et al., 2013) and as demonstrated by case study research (Juan et al., 2019; SEI, 2020). The results provide an integrated analysis of the transition to a bio-based economy, based on the perceptions of different actors in a Swedish context (Papers II and III), thereby adding to existing conceptualizations of the bio-based economy. The formal bio-based economy strategy in Sweden is the research and innovation agenda published by Formas in 2012 (Formas, 2012). The Formas strategy focuses largely on (i) increasing biomass production and consumption to phase out fossil-based resources, and (ii) creating new products and uses for biomass materials. Sustainability is seen as a pre-requisite for the bio-based economy, but not as a goal in itself. The goals and interventions elicited in Papers II and III focus primarily on (i) building a viable agricultural sector over time, (ii) achieving sustainable practices in the agricultural sector, (iii) enabling greater diversity in both agriculture and forestry, (iv) making the existing industrial mode of production in forestry more profitable, innovative and resource-use efficient, and (v) on creating stronger public and political support for the bio-based economy concept. Thus, while partly overlapping, clear differences between Papers II and III and the goals promoted by the Formas strategy can be identified. These include differences in scope, focus, and in terms of what constitutes a goal or a means to an end.

Papers II and III add to a growing body of literature that explores stakeholder visions of the bio-based economy, moving beyond official strategies (German Bioeconomy Council, 2015b; Hansen and Bjørkhaug, 2017; Hausknost et al., 2017; Lynch et al., 2017; Meyer, 2017; Scordato and Bugge, 2019; Sleenhoff et al., 2015; Vainio et al., 2019). As in these studies, the results from Papers II and III point to the dissimilarities in visions across stakeholder groups, and to the discrepancy between formal, official visions or strategies, and stakeholder visions.

Chapter 2 outlines four coinages of the bio-based economy (i.e., the biotechnology vision, the bioresource vision, the bio-ecology vision, and the bio-based economy as a new form of capitalism coinage). This thesis employed the definition of a bio-based economy provided by the European Commission (2018), thereby to a large extent excluding the biotechnology vision of the bio-based economy from the analysis. Therefore, it might not be surprising that the goals elicited in Papers II and III did not fall primarily within the biotechnology or the bio-based

economy as a new form of capitalism coinage. However, the goals fit within the understanding of the bio-based economy promoted by the bioresource vision as well as the bio-ecology vision. Specifically, the goal to advance the existing configuration of the forestry industry (e.g., by increasing its innovation capacity and resource-use efficiency) (Paper II) and the goal to make conventional agricultural production more sustainable (e.g., in terms of reducing the intensive use of resource inputs) (Paper III) fit well within the bioresource vision of the bio-based economy. In contrast, the goal to achieve greater diversity in the forestry sector (Paper II) and to facilitate a shift to regenerative agriculture production (Paper III) align with the emerging bio-ecology vision. Thus, the results indicate that tensions and differences in understandings of the bio-based economy observed elsewhere (e.g., in an EU context) exist also in Sweden. Given the broad reach of the bio-based economy, it may not be surprising that the views on the goals of a transition process differ. However, this further stresses the need to include a broad range of stakeholders in the analysis of potential transition pathways, as the bio-based economy remains a contested and diverse concept.

The present thesis builds on theories of non-linear dynamics (D'Alessandro, 2007; Dokoumetzidis et al., 2001; Espinosa and Walker, 2011; Hjorth and Bagheri, 2006). The results indicate that the goals of the Swedish bio-based economy are coupled and interacting in a transition process. The results also suggest that, based on these configurations, leverage points for interventions may be identified (Hjorth and Bagheri, 2006). Finally, the results stress the endogenous point of view (Richardson, 2011), implying that goal attainment is governed by internal feedback processes and not exogenous factors. Case studies may contribute to theory in different ways, on a continuum from theory development to theory testing (Ridder, 2017). The specification of the relationships presented in Papers II, III, and V may contribute to early stages of theory building and development. Specifically, they may contribute to building integrated, systemic, and causal theories of change toward realizing the goals of the bio-based economy in a Swedish context. Such theories contrast views and studies of the bio-based economy that employ a reductionist and linear perspective on the transition process. For example, the results from the Norrköping case (Paper V) can be contrasted with previous research and projects exploring the emerging industrial symbiosis network in the area (Berlina et al., 2015; LiU, 2020). These studies support integration by analyzing material and energy flows, and how these flows link different actors in the industrial symbiosis network. Nevertheless, these studies do not take a feedback perspective, thereby missing out on potential dynamic and non-linear effects over time.

6.1.2 Identifying and understanding trade-offs and synergies

The results highlight several trade-offs that may arise as a result of how goals interact in a transition process. Previous research on the bio-based economy addressed the topic of trade-offs in different ways. There are studies that mention the need to account for trade-offs in a transition process, while not providing in-depth assessments of the nature of these trade-offs (see e.g., McCormick and Kautto, (2013)). Other studies bring specific examples of what these trade-offs may look like. Re-occurring examples include the need to address land-use conflicts, as well as the need to make priorities in how to allocate biomass between different uses (Choi

et al., 2019; Hertel et al., 2013; Issa et al., 2019; Lewandowski, 2015; McCormick, 2014; Meyer, 2017). A specific example of how such discussions have been unfolding is provided by the food versus fuel debate, centered on the trade-offs and potential negative consequences of increasing the production of energy crops (Kline et al., 2017; Rosegrant et al., 2008; Solomon, 2010). At the core of the food versus fuel trade-off is the limit to arable land, but the debate also links to issues of equity and justice. For example, expanding the production of energy crops might drive an increase in food prices, specifically affecting the poor (Cassman and Liska, 2007). In general, growth in the global demand for biomass, in combination with the increasing number of interventions using land and biomass to meet environmental ends (e.g., biodiversity conservation, carbon sequestration, or offsetting), might result in adverse impacts. These include land grabs (or “green grabs”) and displacement of local communities (De Schutter, 2011; Ernsting, 2014; Fairhead et al., 2012; Scheidel and Work, 2016). Another trade-off mentioned in the literature on the bio-based economy links to the long-standing debate on the potential conflicts between environmental and economic goals (McCormick, 2014; Philippidis et al., 2016).

Finally, in addition to studies that mention the need to account for trade-offs in passing, or studies that provide specific examples of trade-offs, it is possible to find studies that go further and suggest potential ways to address these trade-offs, once they have been identified (Hildebrandt et al., 2014). Yet, how to address trade-offs and set priorities seem to be prevailing issues in the bio-based economy, insufficiently covered by the many strategies and policy agendas aiming to facilitate a transition process (Asveld et al., 2011; Dubois and Juan, 2016; German Bioeconomy Council, 2015a).

The early stage of the “field” of bio-economy research, or the general lack of integrated analyses, may limit the ability to understand and address trade-offs in the transition to a bio-based economy. Another potential issue is that relevant information may be found largely in research areas that are not yet explicitly linked to the bio-based economy discourse and debate. Relevant knowledge may be found, for example, in the proposed field of agricultural trade-off analysis (Kanter et al., 2018; Klapwijk et al., 2014), sector-specific research on forest management (Eckerberg and Sandström, 2013; Sandström et al., 2016; Wang and Fu, 2013), and bio-energy research (McKechnie et al., 2011; Söderberg and Eckerberg, 2013). Another potential barrier to efficiently identifying and addressing trade-offs may be the following: If thinking around the bio-based economy is based in the weak sustainability paradigm, the issue of trade-offs is not so pressing. The notion that different forms of capital are substitutional implies that less attention needs to be paid to absolute limits.

Against this background, the results in the present thesis add to the ongoing scientific debate on trade-offs in the bio-based economy, by re-emphasizing the need to address critical resource limits. Previous studies focusing on the limited nature of biomass in a Swedish context include Börjesson (2016), exploring biomass potential in a growing bio-based economy and how trade-offs may occur in relation to the Swedish environmental quality objectives. The trade-offs linked to land and biomass allocation found in Papers II, III, and V add to existing knowledge by detailing how these trade-offs are created and where in the system to intervene to address

them. However, the results in the present thesis also bring new categories of trade-offs to the discussion, linked to resource inputs, preconditions, social dynamics, and different industry development pathways. Nonetheless, these are not exhaustive. Some important dimensions that may be missing from the analysis in Papers II, III, and V include the distribution of these trade-offs (i.e., who benefits and who loses under different scenarios), and potential negative geographic spill-over effects that may arise as the Swedish bio-based economy unfolds.

