Insights to beachcast management on Gotland, Sweden:
An Industrial Ecology perspective on waste-resource ambiguity

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Abstract

Beachcast or beach wrack, washed-up algae and seaweed, used to be a highly sought-after agricultural resource (fertiliser and soil conditioner) in coastal communities around the world before being replaced by chemical fertilisers, but considering the talks of a circular bio-economy – can we reintroduce it?

Since the abandonment of beachcast in agriculture, the amount of beachcast has significantly increased as an effect of eutrophication caused by the use of chemical fertiliser, and the material is commonly considered waste. Meanwhile, soils have degraded and need the multiple positive effects on agroecosystems that beachcast could provide. So, while harvesting the biomass serves to remedy the adverse ecosystem effects on marine ecosystems (from excessive organic material, i.e. macroalgae blooms), beachcast could potentially contribute to more sustainable food production.

Sadly, it is not simple. This potentially symbiotic process infers uncertainties regarding soil cadmium accumulation, coastal ecosystem effects, and other challenges - and despite multiple studies and attempts at a waste-to-resource conversion of beachcast, the challenges remain unsolved, and a novel take on the topic seems necessary.

On Gotland, Sweden, with a historical tradition of using beachcast in agriculture, a modern governance system for management has emerged from a national policy subsidising beachcast harvesting, which has partly come to connect the marine and agricultural domains, among other actors. In this case, beachcast harvesting is subsidised as a measure to curb eutrophication and reduce the detrimental effects of excessive beachcast, a phenomenon present in the Baltic Sea and many other coastal regions worldwide that are caused by an accelerating nutrient accumulation at sea and sediment stocks. So, by further applying beachcast as a fertiliser in agriculture and horticulture, a practical example of a regional land-marine nutrient loop could be created to make beachcast management more sustainable. However, multiple challenges need to be addressed.

This thesis and case study of Gotland, Sweden, presents an illustrative example of contemporary beachcast governance and management that provides knowledge and insights to support policy development and more sustainable beachcast management practices. insights for policy that can support the development of more sustainable management practices. This is
done by using semi-structured interviews to understand the beachcast governance and management practices based on stakeholder perceptions (Paper I), performing a cost-benefit analysis of beach-cast harvest to assess the economics of closing land-marine nutrient loops in the Baltic Sea region (Paper II), conducting a cultivation experiment to predict future trends in soil cadmium concentration from applying beachcast as fertiliser (Paper III), and mapping regional variations in chemical composition of fresh and composted beachcast to consider future treatments (Paper IV).

The results show that to overcome the challenges and achieve more sustainable practices, the following measures and considerations are essential: further supporting continued experimentation and monitoring of marine ecosystems to handle the harvest-hesitation caused by the uncertainties associated with marine ecosystem effects; sampling of composted material and careful agricultural use to remedy the waste-resource ambiguity associated with Cd contamination; and a continued subsidy and cross-sectoral collaborations to abide managerial and financial responsibility for beachcast activity.

In this in-depth and transdisciplinary case study with a mixed-methods approach, the findings point to a theoretical and practical incongruity in seeking a waste-to-resource conversion of beachcast, which indicates that beachcast cannot compete with commercially viable products in today's intensive agricultural regime. Instead, agroecology, an alternative pathway according to FAO, appears to be a more promising context for beachcast to be acknowledged and receive the necessary investment to resolve its ambiguous resource status.

**Keywords**

Beachcast, natural resource management, policy, circular bio-economy, agroecosystems, governance, sustainable development, industrial ecology
Sammanfattning

Släke, det Gotländska samlingsnamnet för uppspolad alg- och tångmassa, brukade vara en mycket eftertraktad jordbruksresurs (gödselmedel och markvårdare) i kustsamhällen runt om i hela världen innan kemiska gödningsmedel introducerades i jordbruket, men med tanke på hållbarhetsmål som inbegriper konceptet cirkulär bio-ekonomi borde vi kanske återinföra släke som resurs?

