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The bio-based economy, 2030 Agenda, and strong sustainability – A regional-scale assessment of sustainability goal interactions

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ABSTRACT

Policy-makers face the challenge of assessing and implementing sustainability measures, while also dealing with parallel and sometimes conflicting policy agendas, long-term policy impacts, and contested interpretations of sustainability. To support evidence-based decision-making in this context, this paper presents the results from an integrated assessment of sustainability goal interactions. Links between the bio-based economy, the 2030 Agenda, and the so-called strong sustainability paradigm were explored in a regional-scale case. The analysis focused primarily on developments in the forestry and energy sectors. Direct trade-offs and synergies as well as broader systemic impacts were identified. The results show how goals from the bio-based economy, 2030 Agenda and strong sustainability paradigm are mutually interacting. Positive interactions were found within two clusters of goals, offering coherent and synergetic transition pathways within these. The first cluster encompasses developments toward intensified forestry, renewable energy, and closed-loop production systems. The second pathway supports diversified forestry and protection of critical natural capital. However, while internally coherent, trade-offs were identified between these goal clusters, demonstrating the difficulty in simultaneously making progress on goals belonging to different sustainability agendas. The results also stress the need for disaggregation and long-term assessments to identify trade-offs and synergies. Finally, the analysis highlights the theoretical potential but practical challenges of implementing the bio-based economy and 2030 Agenda in a way that adheres to strong sustainability. The analytical framework used in the present study may be adapted and applied to other decision-making contexts. It is particularly useful in settings characterized by uncertainty and unstructured problem spaces.
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1. Introduction

Multiple sustainability agendas and initiatives are emerging in response to environmental and social challenges such as climate change, biodiversity loss, resource depletion, pollution, rising inequality and geopolitical instability. These agendas suggest new ways of structuring societies and economies to facilitate transitions to more sustainable ways of living within geophysical and social boundaries. Yet, despite progress in certain areas, humanity is still largely on an unsustainable trajectory (Fischer et al., 2007). Several critical planetary boundaries are trespassed (Rockström et al., 2009; Steffen et al., 2015) while at the same time basic socio-economic living standards for millions of people are not yet ensured (Raworth, 2012). There is thus a significant need to increase the leverage of sustainability efforts globally (Abson et al., 2017; Dorninger et al., 2020; Fischer and Riechers, 2019; Kallis and March 2015). One challenge in this respect is that sustainability is a contested term. There is no universally agreed on definition of sustainability, nor consensus on how it should be turned into practice (Beckerman, 1994; Leach et al., 2010; Norgaard, 1994). A second challenge is that transitions toward sustainability emerge from changes in highly interconnected systems, where the systemic and long-term implications of actions and interventions may be difficult to foresee (Liu et al., 2015; Sterman, 2009). Consequently,

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sustainability initiatives and agendas are not always coherent, meaning that they promote changes that inhibit or nullify respective visions and goals. Coherent strategies that recognize and mitigate negative interactions (trade-offs) and maximize positive interactions (synergies) are key to more efficiently addressing contemporary sustainability issues (Bowen et al., 2017; ICSU, 2017; Nilsson et al., 2018).

In this paper, we focus specifically on three initiatives and agendas that play central roles in current debates on how to advance sustainability: The bio-based economy, the 2030 Agenda, and the strong sustainability paradigm. Particularly, we aim to assess whether these agendas and initiatives set out a coherent direction for sustainability. The assessment is based on an analysis of how their respective goals interact in terms of synergies and trade-offs. Thereby, the present paper aims to inform priority setting and the development of integrated and efficient implementation strategies.

The bio-based economy is an emerging concept that promotes new uses of biological resources. The idea is that an increasing use of biological resources in society will generate a broad range of sustainability outcomes. For example, the bio-based economy is seen as a central part of the transition to a fossil-free society (Formas, 2012; McCormick and Kautto, 2013). It is also expected to bring regional growth, new business and employment opportunities, health benefits, and cleaner production processes (European Commission, 2018; OECD, 2009). In parallel, the 2030 Agenda and Sustainable Development Goals (SDGs), launched by the United Nations (UN) in 2015, provide a roadmap for realizing transformational change toward sustainability globally. The SDGs set targets for progress in a broad range of areas, including poverty eradication, sustainable cities, renewable energy provision, protection of marine and terrestrial ecosystems, and gender equality (UN General Assembly, 2015). Finally, the strong sustainability paradigm is included in the analysis to capture the contested nature of the term sustainability. From the perspective of the strong sustainability paradigm, a central aim of sustainability is to protect and maintain so-called critical natural capital. Natural capital is "a set of complex systems, consisting of evolving biotic and abiotic elements, that interact to determine the capacity of an ecosystem to directly and/or indirectly provide human society with a wide array of functions and services" (Pelenc and Ballet, 2015, p. 37). Some of this natural capital is considered "critical" as it performs functions that are essential for human survival and wellbeing, and as losses of such natural capital are potentially irreversible (Dedeurwaerdere, 2014; Ekins et al., 2003). The strong sustainability paradigm challenges dominant narratives around technological change as able and appropriate to address sustainability issues (Parker, 2014). It also questions the role of economic growth as a mean to facilitate change toward sustainability. Instead, the strong sustainability frame brings to the forefront the limits and adverse impacts of accelerating growth in material and energy use (Neumayer, 2003).

There is previous research that assesses interactions across the agendas and initiatives included in the present study. Specifically, the impact of the bio-based economy on the SDGs has been explored (El-Chichakli et al., 2016; Heimann, 2018; Issa et al., 2019), as well as the relationship between the bio-based economy and strong sustainability (Loiseau et al., 2016; Ramcilovic-Suominen and Pülzl, 2018; Vivien et al., 2019). However, to the best of our knowledge, interactions across these three initiatives and agendas have not previously been explored in a systemic manner. In order to meet this gap, we develop an analytical framework, drawing on methods from complexity science and systems thinking. We apply it to a regional-scale case, to provide an empirical setting and decision-making context for the study of goal interactions. The remainder of the paper is structured as follows: First, we introduce the case study area and outline the different steps of the analytical framework. Second, we present the results, followed by a discussion of what they imply for decision-making. Third, we discuss the strengths and limitations of the analytical approach. The final section concludes and suggests avenues for future research.

2. Methods

2.1. Case study area and research boundaries

The empirical setting for the study of goal interactions was Norrköping municipality, Sweden. It covers an area of 1495 km^2 and has a population of 141,676 people (Norrköping Municipality, 2020). It is located in Östergötland county, in a landscape dominated by forests (60% of the area), agriculture (25%), and small lakes (County Administrative Board Östergötland, 2014). Norrköping was once a center for the textile industry. Today, its trade and industrial activities are based on manufacturing, as well as technology, food processing, and paper and pulp production (Berlina et al., 2015).

Norrköping constitutes an interesting case due to (i) its ambitious sustainability agenda (Norrköping Municipality, 2017; Norrköping Rådhus, 2019); (ii) the varied landscape and industrial sectors that cover multiple domains relevant to the bio-based economy (Region of Östergötland, 2017); and (iii) ongoing efforts to implement the SDGs (Norrköping Municipality, 2017). While some of these efforts are in early stages of implementation, there is already evidence of change toward sustainability. Examples include new public-private partnerships and novel ways of collaborating around the use of natural resources and production side-streams (Berlina et al., 2015). These developments have created an "industrial symbiosis" network in the region, centered around environmental technologies, by-product re-use, renewable energy, and new logistical solutions. The industrial symbiosis involves actors from forestry, agriculture, the energy sector, the chemical industry, waste processing, and the municipality (LiU, 2020a). The present study analyzes goal interactions in a sub-set of the overall industrial symbiosis network, focusing specifically on combined heat and power (CHP) generation, waste management, forest biomass production, and energy demand-side dynamics.

2.2. Framework for analyzing sustainability goal interactions

The analysis was carried out using a five-step analytical framework, combining cross-impact analysis, network diagramming, identification of key variables (including both drivers and indicators of change), conceptual modeling, and simulation-based analysis (Fig. 1). The framework was developed to translate global sustainability initiatives to national, regional or local contexts, to identify goal interactions and underlying assumptions, and to explore plausible future developments given different goal interactions.

2.2.1. Goal screening

Goal screening was carried out to identify goals of specific relevance to the Norrköping context, linked to each overarching global policy strategy, agenda, or paradigm. The screening was supported by an understanding of the regional context provided by the scientific and gray literature, including regional plans and strategic documents. In addition, four semi-structured interviews were held with stakeholders with expertise linked to the case study area (representing the municipality, researchers, and energy experts). The aim of the interviews was to learn more about regional sustainability challenges, and to ensure the relevance of the final set of goals included in the analysis.