In terms of synergies, the win-win rhetoric of the bio-based economy is to a large extent based on assumptions about prevailing synergies. By increasing the use of biomass, the mainstream bio-based economy narrative presumes that a fossil-free, competitive, equal, ecologically friendly, and socially just society will follow (EU, 2012; OECD, 2009; The White House, 2012; Viaggi, 2018). As previously stated, the promissory discourse on the bio-based economy has met criticism (Birch and Tyfield, 2012; Petersen and Krisjansen, 2015). Nevertheless, there are synergies that may be exploited, and Papers I, II, III, and V outline some of these. They also provide a detailed account of how these synergies arise, and how they can be leveraged. Thus, the results add to the existing knowledge on the potential co-benefits generated by the bio-based economy.

Further, Paper V adds to a small number of papers that address interactions, trade-offs, and synergies across the bio-based economy and the SDGs. Previous studies on interactions between the bio-based economy and the SDGs have assessed these linkages at different scales and with different purposes, but most often at an aggregate level. For example, by using tools for scenario analysis, Heimann (2018) finds that 11 of the 17 SDGs are influenced by the bio-based economy. The paper states that the effect of the bio-based economy on the SDGs depends on how the implementation of the bio-based economy is carried out. In a worst-case scenario, the implementation might impede the attainment of the SDGs, for example in relation to SDGs 13–15. It is argued that regulation, policies, and investments specifically targeting sustainability are needed for the bio-based economy to positively contribute to the fulfillment of the SDGs. It is further stressed that these policies are not in place in a business-as-usual bio-based economy scenario (*ibid*). El-Chichakli et al. (2016) outline how the bio-based economy is particularly relevant to the attainment of 11 SDGs. The authors call for international research collaboration and new research support programs and stress the need to measure the bio-based economy's contribution to the SDGs. Further, they emphasize a general need to design interventions that strengthen the link between bio-based economy initiatives and multilateral policy processes (i.e., the 2030 Agenda, but also treaties such as the Paris Agreement and the Aichi biodiversity targets). They also propose that education programs should be adapted so that they meet the knowledge requirements of the future bio-based economy. Also Schütte (2018) focuses on knowledge generation, proposing that research policy needs to be adapted so that it strengthens the ability of the bio-based economy to contribute to the SDGs. Finally, Issa et al. (2019) find that the bio-based economy could primarily contribute to SDGs 7, 9, 11, 12, and 13, but emphasize trade-offs linked to land-use. The findings in the present thesis, while not comparable in scope or scale to previous studies on the interactions between the bio-based economy and the SDGs, agree that the presence of both trade-offs and synergies are largely dependent on the way the bio-based economy is implemented. Additionally, and perhaps

differently to previous studies, Paper V assesses how progress on the SDGs affects the possibility of making progress on the bio-based economy, thus not solely paying attention to the reverse relationship.

Another general lesson learned from the results is that there is a need to analyze trade-offs and synergies in their larger systemic context. Overall impacts cannot be understood when reducing the analysis to one trade-off or synergy at the time. Different synergies can reinforce each other. Various trade-offs may have spill-over effects, triggering other sources of conflict. Alternatively, synergetic effects in one part of the system may compensate for a trade-off elsewhere. To date, there are seemingly few studies that address these systemic impacts in a bio-based economy context. However, in the broader domain of sustainability transitions research, related studies may be found that assess the interplay of different trade-offs and synergies, see for example Pedercini et al. (2019).

Finally, a note on methods in relation to the identification and analysis of trade-offs and synergies. Paper IV, by examining the parallel 2030 Agenda, uncovers several possibilities for finding new combinations of methods for integrated analysis. The results depict how different methods can be used to address specific aspects of integration, which helps when seeking to identify or mitigate trade-offs or to exploit synergies. Based on the available literature, it seems that dedicated analyses of trade-offs and synergies related to SDG interactions have come relatively far (Paper IV). Thus, this field could potentially inform efforts to identify trade-offs and synergies also across interconnected goals in a bio-based economy context. Additionally, Paper V shows that the understanding of trade-offs and synergies provided by different methods varies significantly (even when applied to the same, well-bounded case). This highlights the importance of the choice of method. However, it may also call for larger attention devoted to mixed-methods analysis when addressing complex systems and the diverse types of trade-offs and synergies found within these.

6.1.3 Contributions of the bio-based economy to sustainability

The literature review places the current understanding and development of the bio-based economy firmly within the weak sustainability paradigm (Paper I). Also, the numerical analysis demonstrates the difficulty in realizing strong sustainability goals simultaneously (in this case in terms of achieving closed-loop production systems and maintaining critical natural capital) (Paper V). These findings are in line with previous work exploring the link between the bio-based economy and sustainability. For example, Loiseau et al. (2016) argue that the bio-based economy (understood as biotechnology and biomass processing) holds a view of capital as highly substitutable. D'Amato et al. (2017) find that the bio-based economy has a strong economic growth imperative and technology focus. Further, the authors stress that limited attention has been given to the potential negative impacts of an increasing demand for biological resources. Ramcilovic-Suominen and Pölzl (2018) find that the bio-based economy aligns with weak sustainability and that it encompasses a view of the relationship between humans and nature as highly utilitarian and instrumental. Another example is provided by Vivien et al. (2019). In their study, they distinguish between the origins of the concept (here

understood as the seminal work on the bio-based economy by Georgescu-Roegen) and the modern-day understanding of the term. The distinction is made on the basis that the original understanding of the bio-based economy concept aligns with strong sustainability, while the modern-day understanding does not.

Complementary to these findings, the results from Papers II, III, and V provide additional, and slightly different perspectives, on the bio-based economy and sustainability. First, the results include transition pathways that promote goals and practices that fit within the realm of strong sustainability (e.g., regenerative agriculture and diversified forestry) (Papers II and III). Second, the results highlight that, theoretically, also less transformative goals might be able to adhere to strong sustainability under certain conditions, such as remaining within critical natural resource limits (Paper V). These findings slightly alter the understanding of the bio-based economy as a business-as-usual scenario that results in weak sustainability outcomes.

In summary, Papers I–V do not provide a final answer to the question of whether the bio-based economy can contribute to sustainability in a way that aligns with both weak and strong sustainability principles. Instead, the results point to theoretical potential and practical difficulties. Nonetheless, the results shed light on tensions inherent in the term sustainability itself, and how these tensions then apply also to the bio-based economy. In doing so, the results may add to, and clarify, some of the seemingly complementary (Bugge et al., 2016), contradictory (Pfau et al., 2014), and contested (Birch et al., 2010; Brunori, 2013; Kröger and Raitio, 2017; Levidow et al., 2012) views on how the bio-based economy can contribute to sustainability.

6.2 The bio-based economy in practice

The following sections outline practical implications following from the operational and contextual understanding of the bio-based economy proposed in this thesis, and from the identified trade-offs and synergies. This is followed by practical implications drawn from the different views on the ability of the bio-based economy to contribute to sustainability.

6.2.1 Understanding and managing the transition to a bio-based economy

There is an ongoing discussion on the multiple definitions and divergent perceptions of the bio-based economy (Asveld et al., 2015; Bugge et al., 2016; Lynch et al., 2017; Sijtsma et al., 2016). The results in the present thesis indicate that there are differences in perceptions also among Swedish stakeholders (Papers II and III). What does this imply in practice? Several difficulties may arise with a lack of shared understanding of the term, as highlighted both in this thesis (Papers I and II) and in previous research and policy debates (Ahmad, 2016; ENRD, 2019; European Commission, 2017; Pavone and Goven, 2017). On this basis, there may be a need for decision-makers and policy-makers in a Swedish context to move the discussion toward broader consensus, both in terms of what the goals of the bio-based economy are and on strategies for realizing these goals. Consensus could be built, for example, by further strengthening existing stakeholder dialogues and partnerships. Similar conclusions have been

made in other national contexts. For example, Birch (2019), after examining bio-based economy policy visions in Canada, writes:

“My conclusion is that current Canadian bio-economy policy frameworks are fragmented as a result of the emergent and contested nature of the Canadian bio-economy policy visions, meaning that the future policy and institutional changes deemed necessary to promote the bio-economy are currently stymied. The policy implications of this conclusion are that Canada will need a single, coherent bio-economy vision which a majority of policy stakeholders can buy into before it can develop a policy strategy to promote and support the bio-economy.” (Birch, 2018, p. 81)

However, some questions arise that may challenge the convergent thinking route. First, given the broad reach of the term, is it possible to find a common understanding and definition of the bio-based economy (globally, nationally, regionally, locally)? Would such a definition run the risk of being too broad, accelerating the issues around the win-win rhetoric (Richardson, 2012) surrounding the concept? Would it, as in criticism of the previous EU-definition of the concept (Brunori, 2013), be so broad that it is impossible to identify key characteristics, opportunities, and risks? And alternatively, under the assumption that it is possible to reach agreement, is it necessary? Another way for decision-makers and policy-makers to approach the bio-based economy could be to abandon the search for agreement altogether. Instead, efforts could be placed in (i) being specific about what the diverse goals of the bio-based economy are, (ii) identifying overlaps and synergies as well as trade-offs and conflicts across these goals, and (iii) having an established and agreed-upon process for addressing these synergies and trade-offs when developing implementation strategies for the bio-based economy. Thus, as opposed to the first option (working toward agreement on the *what*), the second option would allow for different views on the goals, while instead placing emphasis on having a broad-reaching agreement on *how* to make priorities.