Sedan släkeanvändningen övergavs inom jordbruket har mängden släke ökat avsevärt (som en effekt av övergödningen till följd av användningen av kemiska gödningsmedel) och materialet betraktas vanligtvis som avfall. Samtidigt degraderas många jordar till följd av minskad tillförsel av organiskt material, något som släke skulle kunna bidra med till agroekologiska system. Så bortforsling av släke från lämpliga kustremsor skulle teoretiskt sett både kunna avhjälpa de negativa effekterna på marina ekosystem från makroalgblooming (som en följd av övergödningen) samt bidra till en mer hållbar livsmedelsproduktion genom näringscirkulation.

Tyvärr är det i praktiken inte en enkel uppgift att åstadkomma ett sådant cirkulärt resurssystem för släke. Denna till synes symbiotiska process är förknippad med osäkerheter vad gäller kadmiumackumulering i jord, potentiellt negativa effekter på kustnära ekosystem och andra utmaningar - så trots flera studier och försök till en omvandling av släke från avfall till resurs, kvarstår utmaningen med resursomvandlingen och det finns ett behov av ett nytt angreppssätt på släke-problematiken.

På Gotland, Sverige, med en historisk tradition av att använda släke i jordbruket, har ett modernt resurshanteringssystem vuxit fram ur en nationell policy som subventionerar släkeskörd som en övergödningsåtgärd. Systemet har kommit att engagera flertalet olika aktörer och har delvis kopplat samman marina och agrara domän. I det här fallet subventioneras alltså släkeskörd som en åtgärd för att bromsa övergödning och minska de skadliga effekterna makroalgsblooming, ett fenomen som återfinns i Östersjön och många andra kustområden över hela världen som orsakas av en accelererande ackumulering av näringsämnen i havet, inklusive sediment. Så genom att ytterligare använda släke som gödningsmedel i jordbruk och trädgårdsodling, skulle näringscirkulation mellan hav och land i praktiken kunna skapas på regional skala för att göra släkehanteringen mer hållbar, även om flera utmaningar måste lösas.
Denna avhandling och fallstudie av släkeskörd på Gotland, Sverige är ett illustrativt exempel på samtida släkehantering som ger kunskap och insikter till användning för policy som kan stödja utvecklingen av mer hållbar hantering. Detta görs genom semi-strukturerade intervjuer för att förstå släkehanteringen utifrån olika aktörers uppfattningar (Paper I), kostnads-nyttoanalys av släkeskörd och bortforsling för en samhällsekonomisk bedömning av ett kretslopp av släke mellan hav och land i Östersjöregionen (Paper II), odlingsexperiment för att förutsäga framtida trender av kadmiumkonzentration i jord från användning av släke som gödningsmedel (Paper III), samt kartläggning av regionala variationer i kemisk sammansättning av färrsk och komposterad släke för att betänka framtida behandlingsmetoder (Paper IV).

För att klara av utmaningarna och uppnå mer hållbara metoder visar resultaten av avhandlingen att följande åtgärder och överväganden viktiga: att ytterligare stödja en fortsatt experimentering och övervakning av marina ekosystem för att hantera osäkerheterna kring de marina ekosystemeffekterna; kontinuerlig provtagning av komposterad släke och försiktig jordbruksanvändning för att råda bot på avfalls-resurs-ambivalensen som är förknippad med en potentiell Cd-kontaminering, samt en fortsatt subventionering och upprätthållande av tvärsektoriella samarbeten för ett delat ansvarstagande (också ekonomiskt) för släkehanteringen.