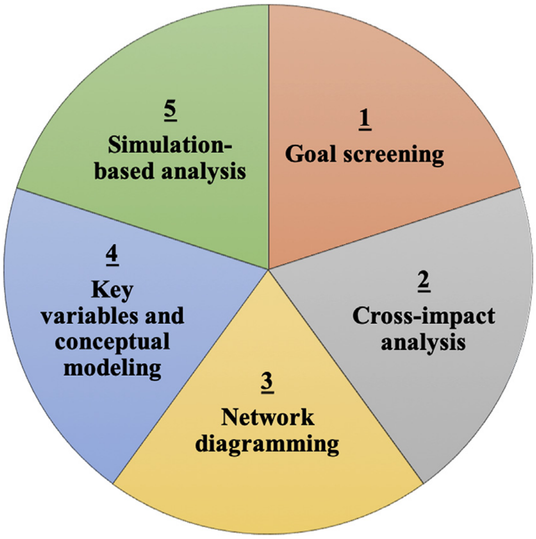

Fig. 1. The five steps of the analytical framework.

2.2.2. Cross-impact analysis

Cross-impact scoring and analysis offer a way to understand how sustainability goals interact in a pairwise manner. Cross-impact analysis has frequently been employed to support integrated analyses of the SDGs (Fader et al., 2018; Nilsson et al., 2016; Weitz et al., 2017), but has to a lesser extent been applied in the context of the bio-based economy or strong sustainability. At the core is an integral scale and typology of goal interactions, indicating whether progress on one goal promotes or hinders progress on other goals. In the present paper, interactions between sustainability goals in terms of competition for resource inputs (e.g., financial resources and means of production such as land and raw materials), shared preconditions for goal attainment (e.g., political support and infrastructure), and the impacts of goal progress were accounted for (Fig. 2). Further, recognizing that sustainability is a contested concept, we assessed whether pairs of goals are aligned (yielding synergies) or promote conflicting understandings of sustainability (entailing trade-offs). The basis for the interaction scoring was expert knowledge and the scientific literature. Our research team carried out the cross-impact scoring, first individually and then together in workshops held in Stockholm or digitally. Each score and supporting literature were presented, and reasons for potential disagreements identified and discussed. For further information on the scoring process, see Appendix A1.

2.2.3. Network diagramming

Network diagramming was used to provide a visual representation of the pairwise interactions identified in the cross-impact analysis described in Section 2.2.2. Drawing on graph and network theory (Newman et al., 2006), the network diagrams comprise nodes (the goals) connected by arrows. The node size indicates how connected a specific goal is, and the arrow size and color denote the strength of an interaction. Trade-offs and synergies are indicated by the arrow color, as well as if the nodes are connected by dashed or full arrow lines.

2.2.4. Identification of key variables and conceptual modeling

The next step consisted of identifying key variables for each goal, representing both drivers and indicators of change. The selection of key variables was based on their ability to measure progress on their associated goal, as well as on their ability to account for dynamic complexity (Kopainsky et al., 2018). An initial systemic mapping of the interactions between the key variables was carried out using Causal Loop Diagrams (CLDs) (Sterman, 2009). CLDs are system maps where variables are connected by arrows. The arrows represent causal relationships, and a plus or minus sign on the arrow head indicates whether the independent and dependent variables move in the same or opposite direction. A central aim of the CLD mapping process is to identify and visualize feedback processes, where reinforcing feedback loops are indicated by an R and balancing feedback loops denoted by a B (Lane, 2008).

2.2.5. Simulation-based analysis

The final step involved simulation-based analysis using a system dynamics modeling approach. Broader systemic impacts of goal interactions were analyzed in an integrated manner and potential future trajectories explored. System dynamics models replicate and analyze how systems behave by specifying and simulating interactions between system components. Key analytical dimensions in system dynamics modeling include feedback processes, delays, and non-linearities (Forrester, 2009; Sterman, 2009). The ability to analyze these dimensions of complex systems makes system dynamics models particularly useful in the study of sustainability transitions (Allen et al., 2016; Köhler et al., 2019). A central aim of system dynamics modeling is to ensure that all variables relevant to explaining an issue of interest are endogenous to the model. Endogenous variables in system dynamics models are variables that are influenced by other variables within the model boundary. In contrast, exogenous variables are influenced by dynamics outside the model boundary. Once there is sufficient confidence in the model's ability to endogenously generate historical behavior patterns for the variables included in the analysis, the model may be used for policy analysis and prioritization (Richardson, 2011; Wheat, 2010). The model presented in the present paper was tested and validated using the procedures outlined by Barlas (1996). The validation process included both structural and behavioral tests to assess the model's ability to replicate historical data, unit consistency tests, and simulation to explore the model behavior under extreme conditions and its sensitivity to parameter changes. Data for parameterization and behavior validation were obtained from the operator of the CHP plant (Johansson, 2014; Skog, 2011), energy expert agencies and interest organizations (IEA, 2010; Swedenergy, 2020), and previous research on the district heating market in the region (LiU, 2020b). Model integration and parameterization were also based on work by Ljungberg (2018) and Wallman et al. (2005).

3. Results

3.1. Goal screening

Seven overarching sustainability goals were identified and included in the analysis (Table 1), reflecting current sustainability challenges and ambitions in the case study area. Two goals are linked to the bio-based economy: to achieve structural change in the currently dominant industrial mode of forestry to allow for greater diversity (e.g., in terms of management practices, productive species, and markets) (BBE1) and to make existing industrial structures in the forestry sector more advanced, innovative and resource-use efficient (BBE2). The choice of these goals was motivated by previous research on the goals of the Swedish bio-based economy (Bennich et al., 2018), the dominance of forestry in the Swedish bio-based economy (Antikainen et al., 2017; Reime et al., 2016), and the central role forestry plays in the industrial symbiosis network in the case study area (Berlina et al., 2015).

Three goals were singled out from the 2030 Agenda. Two of them are linked to energy, reflecting ambitions to increase the share of renewables in the energy mix (SDG target 7.2) and to

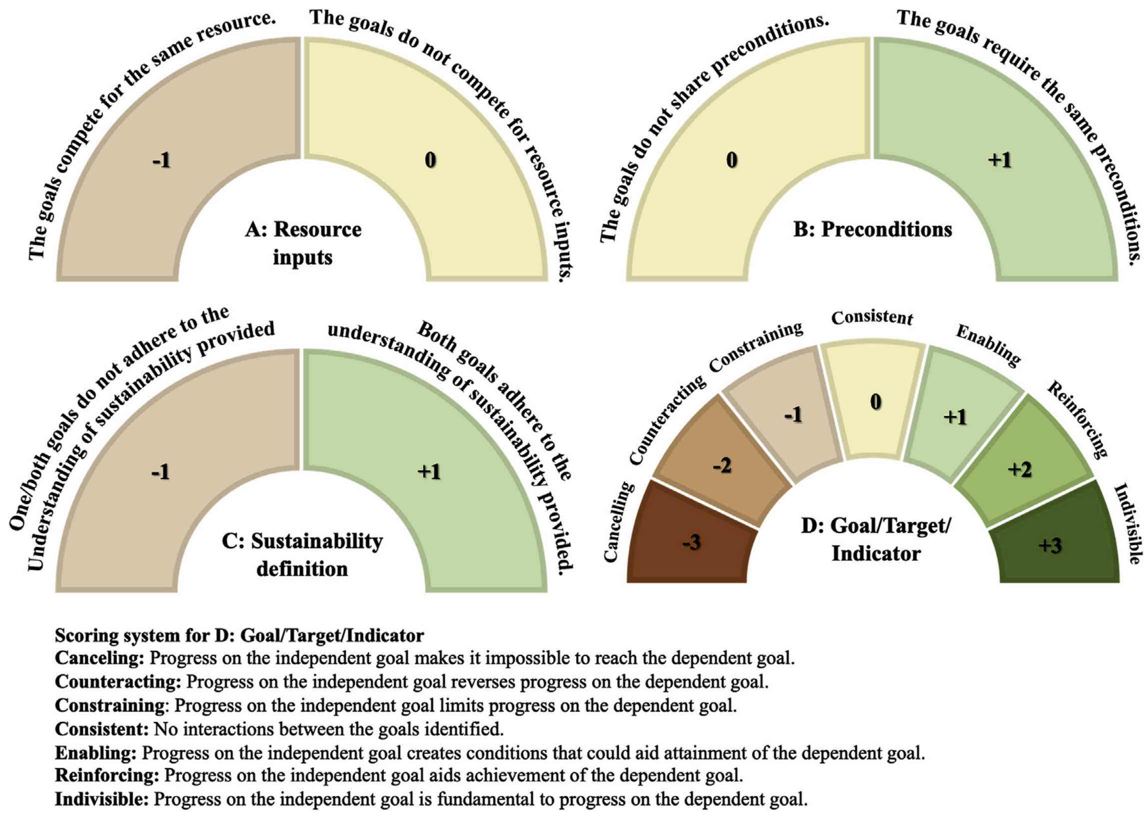

Fig. 2. Goal interaction scoring system, adapted from Fader et al. (2018) and Nilsson et al. (2016).

Table 1
Output from goal screening.