The results present several direct, indirect, and feedback interactions between the goals of the bio-based economy. If these structures are useful representations of the real-world systems underpinning the transition to a bio-based economy, they provide several opportunities for supporting strategy development. First, the proposed interactions allow for finding structural similarities across different parts of the bio-based economy. These similarities may be found in driving reinforcing feedback loops, balancing feedback loops, or combinations of the two, together governing goal attainment. Such generic system structures allow for learning across domains (Kim and Anderson, 2007). Second, a structural understanding allows for determining how connected a given goal is. Highly connected goals merit specific attention due to the way they create systemic impacts. However, less connected goals may also require specific consideration as they will not benefit from progress being made on other goals, but need dedicated efforts in order to be realized (Weitz et al., 2017). Third, the structural understanding may help find and establish novel partnerships, beyond traditional decision-making configurations (Nilsson et al., 2018). The existence of coherent goal clusters across sectors indicates that a diverse set of actors may benefit from collaborating.

Further, after having developed an understanding of the interactions across goals, additional information of relevance for decision-making can be elicited. As described in Chapter 2, this information includes sources of lock-ins, unintended consequences, leverage points, ambiguity, and behavior over time. The analysis of lock-in effects points to sources of resistance to change, and where these sources are found. The identification of unintended consequences resulting from certain actions highlights the need to carefully design interventions to minimize such outcomes. Leverage points are places to intervene in a system, and merit prioritization as they create opportunities for efficient goal attainment. The analysis of system structures may help find new, and perhaps unexpected, leverage points. Further, the results show that different methods generate what could be perceived as ambiguous information about goal interactions. Thus, in decision-making and policy-making, generic statements about goal interactions should be treated with caution. The reading guide (Paper IV) suggests a way to begin to structure the literature on goal interactions and may be used as a practical tool to navigate the existing body of knowledge. Another finding of relevance for decision-making is how the system structures, and the resulting dynamic behavior over time, stress the need to deal with simultaneous change (occurring in different parts of the system at the same time) as well as the need for sequencing (where some interventions or goals are prerequisites for successfully implementing other goals).

In summary, if bio-based economy goal attainment is indeed governed by feedback processes, as suggested by the results in the present thesis, a linear approach to planning will not work (Ben-Eli, 2018; Hjorth and Bagheri, 2006) as the systemic impacts of different interventions would not be fully understood. Feedback also has implications for agency, related to the endogenous point of view (Richardson, 2011). The endogenous point of view stipulates that when addressing an issue, all relevant variables that explain the problem must be included within the boundary of analysis (Yearworth, 2014) instead of seeking explanations that are driven by external (exogenous) forces, outside the control of implementing actors. A feedback system is in principle a closed system, where the dynamics arise as a result of endogenous structures (Richardson, 2011). Thus, uncovering feedback structures in the context of the bio-based economy implies a higher degree of agency to act. This as transition pathways unfold as a result of dynamics of which decision-makers and policy-makers are an integral part, and not as a consequence of external forces.

6.2.2 Dealing with trade-offs and synergies

The presence of both trade-offs and synergies (Papers I, II, III, V) has practical implications. In a sense, the transition to a bio-based economy in Sweden is still in the early stages, or in respect of some goals, not yet occurring (Papers I, II, III) (Ahmad, 2016; Mistra and SFIF, 2016). The early stage of implementation offers an opportunity to act regarding the identified trade-offs and synergies, implying that dedicated efforts might result in more coherent interventions and efficient goal attainment (Nilsson et al., 2012). Trade-offs and synergies are found internally within the sectors of the bio-based economy, across sectors, and between parallel sustainability initiatives and agendas. Thus, the need for collaboration, participation, and deliberation is evident.

Yet, while collaboration, participation, and deliberation are desirable and necessary to deal with both trade-offs and synergies (Juan et al., 2019), many questions remain. What are barriers to efficient, and broad-reaching collaboration in the Swedish bio-based economy? What types of participation have generated successful mitigation of trade-offs and leverage of synergies in past bio-based economy efforts? What should the guiding principles be? And under what conditions are deliberative approaches perceived as legitimate? Previous research indicates that past efforts may not have been sufficiently effective in addressing these questions, in an EU context (Philippidis et al., 2016; Wolfslehner et al., 2020), in Sweden (Andersson and Keskitalo, 2018; Lindahl et al., 2017; Persson, 2013), and generally (Mukhtarov et al., 2017).

6.2.3 Decision-making for weak and strong sustainability

The assessment of the link between the bio-based economy and sustainability, using the weak and strong sustainability paradigms as analytical lenses, provides fundamentally different understandings of this relationship. The results raise several questions for decision-makers and policy-makers. The current understanding of the bio-based economy falls predominantly within the frame of the weak sustainability paradigm (Paper I). If aspiring to continue this development, future policy could include efforts to (i) implement market-based solutions, (ii) support research and innovation, (iii) establish new partnerships (i.e., between public and private actors), and (iv) change regulatory frameworks to remove barriers to the further exploitation of biological resources (Pelenc et al., 2015; Williams and Millington, 2004) (Paper I).

If the assumptions of the weak sustainability paradigm hold is to a certain extent an empirical question (Ekins et al., 2003). These assumptions include placing trust in that decoupling of growth in economic activity from material and energy use is possible, and that degradation of ecosystems around the globe does not pose a threat to human welfare and wellbeing (Cabeza Gutes, 1996). Two issues may be considered in respect to these assumptions. First, there is not much empirical support for decoupling, neither in absolute nor relative terms (Hickel and Kallis, 2019; Parrique et al., 2019). Second, the bio-based economy differs from parallel concepts (e.g., the circular economy) in that it explicitly links the provision of services and goods to the biophysical basis of the economy. If critical natural capital is eroded, what is left to build a bio-based economy on? Promoting a future development in line with strong sustainability would entail using a different logic in the implementation phase, in line with more transformative goals (Papers II and III) or the so-called bio-ecology vision (Bugge et al., 2016). Decision-making and policy-making based on this alternative logic would promote interventions based on a precautionary approach (Antrim, 2019; O’Riordan and Jordan, 1995), and implement measures to protect and maintain critical natural capital (Dietz and Neumayer, 2007; Pelenc and Ballet, 2015). Adhering to the strong sustainability paradigm would also mean acknowledging the risk that the functioning of the biosphere and human wellbeing might be threatened under a bio-based economy business-as-usual scenario (Spash, 2017; Vivien et al., 2019).

Another practical implication is that the uncertainty regarding the sustainability of the bio-based economy may, in itself, constitute a barrier to integrated decision-making. One way to overcome this barrier is to be more explicit about the definition of sustainability employed when implementing the bio-based economy. Otherwise, the root causes of the polarized bio-based economy debate might not be uncovered and addressed.

6.3 Generalizability of results

What can be learned from the Swedish case? How generalizable are the results? This thesis is based on the premise that the goals of the bio-based economy differ across contexts. Thus, the Swedish bio-based economy may be fundamentally different from bio-based economies in other national settings. What may be generalizable, however, is the approach used to translate the global bio-based economy concept to a specific decision-making context. Additionally, systems analysis offers an opportunity to identify generic system structures (Kim and Anderson, 2007; Sterman, 2009). Some of the system structures governing goal attainment identified in the present thesis may be generic, relevant also in other decision-making settings.

There is another way in which the Swedish case can be used to inform transition processes in other contexts. Sweden has been understood as a country with favorable preconditions and an enabling environment for the bio-based economy. Nonetheless, not even in this country context is the transition process seemingly straightforward. There are trade-offs, polarization, divergent views on desirable futures, spill-over effects, and governance issues that have not been addressed. Further, much is yet to be known about the systemic impacts that may arise as the bio-based economy unfolds. Facilitating change in other contexts, with less favorable preconditions, might therefore prove challenging.

On the other hand, considering the multiple goals of the bio-based economy, it is not evident what constitutes favorable preconditions. Some of the premises highlighted as beneficial in Sweden could potentially also halt a transition process. One example is the vast forest resource and the long industrial history of managing this resource. On the one hand, these factors provide a solid basis for the bio-based economy (Formas, 2012). On the other hand, they create a situation where previous investments and developments create lock-ins that may inhibit transformative change (Paper II) (Hansen and Coenen, 2016; Hodge et al., 2017). Other national contexts, less likely to experience lock-in due to past events, may find larger opportunities to facilitate goal attainment despite what might first come across as theoretically less beneficial preconditions.