I denna djupgående och transdisciplinära fallstudie pekar resultaten på en teoretisk och praktisk inkongruens när det kommer till omvandlingen från avfall till resurs av släke. I sin tur är det en indikation på att släke inte kan konkurrera med kommersiellt gångbara produkter i dagens intensiva jordbruksregim. Istället verkar agroekologi, en alternativ väg till intensifiering enligt FAO, vara ett mer lovande sammanhang för att släke ska komma till sin rätt och få till de nödvändiga investeringar som krävs för att lösa dess tvetydiga resursstatus.
List of appended papers and my contributions


*I developed the research idea with Daniel Franzén, and I developed the interview guide with input from my co-authors. I developed and performed the interviews together with Daniel Franzén. I analysed the data, with continuous input from my co-authors. I was responsible for writing the manuscript and publishing the paper.*


*Together with my co-authors I developed the research idea. Together with Tore Söderqvist and Daniel Franzén, I constructed the model and developed the analysis. I wrote sections on ecosystem effects, and contributed with input to other sections.*


*I developed the research idea with my co-authors. The basic model was developed by Jon-Petter and modified by me and Jon-Petter to suit the case, after which I did the calculations. Together with Daniel Franzén, I constructed the experiment and did the data retrievals. I was responsible for writing the manuscript and publishing the paper.*


*Together with my co-author, I developed the research idea, methodology and the analysis, retrieved data, and wrote the manuscript. I was responsible for publishing the paper.*
Table of Contents

1. Introduction 10
   1.1 Natural resource management & sustainability 10
   1.2 Beachcast biomass – bridging land and sea 13
       1.2.1. Beachcast from research and policy perspectives (land-sea interdependency) 14
   1.3 Beachcast activity on Gotland, Sweden 17

2. Research questions 18
   2.3 Research design around a single case study 21
       2.1.1. Scope and scale 22

3. Theoretical and practical background 25
   3.1. Industrial Ecology – the research field 25
       3.1.1. Circular Economy 25
       3.1.2. Systems thinking 26
       3.1.3. Industrial Symbiosis 28
       3.1.4. Transdisciplinarity 31
   3.2. Beachcast – the research topic 33
       3.2.1. Comprehension of (and connections between) beachcast, compost, and biofertiliser 33
       3.2.1. Case studies on beachcast management and treatment (in a land-sea context) 35

4. Methodology 37
   4.1. Multidisciplinary approach 38
   4.2. Mixed-methods approach 39
   4.3. Ethics 41

5. Overview of Papers I-IV 42
   5.1. Paper I. Using stakeholder perceptions to deepen the understanding of beachcast governance and management practices on Gotland, Sweden 42
   5.2. Paper II. Cost-benefit analysis of beach-cast harvest: Closing land-marine nutrient loops in the Baltic Sea region 44
   5.3. Paper III. Future trends in soil cadmium concentration from applying beachcast to agricultural land on Gotland, Sweden 45
   3.3. Paper IV. Regional variations in chemical composition of fresh and composted beachcast on the island of Gotland, Sweden – considering future treatments 46

6. Results & Discussion 47
   6.1. What does the governance system for beachcast management, developed from the LOVA policy scheme, look like, and why? (Paper I) 47
       Governance institutions, structures, and processes 48
6.2. Which aspects of the governance system and stakeholder perceptions of beachcast management are central to the development of more sustainable practices, and how? (Paper I, II)  
- Strong stakeholder engagement and social capital  
- Difficulties of applying a split land-sea vision in practice  
- Seeking to solve the contamination issue  
- Distribution of management responsibility (including financial and technological development) across governance levels/scales and sectors  

6.3. How can the central aspects of developing more sustainable beachcast management practices be addressed? Considerations and measures for policy (Paper I, II, III, IV)  
- Continued experimentation and monitoring of marine ecosystems to handle the harvest-hesitation (1)  
- Consistent sampling of composted material and careful agricultural use to remedy the waste-resource ambiguity (2)  
- Continued subsidy and cross-sectoral collaborations to abide by managerial and financial responsibility for beachcast activity – and realize an example of a bio-based circular economy (or regenerative resource system) (3)  

6.4. What knowledge production, dissemination, and communication has taken place during the conduction of this thesis (beyond scientific articles, bridging science and society)? Possibly affecting perceptions and ultimately policy for resource management 

7. Implications for Policy and Beyond  

7.1. Development of sustainable beachcast management practices - theoretical and practical incongruity  

7.2. Future scenarios for agricultural systems - and their suitability for beachcast (and biofertilisers alike)  

7.3. The 'sparing or sharing' policy stance/debate (on future agricultural systems) - bridging land and sea  

7.4. Thoughts on IE and future research  

8. Conclusions  

References
1. Introduction

1.1 Natural resource management & sustainability

Industrialisation of agricultural practices marked the start of an era of unprecedented development, enabling the extraction and use of natural resources that had never been possible earlier in world history (UNEP, 2019).