Goal			Description/Aim
Bio-based economy (BBE)	BBE1	Diversified forestry	Enable greater diversity in productive species, practices, and uses of forest biomass, based on a fundamental reconfiguration of the current industrial forestry structure.
	BBE2	Advancing current forestry industry structure	Introduce new practices and modes of production in the currently dominant forestry industry structure to make it more advanced, innovative, and resource-use efficient.
Sustainable development goal (SDG)	SDG 7.2	Renewable energy	By 2030, increase substantially the share of renewable energy in the global energy mix.
	SDG 7.3	Energy efficiency	By 2030, double the rate of global improvement in energy efficiency.
	SDG 12.5	Waste	By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse.
Strong sustainability (SS)	SS1	Ecosystem functioning	Maintain the forest ecosystem functioning, representing the aim of the strong sustainability paradigm to prevent degradation of critical natural capital.
	SS2	Closed-loop production systems	Achieve production systems that are no longer based on linear flows of extraction and waste generation. Instead, re-use, recovery, and recycling of products, materials, residues, and energy should be promoted.

increase the rate of energy efficiency improvements (SDG target 7.3) (UN, 2020a). Realizing these goals constitutes challenges both at a national scale in Sweden (SOU, 2017) and in the case study area (Norrköping Municipality, 2009). Moreover, the goal to reduce the waste generation rate was included in the analysis (SDG target 12.5) (UN, 2020b). This target was chosen on the basis that material re-use and views of waste as a resource are central to the notion of industrial symbiosis and a key part of the municipality's work on sustainability (Norrköping Municipality, 2019).

Lastly, two goals representing the principles and ideas promoted by the strong sustainability paradigm were included. There is no consensus on what strong sustainability entails in practice. Yet, a number of key principles can be derived from the literature (Baumgärtner and Quaas, 2009; Dietz and Neumayer, 2007; Ekins et al., 2003). First, we decided to include the overarching goal of maintaining critical natural capital. Specifically, we focused on the forests in the region and the need to maintain the functioning of the forest ecosystem (SS1). The forest ecosystem functioning may be defined as the effects of all processes (i.e., energy and material flows) that jointly sustain an ecosystem (Truchy et al., 2015). Second, the goal to achieve closed-loop production systems was chosen (SS2). A distinguishing feature of such systems is that they are not based on linear flows of extraction and waste, but instead seek to recover and recycle the elements involved in the production of services and goods (Winkler, 2011).

3.2. Cross-impact analysis

The results of the cross-impact analysis are presented in Table 2, showing the sum of the different pairwise interaction scores, as well as the overall sum for each goal (the row sum). A high row sum indicates a large presence of synergies and a row sum below zero a larger share of trade-offs. For an overview of the individual scores and uncertainty measures, see Appendix A1.

The goal to maintain the forest ecosystem functioning (SS1) stands out as having large synergetic potential. Hence, making progress on this goal may aid progress on several other goals included in the analysis. Also, the goals to build closed-loop production systems (SS2) and to reduce waste generation (SDG 12.5) have high row sums, indicating that they hold relatively large synergetic potential. In contrast, the goals related to the bio-based economy have the lowest row sums, suggesting that they bring with them a relatively low degree of synergies. What is also evident from Table 2 is that a majority of the scores are positive, indicating that synergetic interactions are predominant in this particular network of goals.

3.3. Network diagramming

The four network diagrams in Fig. 3 visualize the presence of trade-offs and synergies in the goal implementation stage, in terms of alignment with the sustainability definition employed, and in relation to trade-offs and synergies that arise as a result of making progress in different goal areas. The input to the diagrams was derived from the cross-impact scoring performed in the previous analytical step, as presented in full in Appendix A1.

The visualization of the different types of interactions highlights that there are relatively few resource input trade-offs (Fig. 3a). Those identified were between the goals of the bio-based economy and the goal to increase the share of renewables in the energy mix (SDG 7.2). Synergies in preconditions were more common, indicating that there are many interventions in the implementation stage that could support the attainment of multiple goals. The goal to achieve a greater diversity in the forestry sector (BB1) was the goal that had most synergies in terms of shared preconditions (Fig. 3b). Further, all goals adhere to the understanding of sustainability provided by the strong sustainability paradigm (Fig. 3c). In terms of goal progress interactions, synergies again dominate (Fig. 3d). The most interconnected goal is to maintain ecosystem functioning (SS1), followed by the goal to attain closed-loop production systems (SS2) and the goal to increase the share of renewables in the energy-mix (SDG 7.2). The goal to make the current industrial mode of forestry more advanced, innovative and resource-use efficient (BBE2) does also stand out as relatively highly interconnected. Finally, the network diagramming highlights how the goals belonging to the bio-based economy may be internally conflicting.

While the goal network predominantly contains synergetic interactions, the synergy scores are relatively low (most +1, some +2, seven +3). According to the typology of interactions (Fig. 2) this means that goal progress in most areas may create beneficial conditions for making progress on other goals, but that few goals are indivisibly linked.

3.4. Key variables and causal loop diagram

Twelve variables were identified as key to the attainment of the respective goals. In the context of the bio-based economy (BBE1 and BBE2), a central variable is the *land for productive use*. It traces to what extent the forest resource is used for productive purposes or set aside for other uses. Another key variable is the *harvest residue outtake*. It indicates if the forestry industry is entering new markets, making more use of existing forest resources by allocating production side streams to energy production. Forest management choices in terms of land allocation and the harvest residue outtake affect the total *biomass supply from forestry* (BBE2). In terms of energy provision, heat and electricity production can be based on fossil or renewable sources. The variable *fossil-based fuel input* traces the energy supply that still needs to be substituted with renewables (SDG 7.2). The *heat demand supply gap* tracks whether the fuel input and production capacity are able to meet the local energy demand (SS2). The energy demand is determined by the *total heat demand* from the building stock connected to the district heating system, and may be affected by energy efficiency gains (SDG 7.3). The *waste generation rate* is the waste originating from the region (SDG 12.5). The waste may be used as a fuel input to the CHP plant. Also *waste imports* are used for energy provision if local waste generation is not sufficient or if imports are more financially viable (SS2). While part of the waste is fossil-based and part of it is organic, it is assumed that reducing the *waste fuel input* contributes to the goal to increase the share of renewables in the energy mix (SDG 7.2). The *soil C/N ratio* indicates nitrogen availability in forest soils, and serves as a key variable for ecosystem functioning (SS1). The *soil organic carbon* (SOC) serves as an indicator of the forest ecosystem functioning as a carbon sink (SS1). The net CO_2-emissions are the difference between CO_2 emitted (through burning fuel for energy) and sequestered (through photosynthesis), providing a measure of the closed-loop production system aspiration. The carbon balance is defined as the *difference in CO_2-equivalents* emitted in different energy and forest management scenarios (SS2).

The CLD in Fig. 4 visualizes how the key variables interact, highlighting feedback loops and intersectoral connections. Variables linked to the heat demand and waste generation are found in the upper right of the CLD. The customer base determines the total heat demand. New customers become connected to the district heating system until the maximum number of customers is met (balancing feedback loops B1 and B2). New customers drive the CHP plant expansion.

The upper left part of the CLD depicts variables linked to the energy supply, representing the internal functioning of the CHP plant. CHP capacity is built up over time until it reaches the desired level (balancing feedback loops B3 and B4). The energy supplied is determined by the heat demand, the installed CHP capacity, and the total fuel input to the CHP plant. The plant co-produces heat,

Table 2
Cross-impact matrix for the goals identified in the goal screening step. Synergies and trade-offs between two goals are represented by a positive or negative score, respectively. The darker the green (red) color, the stronger the synergy (trade-off) between the goals.

Goals	BBE1	BBE2	SDG 7.2	SDG 7.3	SDG 12.5	SS1	SS2	Row sum
BBE1	-	-1	2	1	1	5	1	**9**
BBE2	0	-	1	2	1	2	2	**8**
SDG 7.2	1	1	-	1	2	1	5	**11**
SDG 7.3	1	1	2	-	3	2	2	**11**
SDG 12.5	1	1	1	3	-	3	5	**14**
SS1	5	4	4	1	1	-	4	**19**
SS2	1	1	4	1	4	3	-	**14**