In summary, while the Swedish case offers insights that may inform change elsewhere, case- and context-specific conditions must be carefully assessed when aiming to understand and facilitate a transition process. Sustainability transitions are explained by the interplay of a large number of factors (EEA, 2018b; Hansen and Coenen, 2013; Klitkou et al., 2015), where place matters (Hansen and Coenen, 2013; Truffer and Coenen, 2012), and where frames for exploring transitions dynamics may not be transferable (Hansen et al., 2018).

7. Reflections on the research approach

There is an ongoing debate on the methodological needs that research on sustainability transitions should respond to (Köhler et al., 2019, pp. 18–21). The following sections reflect on the research approach used in this thesis, on some of the considerations that formed it, its strengths, and the limitations resulting from the way the research was carried out.

When initially approaching the bio-based economy concept, a first realization was its broad reach, lack of precise meaning, and evolving nature. Instead of ignoring these characteristics, a decision was made to try to develop an approach able to deal with the plurality of views on the meaning of the term. The research design was allowed to emerge during the process, similar to what has been described by Strauss and Corbin (1998) as a flow of work. The final approach made use of multiple data sources and methods, as a means to achieve integration. The aim was for the combination of methods to be able to (i) deal with dynamic complexity; (ii) integrate dynamic interactions across systems/sectors, scales, and time; (iii) recognize the role of power in shaping both problem definitions and potential future pathways; and (iv) take seriously the mental models and values held by a broad group of actors affecting and affected by the evolving bio-based economy. The underlying premise was that by developing such an approach, a better understanding of goal interactions and their sustainability implications would be achieved.

7.1 Strengths of the mixed-methods approach

Drawing on multiple data sources, such as the scientific literature, gray literature, and expert knowledge, in combination with using stakeholder identification and engagement tools, semi-structured interviews, and document analysis, allowed for flexibility. For example, document analysis is described as an efficient, exact, and stable method of analysis, often with broad coverage and availability (Bowen, 2009). This flexibility made it possible to elicit and analyze rich qualitative data and to integrate different knowledge sources. For example, specific attention was given to articulating the goals of the bio-based economy in a Swedish context. This was accommodated using both semi-structured expert interviews (Papers II and III) and by including a “goal screening” stage in the analytical framework used in the Norrköping case (Paper V). Hence, critical discussion on how global agendas can be understood at the national, regional (sub-national), or local level, according to different stakeholder groups, was allowed. Additionally, engaging experts in the formulation of research questions, data collection, and validation supported the integration of actors and stakeholders through participation.

Cross-impact analysis, network analysis, CLDs, and numerical system dynamics modeling enabled a structural understanding of goal interactions. The strength of using these methods in combination is that they highlight different aspects of these interactions. Cross-impact analysis provides an understanding primarily of direct, pairwise goal interactions, and is a method able to handle heterogeneity and soft systems knowledge (Weimer-Jehle, 2006). Network analysis complemented this method by providing further detail on the nature of these interactions, for example by giving a visual account of the distribution of trade-offs and synergies across different goals. CLDs are one of many systems-diagramming approaches, next to for example stock and flow diagrams and sub-system diagrams (Sterman, 2009). However, as compared to

other diagramming approaches, their strength lies in providing a clear feedback perspective (Lane, 2008). Thereby they move the analysis from pairwise and chains of interactions (as uncovered by the cross-impact scoring and network analysis) to feedback thinking.

In terms of system dynamics modeling, it has been suggested as particularly useful for analysis of sustainability transitions, due to the ability of the method to account for dynamic complexity in terms of delays, feedback, and non-linearities (Allen et al., 2016; Köhler et al., 2018). In this thesis, using system dynamics allowed for analyzing goal interactions across sectors, sustainability agendas, initiatives, and paradigms, and established a link between the system structure and system behavior. Thereby, the use of system dynamics modeling supported integration not only across sectors or systems but also over time.

Furthermore, CLDs, cross-impact analysis, network analysis, and numerical system dynamics modeling range from being purely qualitative (CLDs) to semi-quantitative (cross-impact analysis and network analysis), to fully quantitative (system dynamics modeling). Thus, they support the integration of different forms of knowledge when exploring goal interactions, able to draw on multiple data sources in this process. The tools were also applied to analyze goal interactions at different levels of aggregation. From the general/global/universal level of goal interactions (e.g., in the use of cross-impact scoring) to detailed knowledge that can provide the basis for implementation (through the assessment of key variables, CLDs, and the numerical system dynamics modeling). Additionally, the methods were applied using different system boundaries and time horizons. This allowed for contrasting perspectives on goal interactions and their sustainability implications. Further, a shared feature of these analytical methods is that they are transparent, able to provide a visual account of goal interactions, which may contribute to critical discussion and learning.

Finally, network analysis had a different, but related, use in the thesis. Using network analysis supported the identification of patterns in how policy challenges, data sources, methods, and conceptualizations of SDG interactions have been approached in the scientific literature (Paper IV). The emerging clusters across these themes may provide a creative space to identify gaps and novel uses of methods. Thus, this analysis, in combination with the analytical framework proposed in Paper V, could support goal attainment in terms of informing future research designs.

7.2 Limitations

Several measures were taken to ensure validity and reliability in the research design, as presented in Section 3.3. Yet, some limitations that merit consideration when interpreting the results remain, as outlined in the following sections. These are linked to data collection and analysis, and to issues of boundary setting and finding the right level of aggregation. Finally, the present thesis aims to contribute to an integrated understanding of the transition to a bio-based economy and what it implies for sustainability. Ultimately, a hoped-for contribution of this knowledge is to support decision-making in the implementation of the Swedish bio-based economy. The final part of this section includes some notes on the barriers to the efficient

uptake of the knowledge generated in the thesis, specifically in terms of the research design and the limited attention to stakeholder learning.

7.2.1 Limitations in data collection

A first potential limitation is the strict inclusion criteria in the literature review conducted in Paper I. The research boundary was drawn so that only studies that explicitly address the bio-based economy were included in the literature sample. However, related and relevant research may be found in other research domains, such as in the case of agricultural trade-off analysis, research specifically focused on forest governance, or in the life sciences. Thus, on the one hand, the strict inclusion criteria were necessary for finding a manageable scope. On the other hand, they may have resulted in a loss of insight into the relationship between the bio-based economy and sustainability.

Second, some consideration should be given to the limited sample size ($n=14$) of experts that provided the empirical data for the CLDs (Papers II and III). The small number of interviewees was motivated by an aim to capture the richness of the qualitative data provided during the interviews. The experts were carefully chosen, where one of the selection criteria was their perceived ability to represent broader actor groups in the bio-based economy. Further, efforts were made to overcome issues of self-exclusion (Lelea et al., 2014), for example by clearly motivating why a given actor was invited to participate in the study. Nevertheless, the results are exploratory, capturing divergent thinking by a limited number of experts, and the resulting CLDs should be understood through that lens.

A third limitation is related to the data collection in Paper IV. Several thematic sub-codes emerged from the literature. These were refined and then used to re-code the sampled literature. Only if sufficient evidence were provided in the main text of a given paper would it be assigned the relevant sub-code. An issue that arose in this process was that not all papers provide sufficient detail in the main body of text to determine if a given sub-code is applicable. This was specifically evident in the case of the sub-codes under the theme “interaction qualifiers” (Paper IV, pp. 7–8). Interaction qualifiers may be overlooked in the article text, as they often result from the choice of method, known to the researchers in the field but perhaps to a lesser extent to others. To address this limitation, the interaction qualifiers were not included in the subsequent step of network analysis. In general, however, it may still be that some papers were not assigned all applicable codes. This warrants attention when drawing conclusions from the co-occurrence network (Paper IV, p. 11), or when making any quantitative claims regarding the distribution of sub-codes in the sample.

A fourth limitation is linked to the data collection for Paper V. In this study, a key component was the system dynamics model and the representation of the local CHP plant. Issues of limited access to data arose, as the power plant has transferred from public to private ownership. Due to restrictions in data provision, data had to be collected from information that was publicly available, or from technical reports on similar plants. Behavioral replication is a key feature of the validation of system dynamics models. This part of the validation became difficult to carry

out due to a lack of time series data on, for example, delivered heat or fuel input. On the other hand, another key component of the validation of system dynamics models is structural validation. This type of validation was possible to carry out to a larger degree due to more open sources of information on the functioning of CHP plants in general terms, as opposed to data on daily operations at a specific site.

7.2.2 Limitations in relation to data analysis

Potential limitations in relation to data analysis are linked to issues of boundary setting and finding the right level of aggregation. Triangulation allowed for working with different boundaries and granularity in different steps of the research, but with each step critical choices had to be made.

Examples of issues of finding the right level of aggregation are found in Papers II and III. The level of detail varied significantly between the interviews serving as the basis for the CLDs developed in these papers. Thus, in the final stages of CLD revision, choices had to be made to find the right level of detail and balance between different parts of the CLDs. Ultimately, this also meant losing some of the information. At the same time, the CLDs are not simplified to the level of a communication CLD, hence they might prove difficult to read for someone who was not involved in the research process. Further, there are some potential issues linked to the meanings of the terms used, related to a stated limitation of CLDs in general – that they sometimes lack precision (Lane, 2008; Schaffernicht, 2010). Agreement on variable names and their meanings were obtained among the participants in the study (e.g., by using the workbook and iterative rounds of revision and feedback). Outside the scope of the study, however, there may be ambiguity in the meaning and use of the terms. For example, regenerative agriculture production encompasses diverse practices such as agro-forestry (Schaffer et al., 2019) and ecological recycling agriculture (Stein-Bachinger et al., 2013), something that is not evident when reading the CLDs. Another example is the goal to employ more sustainable practices in conventional agriculture. Progress on this goal could be supported by a broad range of practices, such as sustainable intensification, no-till farming, or by using less chemical fertilizer. Each of these practices has slightly different implications and such differences are currently overlooked in the CLDs. A final example is the use of terms such as “legitimacy.” The variable legitimacy appeared as central during the interviews, connecting different sectors of the bio-based economy through the build-up of political support. However, legitimacy is a multi-faceted concept (Beetham, 1991) which is not reflected by the CLDs and related analysis. In-depth analysis of dimensions such as how power conforms to established rules, the justification of these rules, and how they shape actions is needed to fully understand the role of legitimacy the transition to a Swedish bio-based economy.

Issues related to boundary setting and granularity were also evident in the quantitative modeling in Paper V. For example, in the goal screening exercise, a limited number of goals (n=7) were included in the analysis restricting it to network diagramming, rather than network analysis. By adding goals to the analysis, a fuller understanding of the systemic impacts of goal interactions

would have been achieved, and the analytical potential of using network analysis tools could have been utilized to a fuller extent (e.g., in terms of calculating different network metrics).

In system dynamics, a stated limitation of the method is the ease of adding elements to the model. This creates a tendency of developing unnecessarily complex models (Meadows, 1979). At the same time, in the general context of modeling sustainability transitions, a tendency of over-simplification has been identified as a potential issue (McDowall and Geels, 2017). Thus, in the system dynamics modeling in this thesis, specific attention was given to including the right level of detail to capture trade-offs and synergies, while keeping the model simple enough to be communicated to decision-makers and policy-makers. Yet, the model could benefit from adding detail in certain parts (e.g., further incorporating energy demand-side dynamics). Further, for each goal, one or more indicators were chosen and integrated into the model. The choice of variables is critical, as it influences the results in terms of the presence of goal synergies and trade-offs. A multitude of indicators could have been appropriate for each goal, but their inclusion was restricted by data availability, time constraints, and a need to not add unnecessary model complexity. Thus, the final set of indicators is applicable and relevant, but not exhaustive. Additionally, the system dynamics model may be biased toward aspects of goal interactions that are easily quantifiable. If the boundaries had been extended to include soft variables, different insights about interactions across the bio-based economy, SDGs, and strong sustainability might have been reached. On the other hand, adding of those elements would have given rise to a larger degree of uncertainty, related to the quantification of soft variables (Coyle, 2000, 1998).

Finally, the combination of methods is not well suited to capture how causal structures change as sustainability transitions unfold. For example, system dynamics is a deterministic modeling approach, where the behavior created by the model is a result of its defined structure. Thus, the interactions between goals over time may be subject to more fundamental changes than the results indicate but capturing such change would require another approach to boundary setting. Specifically, the boundaries would have to include not only current configurations of goal interactions but also hypothesized future causal structures.

7.2.3 Limited attention to stakeholder learning

The thesis supported stakeholder engagement in the framing of research questions, data collection, and validation. However, the combination of methods used in the thesis remains limited in facilitating and evaluating learning among decision-makers and policy-makers, two factors that are critical to bridging science and policy (Smajgl and Ward, 2013). It has been argued that transdisciplinary modes of research are needed to deal with interlinked issues in the sustainability domain (Leemans, 2017; Miller et al., 2014). Such processes include not only a collaborative process of problem framing, engaging both academics and non-academics, but also a strong focus of the research on reintegration and the practical application of the knowledge generated (Lang et al., 2012).

In addition, a dimension that has not been assessed in this research is the implementation of the suggested interventions. The integrative work, supported by different forms of triangulation, does not provide unified answers to how to prioritize among different goals, or how to address critical trade-offs. Previous research has shown that in integrated projects that address both cognitive (e.g., integrated learning and alignment of mental models) and behavioral (e.g., the creation of commitment among participants) aspects of change, a lack of focus on the implementation phase may inhibit goal attainment (Größler, 2007). To inform the implementation of the bio-based economy, greater attention to these aspects might have been beneficial in the research design stage (e.g., by ensuring a higher degree of participation among responsible decision-makers). Now, the lack of such a design step may reduce the ability of the results to guide practice in the reality of the actors responsible for developing implementation strategies in a Swedish context.

Linked to issues of stakeholder learning, evaluation of learning, and the implementation and reintegration of the knowledge generated in the thesis is the actor dimension. The thesis has focused explicitly on the causal structure of the systems under study, but less on the parallel structures of actors governing change in these systems. By the study of such actor networks, integration could have been supported by addressing a critical barrier to integrated governance: siloed institutional configurations.

Aside from limited attention to active learning, evaluation of learning, and actors, there are other potential barriers to the efficient uptake of the results of the thesis. One example is linked to the numerical modeling in Paper V. It employs a long-term time perspective, which may not align well with the short-term time horizons of decision-making (Meadows, 1979). Another potential barrier is linked to the CLDs. In Papers II and III, the aim was to allow for analysis of transition pathways based on the CLDs. To achieve this aim, a relatively high level of detail was kept in the process of developing the CLDs. However, this could become a barrier for communication and interpretation for someone not familiar with the CLD connotation. Additionally, as discussed also by Dawson (2019), the format for publication in traditional academic journals creates limitations on how CLDs can be represented and explained, potentially constituting a barrier to learning and disseminating the results to the scientific community. Finally, the proposed combination of methods in the present thesis is time consuming and resource intense, perhaps not easily applied in more participatory modes of research.

8. Future research

Many future research avenues could further contribute to an integrated and systemic understanding of the transition to a bio-based economy, both in the Swedish case and generally. The following sections outline some suggestions, focused on refining, comparing, and expanding on the results generated in this thesis.

8.1 Revisit, refine, and endogenize causal system structures

Further work based on the results in this thesis could evolve by revisiting and refining the CLDs and the BBE-SDG model. This could include specifying under what conditions proposed causal relationships hold and probing redundant or missing structures. A central aim when developing CLDs and numerical system dynamics models is to endogenize all variables necessary to explain the issue of interest. Based on the findings in Papers II, III, and V, specific aspects that could be investigated and integrated to a larger extent include the feedback processes governing the supply of labor for regenerative production; the social dynamics playing out between farmers in the shift to regenerative production; dynamics of collaboration in the agriculture supply chain; the build-up of interest and ability to support innovation for environmentally friendly practices in conventional agriculture (which would entail exploring the role of different ownership models); dynamics governing farmers' decisions to target new markets (where suggested variables affecting this decision include the access to capital, willingness to take risk, access to knowledge, and the farmer identity primarily as a food producer); and, finally, further integrating the dynamics governing the expansion of forest land and urban sprawls, respectively. Moreover, specific attention could be directed toward finding additional cross-sectoral interactions and how these are perceived among different stakeholder groups, as such dynamics play a critical role in a transition process. One way to do this could be to use group model building (Vennix, 1994) or mediated modelling (Antunes et al., 2006; Belt, 2004), engaging a larger number of experts in the process. Such initiatives could be coordinated from research institutions, but might as well be led by stakeholders under initiatives such as BioInnovation (BioInnovation, 2019) or the Swedish National Forest Program (Government Offices of Sweden, 2018).

Moreover, Papers II and III provide a list of suggested interventions. The proposed interventions are unequally distributed across the various goals related to the bio-based economy. They form different pathways and bring with them a number of associated questions and uncertainties (Paper II p. 12 and Paper III pp. 17–18). Exploring these interventions in more depth, with the people who have a stake in these decisions, could provide a useful direction for future research.

Finally, efforts to further quantify the CLDs could be made. Paper V is a step in that direction, but given the breadth of the CLDs, there is plenty of room to build on this empirical and quantitative analysis. Simulation-based analysis may help identify critical thresholds, the direction and relative strength of key feedback loops, and the magnitude of change needed to realize the goals of the bio-based economy. Additionally, the quantification step may allow for testing of the suggested interventions.