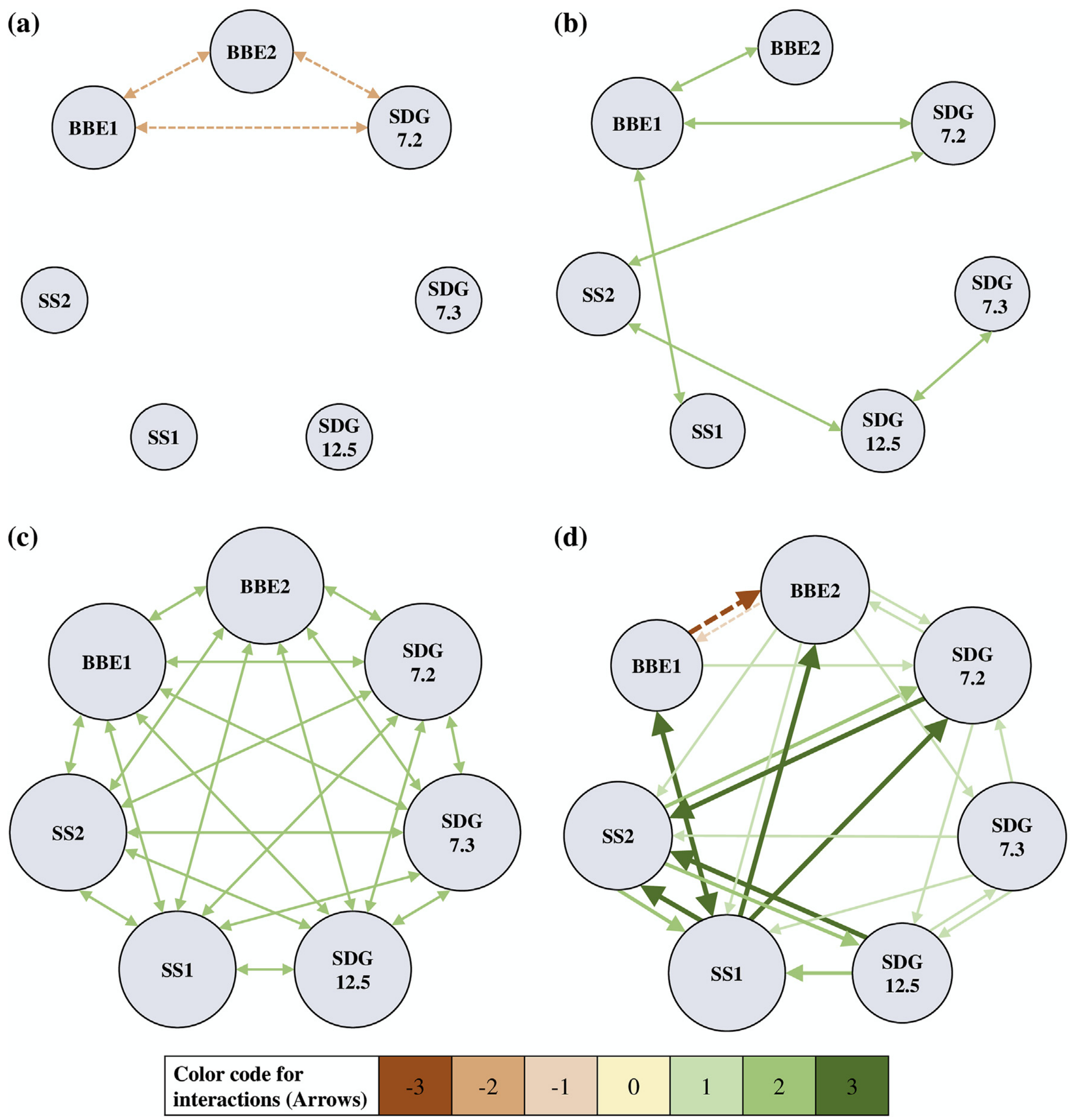

Fig. 3. a-d. Network diagrams showing a) trade-offs in resource inputs, b) synergies steaming from shared preconditions, c) consistency in underlying understanding of sustainability, and d) goal progress interactions. The diagrams indicate trade-offs (orange dashed lines), synergies (full green lines), strength of the interactions (line thickness and color), and goal interconnectedness (node size). For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.

electricity, and steam, but the demand for district heating is the main determinant of the capacity utilization. The plant has different boilers, using fuel inputs from household and industrial waste, fossil-based resources (coal/oil), and biomass. The boilers utilizing waste are used first, as there is a financial compensation for waste handling. The boilers running on biomass are next in line, while fossil-based boilers are least financially and environmentally viable and therefore used last.

The bottom part of the CLD captures the variables linked to the biophysical basis of the forestry sector, such as the C/N ratio and soil organic carbon. Forest biomass growth and regeneration is governed by multiple feedback loops, e.g., the reinforcing feedback of nutrient cycling (R1). There are also balancing feedback loops, such as those linked to decomposition of soil organic carbon (B5) and the harvest residue outtake (B8-9). In combination, these dynamics govern how much locally sourced biomass is available as fuel input to the CHP plant.

3.5. Simulation-based analysis

3.5.1. Scenario specification

Three scenarios (Sc1-Sc3) were developed to analyze how the key variables change over time, as governed by the feedback loops presented in the CLD in Fig. 4. The first scenario (Sc1) explores what happens with the remaining goals if progress is made on the goal of making the existing forestry industry more advanced and resource-use efficient (BBE2). The forest management model employed to reach BBE2 entails maximizing productive forest land and biomass volumes. Harvest residues are collected both at thinning and final felling and sent to the CHP plant. Thereby, the forestry industry utilizes the forest resource to a relatively large extent, turning production side-streams into an energy resource.

The second scenario (Sc2) explores what happens to the other goals if progress is made on the goal of making the forestry sector more diverse (BBE1). Sc2 assumes that no forest land is in

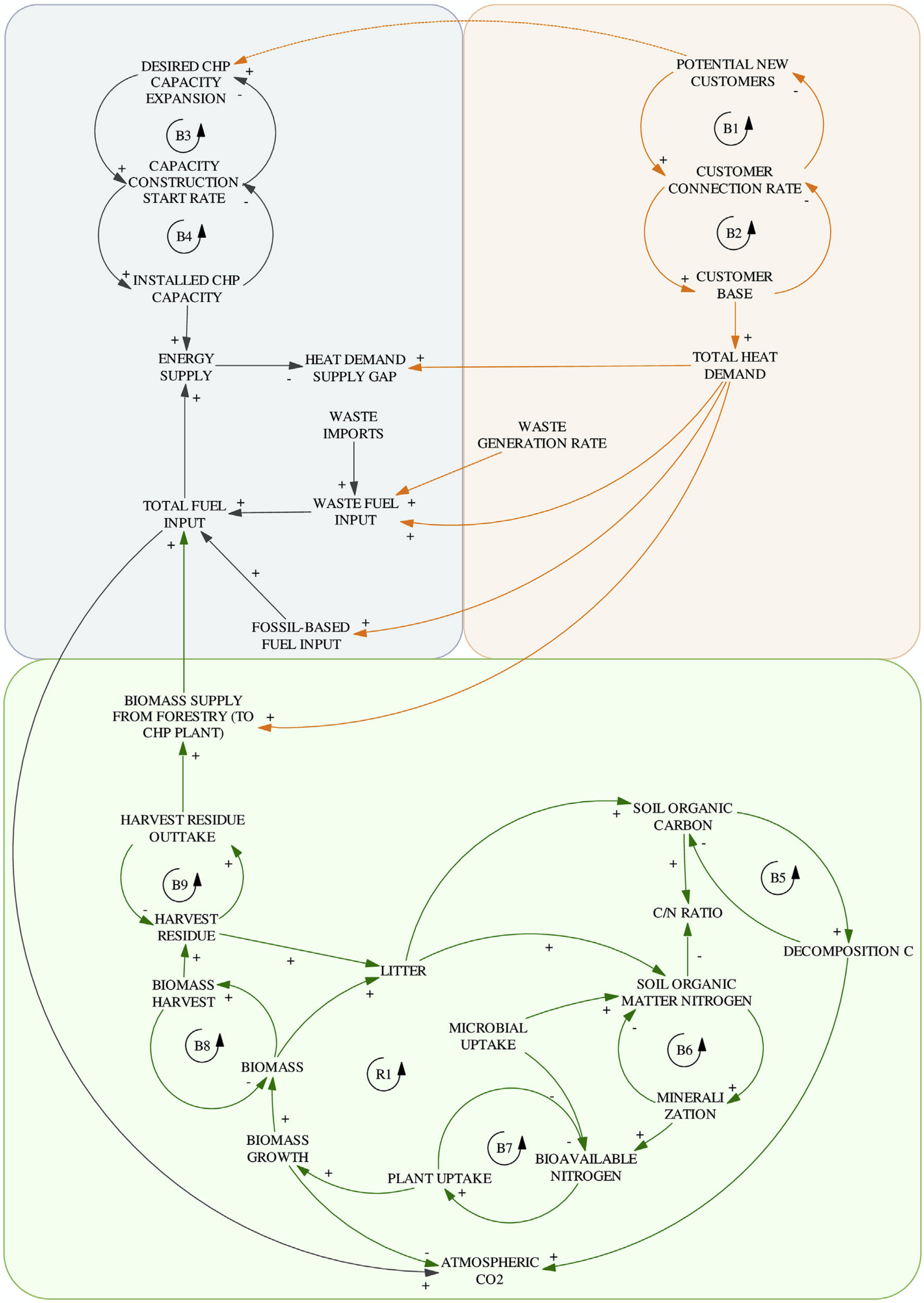

Fig. 4. Causal loop diagram capturing interactions between key variables linked to energy supply (upper left), energy demand (upper right), and forestry (bottom).

productive use, which then implies that no harvest residue is available for energy production. While a development where all productive forest land would be turned into, for example, conservation or recreational areas is not realistic, Sc2 offers a base-line and way to contrast goal progress as taken to its extreme.

The third scenario (Sc3) explores simultaneous progress on multiple goals. Forest management is the same as in Sc2, meaning that no forest is in productive use. Further, progress on SDG 7.2

restricts the use of fossil fuels in the CHP plant, energy efficiency gains are realized in line with progress on SDG 7.3, and progress on SDG 12.5 reduces the waste generation rate. At the same time, an ambition to make progress on the closed-loop production system goal restricts waste imports.

Table 3 specifies assumptions and parameter values for each scenario. In general, the time horizon for the analysis spans from year 2010−2050. The exception is for the forestry sector variables where the time horizon is extended to year 2300, as the impacts of forest management decisions become visible only over several rotation periods. The full model documentation is provided in Appendix A2.

3.5.2. Simulation results

The simulations show the behavior of the key variables in the period 2010−2050 (for forestry-related variables 2010−2300).

Fig. 5a shows the biomass supply from forestry. In Sc1, harvest residues from local sources are available as fuel for the CHP plant, starting from 2018. Harvest residues are extracted at thinning and final felling, with biomass supplies ranging from approximately 41,000 to 77,000 tonnes/year over the simulation period. The biomass supply peaks between 2057 and 2065, then declines over time. The decline is partly a result of exogenous factors that limit forest biomass growth, i.e., higher mean temperatures in combination with constant precipitation. With lower biomass growth, and thus less litter and harvest residues, endogenous feedback loops linked to nutrient availability further restrict biomass growth. The harvest residue outtake also reduces the nutrient availability over the simulated period, thereby contributing to the declining biomass growth rate. In Sc2 and Sc3, no forest is in productive use and the harvest residue outtake is zero, which implies that biomass from local forest resources is not available for energy production.

There is a choice between using fuel inputs from waste, biomass, and fossil-based resources in the CHP plant. Fig. 5b shows the use of fossil-based fuel input for the different scenarios, where a reduction in use of fossil-based fuel input indicates progress on SDG 7.2. In Sc1, the fuel inputs to the CHP plant are primarily biomass and waste. The fossil-based fuel input starts at 353 GWh in 2010. It then stabilizes at around 300 GWh between 2018 and 2021, and thereafter steadily declines to reach zero at 2045. In Sc2, the use of fossil-based fuel input is higher as biomass from local sources is not available. The use of fossil-based fuel input shows a similar pattern to Sc1, with an initial peak and subsequent decline over time, to 211 GWh in 2050. Sc3 prohibits the use of fossil fuels from 2018.

Fig. 5c presents the development of the heat demand supply gap. The heat demand supply gap is zero in both Sc1 and Sc2, which implies that energy provision is secured. In contrast, with strict limits to local biomass supplies and restrictions to the use of fossil-based resources, Sc3 results in a positive heat demand supply gap. The maximum deficit is 991 GWh/year early in the simulated period, but then declines over time due to energy efficiency gains. The deficit in 2050 is 555 GWh, demonstrating how energy efficiency measures may substantially reduce heat demand.

Fig. 5d depicts the waste fuel input used in the CHP plant, indicating a continuous dependency on waste as a fuel input in both Sc1 and Sc2. The maximum waste fuel input in both scenarios occurs in year 2014, providing approximately 682 GWh. From 2018 and onwards the use of waste is restricted to the value of that year (max. 668 GWh/year), but this still permits relatively extensive use of waste in the CHP plant. In Sc3, no waste imports are allowed and efforts are made to reduce the local waste generation rate, which consequently limit the use of waste as a fuel input and thereby aid progress on SDG 7.2. The energy provision from waste in Sc3 ranges from 682 GWh in 2014 to 49 GWh in 2050.

Fig. 5e shows the soil C/N ratio. The soil C/N ratio starts from relatively high levels, but declines for all scenarios over the simulated period. The reference C/N ratio is 37.4 (year 2010), then declining to 30.3 in Sc1 and 27.3 in Sc2 and Sc3 (year 2300). The higher soil C/N ratio in Sc1 is explained by the removal of nutrients following the harvest residue outtake.

Fig. 5f displays changes to soil organic carbon. Forest management affects the SOC level. In Sc2 and Sc3, SOC levels increase until 2160, and decrease thereafter. Natural recycling of nutrients through tree death and litterfall contributes to the build-up of SOC. The decline in SOC after 2160 is explained by the combination of higher annual mean temperatures and steady precipitation rates that restricts biomass growth. In Sc1, the levels of SOC are lower and show a steeper decline. The final difference in SOC between Sc1 and Sc2/Sc3 is −10.4 tonnes/hectare (representing an annual loss 0.037 tonnes/hectare). The final difference in terms of CO_2-equivalents is −2,700,976 tonnes (an annual loss of 9578 tonnes CO_2-equivalents). The difference is explained by the removal of

Table 3
Scenario specification.

Sustainability goal	Variable	Scenario		
		Intensive use (Sc1)	Diversified (Sc2)	Strict sustainability (Sc3)
BBE1; BBE2	Land for productive use (ha)	71,102	0	0
BBE1; BBE2	Harvest residue outtake fraction (percentage)	20% at both thinning and final felling	0	0
BBE2	Biomass supply from forestry (tonnes/year)	Endogenous	Endogenous	Endogenous
SDG 7.2	Fossil-based fuel input (GWh/year)	Endogenous	Endogenous	0 from 2018
SDG 7.2	Waste fuel input (GWh/year)	Endogenous	Endogenous	Endogenous
SDG 7.3	Total heat demand (GWh/year)	16% reduction from ref. year 2020−2035, 26% by 2050	16% reduction from ref. year 2020−2035, 26% by 2050	34% reduction from ref. year 2020−2035, 44% by 2050
SDG 12.5	Waste generation rate (tonnes/year)	27,000	27,000	40% reduction by 2050
SS1	Soil organic carbon (tonnes/year)	Endogenous	Endogenous	Endogenous
SS1	Soil C/N ratio	Endogenous	Endogenous	Endogenous
SS2	Waste imports (tonnes/year)	Endogenous	Endogenous	0 from year 2018
SS2	Heat demand supply gap (GWh/year)	Endogenous	Endogenous	Endogenous
SS2	Difference in CO_2-equivalents (tonnes/year)	Endogenous	Endogenous	Endogenous

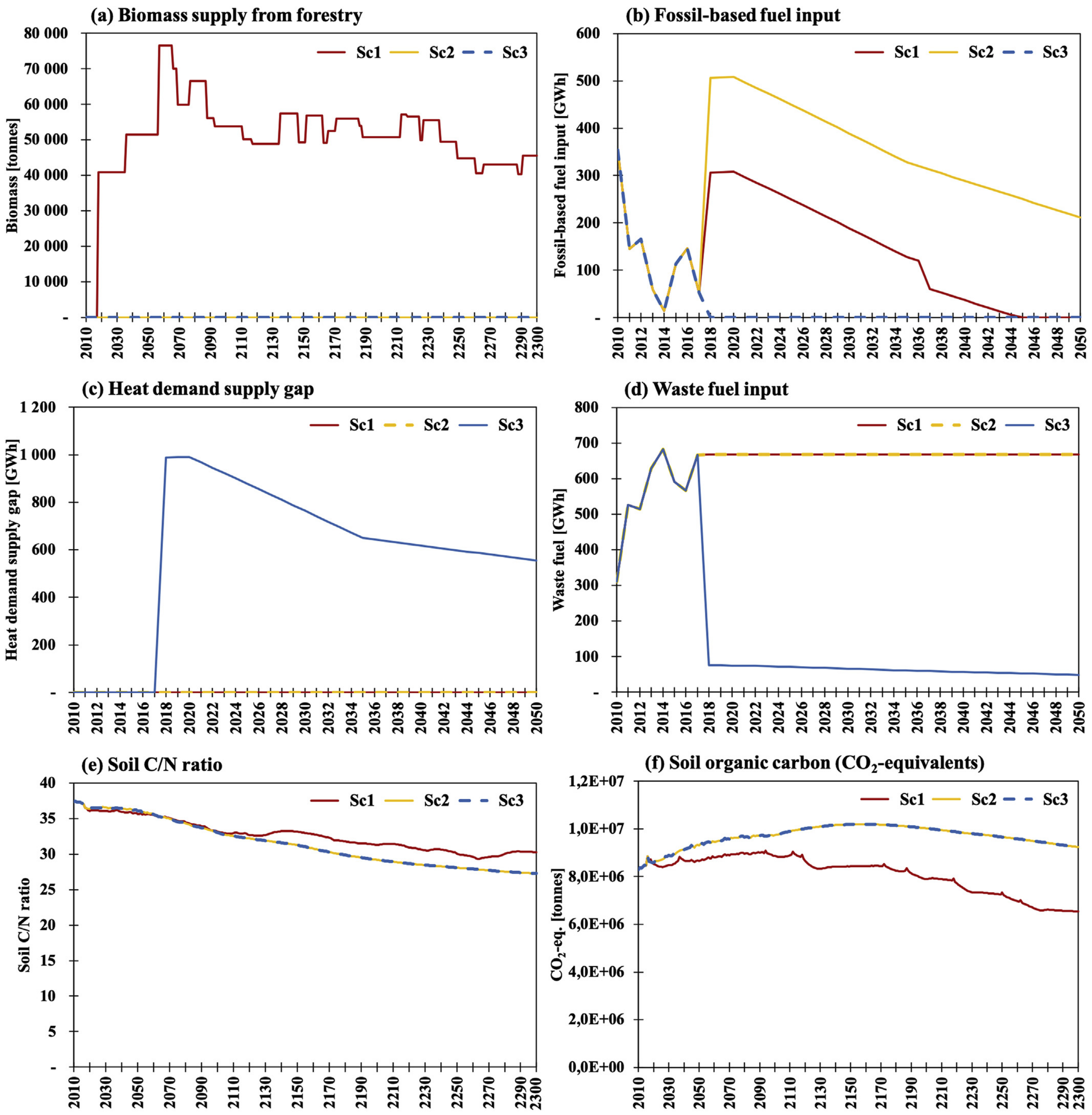

Fig. 5. a-f. Simulated results for the three scenarios described in 3.5.1. The graphs show how the biomass supply from forestry, fossil-based fuel input, heat demand supply gap, waste fuel input, soil C/N ratio, and soil organic carbon develop over time in the different scenarios.

substrate in the form of forest residue following the harvest residue outtake in Sc1.