8.2 Comparative studies on goal interactions in a transition process

The results in this thesis derive from analyzing bio-based economy developments within a sector-specific and national context. Yet, commonalities in goal interactions, hindrances, and opportunities to support a transition process may be found in other contexts. Thus, an avenue for future research could be to design and carry out comparative studies. Potential frameworks and tools for finding structural similarities or differences include the Multi-Level Perspective (MLP) framework (Geels, 2019). The MLP framework is widely used to analyze transitions as they emerge from protected niches in larger landscapes and environments. Its potential in shedding new light on the integrative challenges of the bio-based economy has been highlighted previously (Marsden and Farioli, 2015). Comparing different applications of the MLP framework to reveal similarities and differences across contexts may enable learning, for example in relation to the development of bio-clusters (Hermans, 2018) or to transitions in the forestry sector (Falcone et al., 2020). Another approach to contrast and learn from cross-case transition dynamics would be to search for so-called generic or transferrable structures (Forrester, 2009). This could be facilitated by the use of system archetypes (Braun, 2002; Kim and Lannon, 1997). System archetypes are commonly used to specify structures that give rise to specific behavior patterns across various types of systems, but have not yet been applied in a bio-based economy context.

Finally, to find similarities and differences across transition processes in various contexts there may be a need to better document and systematically collect the knowledge generated from different studies (Nilsson et al., 2018). The reading guide provided in Paper IV partly responds to this need by proposing a structure to support coding and mapping of studies from a broad range of disciplines and fields. In its current form, the reading guide is based on themes frequently occurring in literature addressing SDG interactions. Thus, it does not provide an exhaustive list of potential themes and guiding questions for coding. However, it offers a basis to depart from, and a structure that is flexible enough to incorporate extensions.

8.3 Research to achieve a higher degree of horizontal and vertical integration

To build further on the results presented in this thesis, future studies should consider *horizontal integration*. On the national scale, additional bio-based economy sectors may be added to the analysis. Examples of relevant domains include waste management, food processing, the chemical industry, parts of the tourist industry, and the sectors linked to the management and use of aquatic biological resources. Another need linked to horizontal integration is to further explore interactions across parallel policy processes and agendas within a Swedish context (e.g., the 2030 Agenda, the Paris Agreement, and the Swedish national environmental quality objectives).

On the regional scale, several opportunities for horizontal integration arise from the Norrköping case. Foremost, it would be worthwhile to add the sectors already part of the industrial symbiosis network (Figure 2). On the energy-side, the production of biogas and ethanol, and the interactions with regional farms could be included in the analysis. On the forestry sector

side, paper and pulp production could be added, as this is the main market for forest biomass. Additionally, waste processing has multiple links with other sectors in the region. Another dimension that may be particularly interesting to investigate in future research is how the soft variables identified as critical in Papers II and III play out in the Norrköping case, as Paper V largely focuses on the physical or bio-physical aspects of goal interactions (e.g., energy and material flows). Furthermore, additional key variables could be included within the existing model structure developed in Paper V, including indicators for biodiversity or the financial aspects of the operation of the CHP plant. Accounting for and integrating these various sectors and variables could generate a better understanding of goal interactions and thereby enable more comprehensive decision support.

Finally, in respect to horizontal integration, an aspect that merits consideration is that a transition to a bio-based economy may blur traditional sector boundaries. For example, views on the agricultural sector might change if production moves to laboratories, biotechnology might change the premises of biomass growth, and decentralized modes of production make primary biomass producers take on the role of biomass processors. Thus, questions arise around how to draw, or redraw, traditional sector boundaries when seeking to support horizontal integration in the transition process.

Vertical integration is another dimension that could be supported by further research. While this thesis considers developments on the global, national, and regional scale, it only considers the presence and consequences of cross-scale dynamics and geographic spill-overs to a lesser extent. In analyzing cross-scale interactions, in Sweden and internationally, potential approaches to draw on include meta-coupling frameworks (Liu, 2017), nexus-approaches (Hoff, 2018), and the MLP framework (Geels, 2019). Linked to vertical integration is also a need for research on integrated governance across scales, and issues of legitimacy and justice. One of the starting premises of the thesis is that integrated governance is both desirable and necessary to develop coherent strategies for sustainability in the bio-based economy. However, it is not certain that integrated governance initiatives and processes result in outcomes that are efficient in realizing transformative change (Dawson, 2019) or perceived as legitimate and just among stakeholders (McDermott et al., 2019; Tallberg et al., 2018). Thus, future research that could complement the results of this thesis would entail exploring integrated governance for the bio-based economy as a feedback process across scales, specifically addressing issues of legitimacy and justice.

8.4 Research to achieve higher degrees of actor integration and participation

Further, as outlined in Chapter 2, *integration across actor groups* is key to sustainability governance. The present thesis remains silent on the actor dimension, as it does not have an explicit focus on the interactions of actors responsible for, or engaged in, the implementation of the bio-based economy. The lack of focus on actor interactions has already been highlighted as a gap in the literature on SDG interactions (Paper IV). In the bio-based economy context, previous work has generally focused on specific aspects of these interactions, while more

comprehensive studies on bio-based economy governance and actor interactions are only beginning to emerge (Birner, 2018).

There are several ways in which better integration across actors could be achieved, but here the potential in using tools from complexity science is highlighted. For example, agent-based modeling could be used to answer to questions such as: Given different perceptions of trust and risk, who will take the lead in the transition process and what impacts will follow? Given different views of the public on the bio-based economy, what pathways to a bio-based economy may form? Network analysis is another method commonly used to map interactions in actor networks. It has previously been used in a bio-based economy context, for example to create an understanding of what and how actors collaborate and exchange information in Swedish biorefinery networks (Bauer et al., 2018), the Finnish forest-based bio-based economy network (Korhonen et al., 2018), or the German equivalent (Giurca, 2020; Giurca and Metz, 2018). Such knowledge could be used as a basis for critically examining established network structures, and for setting up novel partnerships. There is plenty of room to build further on existing studies.

A different direction for research on actors in the bio-based economy is to advance an understanding of intersectionality. Intersectionality refers to “the interaction between gender, race and other categories of difference in individual lives, social practices, institutional arrangements, and cultural ideologies and the outcomes of these interactions in terms of power” (Davis, 2008, p. 68). Having roots in feminist theory, it is an analytical framework that may be used to understand how power structures form and interact. Using intersectionality as a theoretical framework has begun to gain prominence in research on sustainability transitions, for example in a climate change context (Kaijser and Kronsell, 2014). In the bio-based economy, it has been used in relation to the biotechnology or “bio-economy as a new form of capitalism” coinages. In these domains, scholars have been exploring gendered bio-economies, shedding light on how reproduction has increasingly become a source of accumulation of capital. This research has also begun to show how so-called contemporary bio-economic activities (e.g., surrogacy, egg donation, or genetic testing) have gendered impacts (Lamoreaux, 2018), and points to divides in how what can be referred to as the “fertility industry” operates in the Global North and South (Namberger, 2019; Vora, 2015). These studies reveal new tensions in the bio-based economy debate, spanning the local to the global level. Employing the lens of intersectionality also in the context of the bioresource or bio-ecology visions of the bio-based economy could be a direction for future research (EU, 2015). The green sectors have traditionally been gender unbalanced in Sweden (Johansson et al., 2019; Swedish Forest Agency, 2017). Factors such as class and nationality are linked to different types of vulnerability in these sectors (Svensson et al., 2013; Wikström and Sténs, 2019). The intersectionality frame could contribute knowledge on how the emerging bio-based economy may reinforce or mitigate such issues.

Integration across actors is also related to ensuring a higher degree of participation in the actual research process. This is important for several reasons. First, participation can capture dimensions and stakeholder perspectives currently missing from the discourse. Second, greater stakeholder engagement would enable moving from divergent to convergent thinking. Third,

higher degrees of participation could generate ownership and commitment to action when moving forward in the implementation stage (Antunes et al., 2006; Reed, 2008; Stave, 2010). To enable higher degrees of participation in research on the bio-based economy, not only interdisciplinary but also transdisciplinary approaches and principles may prove useful. Transdisciplinary approaches hold the potential to meet societal challenges by engaging stakeholders in every part of the research process, bridging academic and non-academic actors to promote solutions to real-world problems (Lang et al., 2012).