The CO_2-emissions in the different scenarios vary depending on the fuel input used in the CHP plant and the forest management model employed. Fig. 6 shows the difference in CO_2-equivalents emitted in the simulated scenarios, calculated as the CO_2-equivalents emitted in the low intensive forest management scenario (Sc2/Sc3) minus the net emissions in the high intensive forest management scenario (Sc1). The results show that in Sc1, as compared to Sc2/3, there is a reduction in CO_2-equivalents emitted, ranging from 56,000 to 73,000 tonnes/year. Hence, the loss of SOC in Sc1 (resulting from the intensive forest management model) is compensated for as the use of forest biomass in the CHP plant supports the phasing out of fossil fuels. Moreover, not all forest biomass available in SC1 is needed as a fuel input, due to the boiler capacity and priority order. Thus, biomass is available to replace additional fossil-based energy resources in the municipality, holding the potential to generate further climate benefits.

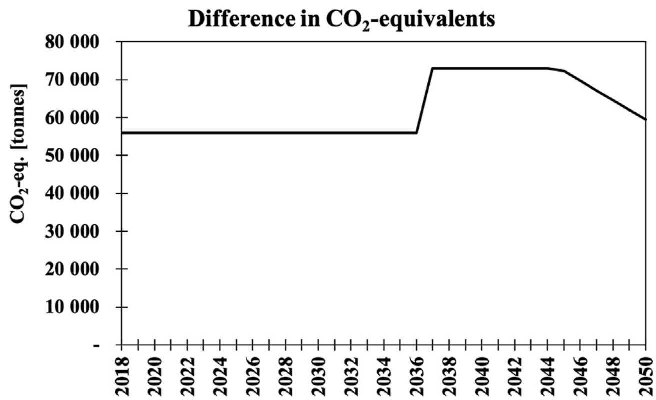

Fig. 6. Difference (potential reduction) in CO_2-emissions (in CO_2-equvivalents) between the intensive forest management scenario (Sc1) and the diversification (Sc2)/strict sustainability (Sc3) scenarios.

4. Discussion

4.1. Policy implications

The case of Norrköping captures how global and national policy agendas play out at the regional scale. A number of implications for priority setting and the development of coherent implementation strategies follow from the results. The outputs from the cross-impact analysis indicate that the goals related to maintaining critical natural capital (SS1), achieving closed-loop production systems (SS2), and waste management (SDG 12.5) should get priority. Pursuing strategies linked to these goals holds the potential to positively influence the attainment of several other goals. Less resources should be allocated to the goals of the bio-based economy, as the cross-impact analysis suggests that they are relatively less synergetic.

The network diagramming provided more detailed information on the nature of the goal interactions. Trade-offs in terms of competition for resource inputs between the goals of the bio-based economy and increasing the share of renewables in the energy mix (SDG 7.2) were highlighted. These trade-offs imply that critical choices on resource allocation have to be made. In contrast, the results suggest that the remaining goals do not compete for resource inputs, which makes their implementation relatively easier. The network diagrams also provide more detailed information on the presence of shared preconditions, where the goal to facilitate a shift to diversified forestry (BBE1) stands out as specifically synergetic. This nuances the picture of BBE1 as a goal with few synergies. In terms of goal progress interactions, the two goals related to the bio-based economy are internally conflicting, which again strengthens the argument for giving them low priority. In contrast, SS1, SS2 and SDG 7.2 stand out as highly interconnected and synergetic. This ranking is similar to the output from the cross-impact matrix, with the difference that SDG 7.2 and not SDG 12.5 appears to be relatively more synergetic. Overall, the many positive interactions but generally low synergy scores seen in the network diagrams imply that goal progress in parts of the network of goals aids overall progress, but that the effects may be small.

The conceptual modeling and simulation-based analysis added to the output from previous steps by identifying dynamic and systemic interactions over time. The results show that, despite the large number of synergies found in previous steps, it is seemingly difficult to realize coherent implementation strategies across all goals. Instead, two bundles of internally coherent goals emerged. Additionally, the two goals of the bio-based economy came forward as central in a transition process. This as they serve as the foundation for making progress on many other goals.

A first cluster of coherent goals emerged in Sc1, demonstrating the potential to leverage synergies between making the existing industrial forestry structure more advanced (BBE2), SDG 7.2 and SS2. This as progress on BBE2 brings relatively large biomass quantities for energy production, which increases the share of renewables in the energy mix while the local demand for heat is met. However, trade-offs that were largely silent in the previous analytical steps also become apparent. The optimum range for the C/N ratio is 25–30 (Gundersen et al., 2006). Sc1 exceeds the optimum range at the end of the simulated period, which is not the case in Sc2/Sc3, indicating an increased risk of nutrient imbalance or limitation. Thus, relative to the less intensive forest management pursued in Sc2/Sc3, forest management in Sc1 does not contribute to SS1 to the same extent. Additionally, progress on BBE2 results in a loss of SOC, further compromising progress on SS1. However, if forest harvest residues are used to replace fossil-based resources for energy production, the results indicate that there is still a climate benefit in terms of reducing CO_2-emissions. Hence, climate change mitigation could motivate intensive forest management in this case, despite SOC losses.

The second cluster of coherent goals was found in Sc2. In this scenario, progress is made on BBE1, providing an opportunity to compare impacts of different forest management practices. The loss of SOC is lower than under the intensive forest management scenario and the final C/N ratio is within the optimal range, stressing that progress on BBE1 may be beneficial to the attainment of SS1. However, while the local energy demand is still met in this scenario, energy production is to a larger extent based on the use of fossil fuels. Thus, a goal conflict is created between BBE1 and SDG 7.2, as well as between BBE1 and SS2.

Sc3 entails maximizing progress on BBE1 in a similar manner as in Sc2, but also entails advancing progress in other areas. The results show that limited availability of local biomass (through progress on BBE1), waste (through progress on SDG 12.5 and SS2), and a reduction in the use of fossil-based resources (progress on SDG 7.2) make it difficult to meet local heat demand (compromising the attainment of closed-loop production systems in accordance with SS2). Another finding is that energy efficiency (SDG 7.3) plays a more important role than what was indicated by the previous analytical steps, as it helps mitigate trade-offs. However, despite substantial energy efficiency gains, it was still not possible meet local heat demand in Sc3. Hence, Sc3 demonstrates the difficulty in finding broad reaching and coherent strategies that generate simultaneous progress on all goals.

Finally, the results emphasize that facilitating progress that adheres to the principles of strong sustainability might be challenging. While theoretically possible, it may be practically difficult to simultaneously fulfill its requirements, as demonstrated by the lack of scenarios where both closed-loop production systems and protection of critical natural capital were achieved. These findings are in line with previous studies on the relationship between the bio-based economy and sustainability (D'Amato et al., 2017; Ramcilovic-Suominen and Pülzl, 2018; Vivien et al., 2019). A critical next step in the implementation of the bio-based economy and the 2030 Agenda is thus to find conditions where their respective goals can contribute to strong sustainability.

4.2. Strengths and limitations of the analytical approach

The analytical framework applied in the present paper aims to provide an integrated basis for prioritizing among sustainability goals and for developing coherent strategies for goal attainment. One strength of the approach is that the steps of the analysis help create an understanding of what global agendas and initiatives mean in context. For the bio-based economy, one challenge in this respect is its broad reach, and the need to derive specific goals from the many possible focus areas linked to the use of biological resources. For the 2030 Agenda, the challenge lies in translating global goals to national, regional, and local contexts. For the strong sustainability paradigm, a challenge lies in using the concepts it provides (e.g., critical natural capital) to guide practical action. The analytical framework allows for critical discussion on what constitutes a goal, definitions, and on the meanings of the terms used.

Another strength of the approach is its ability to account for and contrast multiple understandings of goal interactions through methodological triangulation. The methods included in the framework emphasize different features of goal interactions, thereby bringing complementary perspectives. The cross-impact analysis and network diagramming focus specifically on direct and pairwise interactions. Conceptual modeling and simulation-based analysis instead take a feedback perspective, highlighting that key variables are often both drivers and indicators of change embedded in larger systems structures. Simulation-based analysis also provides quantitative measures of interactions over time, accounting for delays and potential non-linear effects. Additionally, the methods included in the framework have in common that they are transparent, providing a visual account of how the goals interact, which could enable critical discussion and learning among stakeholders. The ability to elicit and integrate different perspectives on goal interactions is specifically important in sustainability transitions, as they are characterized by large uncertainty, unstructured problem spaces, and contested issues.

A potential weakness of the approach is that the assessment is sensitive to the input data, whether provided by stakeholders, experts, or the scientific literature. Despite the objective to contrast and find reasons for contradictory results, errors may be transmitted through the different analytical steps. Further, sustainability transitions entail changes to causal structures, i.e., changes to the way sustainability goals interact. Such changes are not well captured by the methods included in the analytical framework. A way to address this could be to add emphasis to the scenario analysis, to build more elaborate narratives, and to develop alternative storylines linked to potential future goal interactions and their implications. Finally, some limitations of our study may be derived from the way the framework was applied. For example, given the relatively low number of goal interactions assessed, the network analysis in the present application was limited to network diagramming. However, we strongly believe that quantitative network analysis would be a useful tool in a context where a larger set of goals is analyzed, as it allows for calculations of network density, centrality, or the distance between two interconnected goals. These additional metrics could support policy prioritization. For example, they could help single out highly connected goals with large systemic impact or identify goals that need special attention as their fulfillment is not aided by progress on other goals. These metrics could also help establish collaborations across traditional departments and stakeholder groups. Finally, a higher degree of stakeholder engagement should be supported in future applications of the framework, if seeking to strengthen the ability to integrate different perspectives, enable critical discussion, and inform decision-making.

5. Conclusions

Global sustainability agendas have ramifications in national, regional and local contexts. This study demonstrated how goals linked to the bio-based economy, the 2030 Agenda and SDGs, and the strong sustainability paradigm interact in a regional setting. A large number of synergies were found across the network of goals included in the analysis. Specifically, two bundles of coherent and mutually supporting goals were identified. The first cluster includes a development toward making the existing structure of the forestry industry more advanced and resource-use efficient, increasing the share of renewables in the energy mix, and building closed-loop production systems. The second cluster encompasses the goal to support a structural shift in the forestry industry (to realize greater diversity in practices, species, and forest values), and the goal to maintain and protect critical natural capital. However, multiple trade-offs exist between these two clusters, implying that simultaneous progress on all goals might be difficult to realize.

Another finding is that the goal priority order (based on the ambition to maximize synergies and mitigate trade-offs) changed with the method employed, stressing the need for methodological triangulation, and that disaggregation and extended time horizons are crucial for detecting trade-offs and synergies. Finally, the results show how all goals hold theoretical potential to contribute to sustainability in accordance with the notion of strong sustainability, as suggested by the cross-impact analysis. However, this theoretical potential may be difficult to realize in practice, given that the quantitative simulation-based analysis did not find any scenarios that resulted in simultaneously fulfilling the goals of strong sustainability (i.e., maintaining critical natural capital and achieving closed-loop production systems).

There are several opportunities for future research in the context of the Norrköping case. A larger number of the sustainability challenges facing the region in the coming years could be reflected in the analysis, for example by expanding the boundaries to include the agricultural sector and additional energy supply-demand dynamics. Also, research exploring how to develop coherent strategies in support of strong sustainability is critical. Finally, applying the analytical framework in a way that supports a higher degree of stakeholder participation could be a way to enable learning, critical discussion, and ownership of the results. Thereby, the ability of the sustainability roadmaps included in the analysis to effectively meet cross-cutting challenges on the regional scale could be enhanced.

In conclusion, agendas and initiatives for sustainability are currently developing in parallel, but may still be overlapping and mutually interacting. Our study presents a case where there is significant potential to utilize synergetic effects in the implementation of different sustainability initiatives. At the same time, there are no all-encompassing win-win scenarios. Critical choices have to be made, and integrated analysis of goal interactions may be one way to support priority setting and strategy development in such contexts.

CRediT authorship contribution statement

TB designed the study. TB, SB, IS, and AD carried out the cross-impact scoring. TB and SB jointly developed the simulation model. All authors contributed to the analysis and the writing proces

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A1 and A2. Supplementary data

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References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., Lang, D.J., 2017. Leverage points for sustainability transformation. Ambio 46, 30–39. https://doi.org/10.1007/s13280-016-0800-y.

Allen, C., Metternicht, G., Wiedmann, T., 2016. National pathways to the Sustainable Development Goals (SDGs): a comparative review of scenario modelling tools. Environ. Sci. Pol. 66, 199–207. https://doi.org/10.1016/j.envsci.2016.09.008.

Antikainen, R., Dalhammar, C., Hildén, M., Judl, J., Jääskeläinen, T., Kautto, P., Koskela, S., Kuisma, M., Lazarevic, D., Mäenpää, I., Ovaska, J.-P., Peck, P., Rodhe, H., Temmes, A., Thidell, Å., 2017. Renewal of Forest Based Manufacturing towards a Sustainable Circular Bioeconomy (Reports of the Finnish Environment Institute No. 13). Finnish Environment Institute (SYKE), Helsinki, Finland.

Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. Syst. Dynam. Rev. 12, 183–210.

Baumgärtner, S., Quaas, M.F., 2009. Ecological-economic viability as a criterion of strong sustainability under uncertainty. Ecol. Econ. 68, 2008–2020. https://doi.org/10.1016/j.ecolecon.2009.01.016.

Beckerman, W., 1994. "Sustainable development": is it a useful concept? Environ. Val. 3, 191–209.

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.

Berlina, A., Lindberg, G., Mikkola, N., Smed Olsen, L., Teräs, J., 2015. The Potential of Industrial Symbiosis as a Key Driver of Green Growth in Nordic Regions (Nordregio Report No. 2015:1). Nordic Centre for Spatial Development (Nordregio), Stockholm, Sweden.

Bowen, K.J., Cradock-Henry, N.A., Koch, F., Patterson, J., Häyhä, T., Vogt, J., Barbi, F., 2017. Implementing the "Sustainable Development Goals": towards addressing three key governance challenges—collective action, trade-offs, and accountability. Curr. Opin. Env. Sust. 26 (27), 90–96. https://doi.org/10.1016/j.cosust.2017.05.002.

County Administrative Board Östergötland, 2014. Regionalt Miljöövervaknin gsprogram I Östergötlands Län 2015-2020.

Dedeurwaerdere, T., 2014. Sustainability Science for Strong Sustainability. Université catholique de Louvain and Fonds National de la Recherche Scientifique, Belgium. https://doi.org/10.4337/9781783474561.

Dietz, S., Neumayer, E., 2007. Weak and strong sustainability in the SEEA: concepts and measurement. Ecol. Econ. 61, 617–626. https://doi.org/10.1016/j.ecolecon.2006.09.007.

Dorninger, C., Abson, D.J., Apetrei, C.I., Derwort, P., Ives, C.D., Klaniecki, K., Lam, D.P.M., Langsenlehner, M., Riechers, M., Spittler, N., von Wehrden, H., 2020. Leverage points for sustainability transformation: a review on interventions in food and energy systems. Ecol. Econ. 171, 106570 https://doi.org/10.1016/j.ecolecon.2019.106570.

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B.D., Toppinen, A., 2017. Green, circular, bio economy: a comparative analysis of sustainability avenues. J. Clean. Prod. 168, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053.

Ekins, P., Simon, R., Deutsch, L., Folke, C., De, R., E, G., 2003. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecol. Econ. 165–185. https://doi.org/10.1016/S0921-8009(02)00272-0.

El-Chichakli, B., Braun, J. von, Lang, C., Barben, D., Philp, J., 2016. Five cornerstones of a global bioeconomy. Nature 535, 221–223. https://doi.org/10.1038/535221a.

European Commission, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy. society and the environment Updated Bioeconomy Strategy, Brussels.

Fader, M., Cranmer, C., Lawford, R., Engel-Cox, J., 2018. Toward an understanding of synergies and trade-offs between water, energy, and food SDG targets. Front. Environ. Sci. 6, 1–11. https://doi.org/10.3389/fenvs.2018.00112.

Fischer, J., Riechers, M., 2019. A leverage points perspective on sustainability. People Nat. 1, 115–120. https://doi.org/10.1002/pan3.13.

Fischer, J., Manning, A.D., Steffen, W., Rose, D.B., Daniell, K., Felton, A., Garnett, S., Gilna, B., Heinsohn, R., Lindenmayer, D.B., MacDonald, B., Mills, F., Newell, B., Reid, J., Robin, L., Sherren, K., Wade, A., 2007. Mind the sustainability gap. Trends Ecol. Evol. 22, 621–624. https://doi.org/10.1016/j.tree.2007.08.016.

Formas, 2012. Swedish Research and Innovation Strategy for a Bio-Based Economy. Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), Stockholm.

Forrester, J.W., 2009. Some Basic Concepts in System Dynamics. Sloan School of Management Massachusetts Institute of Technology, Boston.

Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests — effects of air pollution and forest management. Environ. Rev. 14, 1–57. https://doi.org/10.1139/a05-015.

Heimann, T., 2018. Bioeconomy and SDGs: does the bioeconomy support the achievement of the SDGs? Earth's Future 7, 43–57. https://doi.org/10.1029/2018EF001014.