This thesis can contribute to higher degrees of participation specifically through the analytical framework presented in Paper V. It was designed to be used in settings with high degrees of stakeholder involvement. To achieve this aim, four alterations to the framework might be needed. First, the process and application of the framework should ideally pay specific attention to stakeholder learning. The tools included in the framework are well-suited to revealing existing knowledge, values, and beliefs held by decision-makers and policy-makers. Yet, there is a need to devote attention to the factors that would likely influence the uptake of new knowledge, as well as to creating the necessary conditions for this uptake to take place in the application of the framework. Second, steps to evaluate stakeholder learning need to be incorporated in the participatory research process, to assess its effectiveness. Third, institutional barriers to integrated governance and other hindrances linked to implementation should be identified. By identifying such barriers as an integral part of the research process, the development of efficient strategies to address these may be supported. Fourth, the process should include efforts to measure and evaluate the long-term impacts of proposed interventions in an integrated way.

8.5 Research on the bio-based economy and strong sustainability

Lastly, there is still room to explore different understandings of sustainability in relation to the bio-based economy, and how these understandings shape the development of the bio-based economy in practice. Specifically, more work is needed to understand what strong sustainability implies in the context of the bio-based economy. This thesis offers some immediate opportunities to build on. For example, the frames of weak and strong sustainability could be applied to formally analyze the transition pathways presented in Papers II and III, to explore to what extent these can inform transformational strategies for strong sustainability. A related question is which actors would be more immediately in favor of implementing such strategies.

9. Conclusions

This thesis has aimed to advance an integrated and systemic understanding of the bio-based economy and what it implies for sustainability. First, it has done so by providing a detailed and operational analysis of transition pathways to a bio-based economy in a Swedish context. Second, it has showcased how the multiple goals of the bio-based economy interact in the transition process, both internally to the bio-based economy and with goals promoted by parallel sustainability initiatives. Third, the thesis has used the weak and strong sustainability paradigms to clarify root causes of the polarized debate on what the bio-based economy implies for sustainability. This section outlines the main conclusions and implications for decision-making in support of the transition process. Further, it comments on the methodological contributions of the thesis.

A central aspect of developing a context-specific and operational understanding of the bio-based economy in a Swedish setting was to clarify its goals. It can be concluded that the perceptions of what the bio-based economy could and should be differ among the actors engaged in, or impacted by, the transition process. The suggested goals are diverse in nature and have broad reach. While some goals promote change that entails relatively small changes in bio-based economy related sectors, others encompass visions of transformative change that would fundamentally alter existing structures. **The diversity in perceptions stresses the importance of actively seeking to capture and integrate multiple perspectives on the bio-based economy.** This can be done to reduce the risk of overlooking the views of actors that may be key to successful implementation. The lack of agreement on the meaning and goals of the bio-based economy has been identified as a general issue in global academic and policy debates. However, despite differences in how the bio-based economy is understood also in a Swedish context, the results indicate that the goals of the bio-based economy are not necessarily incompatible with each other. **Instead, there is large potential for working across sectors to address shared goals and challenges in the transition to a bio-based economy.**

The integrated and systemic conceptualization of the bio-based economy presented in this thesis complements single-sector analyses or views of the transition process as a linear series of cause-and-effect events. Approaching the transition process on the premise that it is dynamic and non-linear has several implications for setting priorities and developing coherent strategies for goal attainment.

First, the integrated conceptualization of the Swedish bio-based economy underlines that efficient implementation strategies must seek to minimize unintended consequences and policy resistance. The results uncovered dynamics that give rise to unintended consequences and policy resistance, for example in terms of how prospects of nature conservation may lead to forest management that does not promote high nature values, and how certain transition pathways may erode the perceived legitimacy of the green sectors. Furthermore, dynamics in both the forestry and agricultural sectors operate in ways that create path dependency and lock-in effects.

Second, critical trade-offs exist and need to be addressed in all stages of implementation.

These include often-debated conflicts over the allocation of land and biomass for different uses. The results also revealed trade-offs linked to the future development of the forestry industry, to different modes of agricultural production, between investing in different types of technologies, and across environmental and economic goals of the bio-based economy.

Third, there are several opportunities for exploiting synergetic effects, where implementation strategies could support goal progress in multiple areas simultaneously.

Interventions and goals that are highly synergetic include ensuring successful generation shifts in the agricultural sector, investments in R&D and innovation capacity in the forestry sector, and investing in national plant breeding programs. Furthermore, a shared feature among many of the goals and proposed interventions is that they are not prescriptive. The desired change aims to strengthen the ability of the green sectors to deal with uncertainty, for example through creating a strong foundation of active and diverse forest management and by expanding the capacity, sustainability, and innovation potential of the agricultural sector. Promoting these goals and interventions may help the actors engaged in these sectors cope with the complexity of the transition process and increase the viability of the bio-based economy in the long term.

Fourth, trade-offs and synergies are not only present internally to the bio-based economy, but also in respect to goals of parallel sustainability initiatives and agendas.

By mapping the trade-offs and synergies between these different initiatives and agendas, it becomes possible to set priorities in terms of what goals to promote in order to maximize synergetic effects while minimizing trade-offs. However, the results demonstrated how the ability to uncover trade-offs and synergies relies heavily on the methods and research boundaries employed, and that the resulting priority order changes significantly. For example, a pairwise assessment of goal interactions in the Norrköping case indicated that the goals related to the bio-based economy should be given low priority, as they were seemingly less synergetic compared to goals belonging to parallel agendas. In contrast, when goal interactions were assessed in their wider systemic context, the priority order changed, and the goals of the bio-based economy appeared central for realizing the goals of parallel sustainability initiatives in Norrköping. This emphasizes the complexity of analyzing goal interactions in sustainability transitions and that setting priorities may not be a straightforward undertaking.

Fifth, the systemic and integrated conceptualization of the Swedish bio-based economy reveals leverage points and associated systems interventions.

The leverage points and proposed interventions are critical as they offer a basis for developing efficient strategies to facilitate a transition process. The leverage points are found in a broad range of areas, and the interventions include both top-down policy (e.g., financial instruments such as taxes or subsidies) and bottom-up initiatives (e.g., communication schemes developed by farmers to engage local communities in regenerative production). The leverage points and proposals specifically stress (i) the importance of considering the soft aspects of a transition process (e.g., the dynamics governing conflict, polarization, self-motivation, collaboration, legitimacy, and public and political support), adding to the currently dominant technological and engineering

logic; and (ii) the need to consider the timing and order of interventions, as some goals and interventions are preconditions for other change processes to occur.

The methodological contribution of the thesis lies in the review and application of a combination of systems thinking tools and methods. Employing a mixed-methods approach created an opportunity to contrast the analytical output from each step of the research, making it possible to arrive at different conclusions than what would have been possible if relying on one single method. Aside from methodological plurality, the thesis stresses the need for disaggregation, and for taking a longer time horizon when analyzing sustainability transitions. The overall approach offers valuable insight for future studies on sustainability transitions in the context of the bio-based economy and beyond. More specific methodological contributions include the analytical framework developed in Paper V. This framework may be particularly useful in situations where the problem space is unstructured, where multiple goals are interacting (and potentially contested), and where change in these goals is related to dynamic complexity. Additionally, the specific methodological contributions of the thesis include the review and mapping of the research field of SDG interactions. The research approaches and research gaps found in this study may guide future research on sustainability goal interactions, also outside the initial SDG context. Furthermore, the reading guide provided in Paper IV proposes a way to structure and compare knowledge on sustainability goal interactions. It is thereby intended to make the knowledge more accessible, both to an academic and non-academic audience.

Finally, the thesis provides an answer to the overarching question **of whether the bio-based economy can constitute a viable pathway to sustainability.** The mainstream discourse surrounding the bio-based economy adheres largely to the principles of the weak sustainability paradigm, and current developments generate such sustainability outcomes. Based on the weak sustainability logic, limited attention is given to biophysical and social limits to growth. Promoting a future development in line with weak sustainability includes expanding economic activity in bio-based economy sectors, establishing new markets, increasing market competitiveness, directing funding to R&D, setting up private-public partnerships, and supporting commercialization of novel biomass applications.

The ability of the bio-based economy to contribute to strong sustainability is less evident. In theory, it may be possible to envision alternative bio-based economy pathways that align with strong sustainability. Specifically, the results suggest that the bio-based economy may support the maintenance of critical natural capital and help build closed-loop production systems. Yet, a general conclusion is that it may be challenging to turn theory into practice. This is partly due to a lack of coherent strategies that can simultaneously realize the goals of the bio-based economy, the 2030 Agenda, and strong sustainability. Finding conditions that would enable such outcomes is a critical next step if the bio-based economy should constitute a viable pathway to sustainability according to the notion of strong sustainability.

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Appendix I. Glossary of terms and terminology⁵

2030 Agenda: Sets out a (global) vision of transformational change toward sustainability and includes 17 Sustainable Development Goals (SDGs), 169 targets, and over 230 indicators for measuring their progress.

Agriculture:

Conventional agricultural production (intensive, industrial, modern): Conventional farming systems vary depending on context, but are often large-scale, capital and technology intensive, and dependent on single crops/high-yield hybrid crops, fertilizers, pesticides, mechanized farm work, and agribusiness.