ICSU, 2017. A Guide to SDG Interactions: from Science to Implementation. International Council for Science (ICSU), Paris, France. https://doi.org/10.24948/2017.01.

IEA, 2010. Combined Heat and Power [WWW Document]. https://iea-etsap.org/E-TechDS/PDF/E04-CHP-GS-gct_ADfinal.pdf (accessed 6.20.25).

Issa, I., Delbrück, S., Hamm, U., 2019. Bioeconomy from experts' perspectives — results of a global expert survey. PloS One 14, e0215917. https://doi.org/10.1371/journal.pone.0215917.

Johansson, L.C., 2014. E.ON Värme Sverige AB Panna 11, Händelöverket — Eldning av returträ Temadag Skadegruppen [WWW Document]. https://www.vok.nu/wp-content/uploads/2014/11/Erfarenheter-från-Panna-11-Händelöverket.pdf (accessed 6.6.20).

Kallis, G., March, H., 2015. Imaginaries of hope: the utopianism of degrowth. Ann. Assoc. Am. Geogr. 105, 360–368. https://doi.org/10.1080/00045608.2014.973803.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Tr. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Kopainsky, B., Tribaldos, T., Ledermann, S.T., 2018. A food systems perspective for food and nutrition security beyond the post-2015 development agenda. Syst. Res. Behav. Sci. 35, 178–190. https://doi.org/10.1002/sres.2458.

Lane, D.C., 2008. The emergence and use of diagramming in system dynamics: a critical account. Syst. Res. 25, 3–23. https://doi.org/10.1002/sres.826.

Leach, M., Stirling, A.C., Scoones, I., 2010. Dynamic Sustainabilities: Technology, Environment, Social Justice, Pathways to Sustainability. Routledge, London.

LiU, 2020a. Industrial Symbiosis in Sweden - Norrköping Industrial Symbiosis Network [WWW Document]. URL. http://www.industriellekologi.se/symbiosis/norrkoping.html (accessed 3.23.20).

LiU, 2020b. Norrköpings framtida fjärrvärmemarknad [WWW Document]. URL. https://liu.se/artikel/norrkopings-framtida-fjarrvarmemarknad (accessed 6.26.20).

Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K.C., Gleick, P., Kremen, C., Li, S., 2015. Systems integration for global sustainability. Science 347, 1258832. https://doi.org/10.1126/science.1258832.

Ljungberg, S., 2018. Will Substituting Fossil Fuels with Biofuels Lead to a Net Reduction in CO2 Emissions? — the Case of District Heating in Norrköping Municipality. Stockholm University, Department of Physical Geography, Stockholm, Sweden.

Loiseau, E., Saikku, L., Antikainen, R., Droste, N., Hansjürgens, B., Pitkänen, K., Leskinen, P., Kuikman, P., Thomsen, M., 2016. Green economy and related concepts: an overview. J. Clean. Prod. 139, 361–371. https://doi.org/10.1016/j.jclepro.2016.08.024.

McCormick, K., Kautto, N., 2013. The bioeconomy in europe: an overview. Sustainability 5, 2589–2608. https://doi.org/10.3390/su5062589.

Neumayer, E., 2003. Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms. Edward Elgar Publishing, Cheltenham, UK.

Newman, M., Barabási, A.L., Watts, D.J., 2006. The Structure and Dynamics of Networks. Princeton University Press.

Nilsson, M., Griggs, D., Visbeck, M., 2016. Map the interactions between sustainable development goals. Nature 534, 320–322. https://doi.org/10.1038/534320a.

Nilsson, M., Chisholm, E., Griggs, D., Howden-Chapman, P., McCollum, D., Messerli, P., Neumann, B., Stevance, A.-S., Visbeck, M., Stafford-Smith, M., 2018. Mapping interactions between the sustainable development goals: lessons learned and ways forward. Sustain. Sci. 13, 1489–1503. https://doi.org/10.1007/s11625-018-0604-z.

Norgaard, R.B., 1994. Development Betrayed: the End of Progress and a Co-evolutionary Revisioning of the Future. Routledge, London.

Norrköping Municipality, 2009. Energiplan för Norrköpings kommun 2009-2030.

Norrköping Municipality, 2017. KS 2017/0149 Inriktningsdokument för miljöpolitiken i Norrköpings kommun.

Norrköping Municipality, 2019. Avfallsplan - Samrådsversion.

Norrköping Rådhus AB, 2019. Norrköping Rådhus AB 2018 - Hållbarhetsrapport [WWW Document]. https://norrkoping.se/download/18.65a4e56e1692a008d701326/1553590355737/RadhusAB-hållbarhetsrapport.pdf (accessed 3.23.20).

Norrköping Municipality, 2020. Municipal facts 2019 [WWW Document]. https://www.norrkoping.se/download/18.2b7f0b9316b3fde7751b7f/1561450381664/NKPG_i_siffror_2019_engelska.pdf (accessed 3.23.20).

OECD, 2009. The Bioeconomy to 2030 Designing a Policy Agenda - Main Findings and Policy Conclusions. Organisation for Economic Co-operation and Development (OECD).

Parker, J., 2014. Changing material practices 'Techné' and technology. In: Critiquing Sustainability, Changing Philosophy, Routledge Studies in Sustainability. Taylor & Francis Group, London; New York.

Pelenc, J., Ballet, J., 2015. Strong sustainability, critical natural capital and the capability approach. Ecol. Econ. 112, 36–44. https://doi.org/10.1016/j.ecolecon.2015.02.006.

Ramcilovic-Suominen, S., Pülzl, H., 2018. Sustainable development — a 'selling point' of the emerging EU bioeconomy policy framework? J. Clean. Prod. 172, 4170–4180. https://doi.org/10.1016/j.jclepro.2016.12.157.

Raworth, K., 2012. A safe and just space for humanity: can we live within the doughnut. Oxfam Discussion Papers 8, 1–26.
Region of Östergötland, 2017. Bio-economy Roadmap for the Region of Östergötland (Handlingsplan för bioekonomi i Östergötland).
Reime, M., Røste, R., Almasi, A., Coenen, L., 2016. Report: the Circular Bioeconomy in Scandinavia. SusValueWaste, Oslo, Norway.
Richardson, G.P., 2011. Reflections on the foundations of system dynamics. Syst. Dynam. Rev. 27, 219–243. https://doi.org/10.1002/sdr.462.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.
Skog, E., 2011. P15-projektet, Händelö [WWW Document]. URL. https://www.vok.nu/wp-content/uploads/2013/11/Panndagarna2011_Erik_Skog.pdf (accessed 6.20.25).
SOU, 2017. Kraftsamling För Framtidens Energi - Betänkande Av Energikommissionen. Statens Offentliga Utredningar, Stockholm.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347, 1259855. https://doi.org/10.1126/science.1259855.
Sterman, J.D., 2009. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, Boston.
Swedenergy, 2020. Tillförd energi till fjärrvärme och kraftvärme - äldre statistik [WWW Document]. https://www.energiforetagen.se/statistik/fjarrvarmestatistik/tillford-energi/tillford-energi-till-fjarrvarme-och-kraftvarme/ (accessed 6.6.20).
Truchy, A., Angeler, D.G., Sponseller, R.A., Johnson, R.K., McKie, B.G., 2015. Linking biodiversity, ecosystem functioning and services, and ecological resilience. Advances in Ecological Research. Elsevier, pp. 55–96. https://doi.org/10.1016/bs.aecr.2015.09.004.
UN, 2020a. Sustainable Development Goal 7 - Ensure access to affordable, reliable, sustainable and modern energy for all [WWW Document]. https://sustainabledevelopment.un.org/sdg7 (accessed 2.3.20).
UN, 2020b. Sustainable Development Goal 12 - Ensure sustainable consumption and production patterns [WWW Document]. https://sustainabledevelopment.un.org/sdg12 (accessed 2.3.20).
UN General Assembly, 2015. Transforming our world: the 2030 agenda for sustainable development - resolution A/RES/70/1 adopted by the general assembly on 25 september 2015 [WWW Document]. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, 5.12.20.
Vivien, F.-D., Nieddu, M., Befort, N., Debref, R., Giampietro, M., 2019. The hijacking of the bioeconomy. Ecol. Econ. 159, 189–197. https://doi.org/10.1016/j.ecolecon.2019.01.027.
Wallman, P., Svensson, M.G.E., Sverdrup, H., Belyazid, S., 2005. ForSAFE—an integrated process-oriented forest model for long-term sustainability assessments. For. Ecol. Manag. 207, 19–36. https://doi.org/10.1016/j.foreco.2004.10.016.
Weitz, N., Carlsen, H., Nilsson, M., Skånberg, K., 2017. Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustain. Sci. 13, 531–548. https://doi.org/10.1007/s11625-017-0470-0.
Wheat, I.D., 2010. What can system dynamics learn from the public policy implementation literature? Syst. Res. 27, 425–442. https://doi.org/10.1002/sres.1039.
Winkler, H., 2011. Closed-loop production systems—a sustainable supply chain approach. CIRP J. Manuf. Sci. Tec. 4, 243–246. https://doi.org/10.1016/j.cirpj.2011.05.001.