Regenerative agricultural production: Different forms of regenerative production (e.g., agro-forestry and ecological recycling agriculture) have in common that they place ecosystem functioning at the center of the agricultural practice, entailing diversity in species, management, markets, and values. Thus, regenerative agriculture maintains and regenerates biotic interactions and ecosystem functioning/services

Agro-forestry: Natural resource management that integrates trees on farms and in the broader agricultural landscape. The aim is to support diversified and ecologically based production that increasingly delivers social, economic, and environmental benefits.

Bio-based economy: A concept that covers all sectors, systems, processes, functions, and principles that rely on biological resources. It has performative power, in the sense that the way the concept is understood; the goals promoted under its umbrella; and the associated strategies have an impact on real-world systems, practices, and processes. The way it is understood is largely shaped by developments in the political domain, making it a policy-driven concept. However, the meaning of the term bio-based economy is also shaped by actors outside the political arena.

Conceptualizations (visions/coinages): *The biotechnology vision* understands the bio-based economy as an economy promoting an increasing use of biotechnology in society, where hoped-for outcomes include economic growth, climate change mitigation, and productivity gains. *The bioresource vision* understands the bio-based economy as a biomass economy, where the biomass resource is in focus (rather than the technologies applied to it). *The bio-ecology vision* has a strong focus on sustainability, promotes biodiversity, and optimized use of energy and nutrients, while wanting to steer away from monocultures and practices that cause soil degradation. *The bio-economy as a novel form of capitalism* refers to an understanding of the bio-based economy arising out of academic literature that focuses on the life sciences and capitalism in a diversity of areas. These areas include genetically modified organisms, stem cells, venture capital, bioprospecting, and biobanking.

⁵ The glossary provides clarification on the use of terms in this thesis and appended publications. The definitions are examples of common usage drawn from a wide range of sources.

Goals: The specific goals of the bio-based economy in each decision-making context. May also be referred to as objectives or desired change processes.

Transition: The process of realizing the goals of the bio-based economy. Due to the lack of shared meaning of the term bio-based economy, various views exist on whether the transition is already underway, in what stage it is, or if is happening at all.

Biological resource (bio-based resource): Resources of biological origin, including animals, plants, micro-organisms, and derived biomass, as well as organic waste.

Biorefinery: Broadly understood as a class of processes that refine different forms of biomass into one or several products.

Complexity: This thesis is concerned with *dynamic complexity*, arising from the interactions among different entities in a system. Dynamic complexity can be contrasted with *detail complexity*, arising because of a large number of elements in a system.

Causal loop diagram: A diagramming method used to map and analyze systems. Causal loop diagrams display causal relations between variables, with a specific focus on feedback loops.

Closed-loop production systems: Production systems that do not extract resources and generate waste in linear flows, but instead recover and re-use products, materials, residues, energy, and nutrients.

Critical natural capital: The set of environmental resources (natural capital) that performs functions that are fundamental to human survival and well-being, for which losses would be irreversible, immoderate, or irreplaceable.

Diversified farming: A diversified farming system promotes diversification across scales (ecological, spatial, and temporal). It offers a way to realize agricultural production that is regenerative.

Ecological Recycling Agriculture (ERA): A type of agriculture based on recycling principles, diverse crop-rotation schemes (combining fodder crops, food crops, and a high share of symbiotic nitrogen-fixing legumes such as clover), and a balance between crop and animal production on each farm.

Endogenous variables: Variables in a model that are influenced by other variables in a model.

Exogenous variables: Variables in a model that are influenced by variables outside a model's boundary.

Expert knowledge: The information held by an expert. It can be obtained in different ways, including through a professional role or formal qualification but also through experience. Expert knowledge comes in various forms, including technical knowledge (e.g., information about processes governed by rules, operations), process knowledge (information about actions, interactions, organizational configurations, events), and interpretative knowledge (subjective orientations, perceptions, interpretations).

Framing: Different ways of representing a system and the goals of this system. Several elements work together to create framings, including context, meanings, narratives, and values.

Forestry:

Diversified: Refers to forest management approaches that promote diversity in both the operation processes and in the outputs these processes deliver.

Conventional/industrial: Refers to forest management based on monocultures, even-aged stands, and clear-cuts, with the main aim to promote productive forest values.

Forestry sector: Understood to encompass all economic activities that depend predominantly on the production of goods and services from forests. This includes activities that depend on wood fiber (e.g., round wood, wood derived fuel, sawn wood, paper and pulp, furniture) but also non-wood forest products, recreation and tourism, subsistence use of forests, and hunting.

Feedback:

Reinforcing feedback loop: A circular causality, amplifying changes in a system.

Balancing feedback loop: A circular causality, dampening changes in a system.

Green sectors: Encompassing companies and industries based on farming and forestry.

Intervention: Used in this thesis to refer to the actions by individuals and institutions, public and private, to support goal attainment in the bio-based economy. Thus, the term intervention refers to both top-down policy and bottom-up initiatives, carried out under different modes of governance.

Integration: The act of viewing a system in a holistic manner, instead of reducing it to separate parts. This thesis takes a systems-thinking approach to integration. A central assumption is that each part of a system acts differently when isolated from rest of the system.

Interaction: Used to denote that a relationship exists between two variables or entities. Similar terms include interconnections, interlinkages, linkages, and connections.

Interdisciplinary research: Research that aims to integrate perspectives, tools, concepts, theories, and data from two or more disciplines.

Linear relationship: A relationship between two system entities or elements where the proportion between cause and effect is constant.

Leverage point: Places to intervene in a system where a small initial change may create significant and lasting improvements.

Lock-in: A result of path dependency, a situation where it is difficult to reverse, change, or escape an existing system configuration.

Mental model: A model that is constructed and simulated in the conscious mind, holding assumptions about separate parts of real systems, and used to guide everyday decisions.

Model: A simplified representation of a system.

Natural capital: Environmental resources. Includes, for example, fossil- and mineral-based deposits, renewable resources, and ecosystem services (e.g., pest control, nitrogen fixation, pollination and purification of air and water).

Non-linear relationship: A relationship between two system elements where the cause does not generate an effect that is proportional.

Path dependency: A rigid (and potentially inefficient) development pattern resulting from former decisions and processes.

Primary production: The first step of the biomass supply chain (e.g., in a food production system). It may include growth and harvesting of crops and forest biomass, or the rearing of livestock.

Policy:

Coherence: Policy-making that systematically reduces conflicts and promotes synergies between and within different policy areas to realize jointly agreed upon outcomes.

Integration: The process generating policy coherence (oftentimes these two terms are used interchangeably).

Resilience: The capacity of a system to continue to develop when undergoing change, for example caused by stress or disturbance.

Resource:

Non-renewable: Resources that take a relatively long time to replenish and therefore become limited in supplies. Examples include coal, oil, and natural gas.

Renewable: Resources that replenish naturally over a relatively short time. One example of a renewable resource is biomass.

Stock: A quantity (material or information) that has accumulated in a system over time.

Stock and flow diagram: A diagram type and language that emphasizes accumulation (stocks) and how these accumulated quantities are affected by their inflows and outflows.

Social-ecological systems: Systems characterized by interconnections, dynamic relationships, and interdependencies between humans (the social) and the environment (the ecological).

Sustainability:

Weak sustainability: Refers to an understanding of sustainability according to which different forms of capital are substitutional, where there are no limits to growth in economic activity, and where economic growth and technological change are key to

ensuring sustainability. Sustainability is achieved when the wellbeing or welfare derived from the total capital stock is growing or non-declining over time.

Strong sustainability: Refers to an understanding of sustainability where substitution between different forms of capital is perceived as restricted, specifically in relation to natural capital due to its life-supporting functions and the uncertainty that comes with substitution. Central to sustainability is the maintenance and protection of natural capital.

Sustainable Development Goals: The 17 goals formally included in the 2030 Agenda.

Synergy: The interaction of two or more entities where their combined effect is greater than the sum of their individual effect. Synergies in the context of the transition to a bio-based economy can be found in all stages of implementation, for example between goals or means of implementation.

System: Many definitions exist of a system, each with their own perspective. In the present thesis, a view of a system is employed that sees systems as a complex set of elements that are mutually interacting for a common purpose.

System boundary: Conceptual boundary distinguishing endogenous from exogenous variables in a feedback system.

Systems dynamics: A method and tool for systems thinking.

Systems thinking: The mental effort to uncover endogenous sources of systems behaviors.

Trade-off: A situation where there is a conflict, i.e., where there is a need to sacrifice some aspect to make progress on another, as both cannot be achieved at the same time.

Transdisciplinary research: Here defined as a process of collaboration between academic and non-academic actors with the aim to create new theory and knowledge, often in relation to a specific real-world problem.