As much as ceased starvation and improved health (in parts of the world) can be attributed to this development - the accompanying changes in material flows have also entailed environmental degradation, social injustice, and economic and geopolitical tension - effects deemed unsustainable (UNDP, 2020). At the same time, however, education has informed us of this, and a safe operating space for humanity to stay within planetary boundaries has been and is being explored (Rockström et al., 2009), and international collaborations have led to the formulation of Sustainable Development Goals that suggest actions from local to global scale (United Nations General Assembly, 2015).

Food production is said to connect all Sustainable Development Goals (SDGs) (Rockström & Sukhdev, 2016), and sustainable development of natural resource management relating to agriculture is addressed by a range of research fields with varying approaches to problem framing and solving. Despite the different approaches, however, the shared notion in society is that strategies should encourage the transformation of linear resource flows to circular, substituting finite resources with renewable alternatives and achieving waste-to-resource conversions (European Commission, 2002).

Among the most revolutionary aspects of industrialization, is the technological development that facilitated chemical fertilizer production through the Haber-Bosch process for nitrogen production, and mining for phosphorus (UNDP, 2020). Both processes currently rely on fossil fuel inputs, and phosphorus (being finite) approaches a peak (Daramola & Hatzell, 2023). Moreover, human-induced changes in phosphorus (P) and nitrogen (N) concentrations in the biosphere have caused imbalances that alter natural and managed ecosystems worldwide, with eutrophication from nutrient leakage.
from land to sea being one of the most severe (Peñuelas et al., 2013). As a result, Rockström et al. (2009) conclude that the planetary boundaries for P and N are transgressed and stress the urgency in creating nutrient cycles of the biochemical flows of phosphorus (P) and nitrogen (N) at the local and regional scale to make future food production sustainable.

The Food and Agricultural Organisation (FAO) has defined a so-called “towards sustainability scenario” for food production in their report “The Future of Food and Agriculture – Alternative Pathways” (FAO, 2018), for which chemical fertiliser is eliminated by the year 2050. Increased investments in developing sustainable agricultural practices\(^1\) are expected to ensure the transition towards more sustainable use of natural resources in agriculture than practiced today and contribute to moving towards circular economies, i.e. economies based on reusing and recycling material that we have come to define as waste, with limited impacts on ecosystems (FAO, 2018).

"There will come a time when humanity will recall the twentieth century as a period when limited resources were squandered by a wasteful society. To rectify this situation, research should be continued to encourage more sustainable agricultural production methods to be practised by enabling organic wastes to be economically utilised." (Sims, 1996)

Several international policies and legislation at various scales of governance address the importance of exploring alternative sources of fertilisers in the form of using and valorising wasted supplies of nutrients, particularly the EU Common Agricultural Policy (CAP), EU and national soil conservation laws, water conservation law, fertiliser law, circular economy law and organic farming law (Garske et al., 2020).

At a Swedish national level, the government committee directive (Swe. “Ett fossilberoende jordbruk”) set to investigate possible pathways to a fossil-free agricultural system, targeting the use of mineral fertiliser (Regeringen Dir 2020:16, 2020). Thereto, the Swedish National Food Contingency Plan addresses the need for alternative fertilisers by stating that the agricultural sector needs to support models for fossil-free farming that aims to close

\(^1\) e.g. "Low-input precision agriculture, agroforestry, intercropping, and organic agriculture and/or other resource and climate-friendly production methods"
nutrient loops and facilitate the use of alternative fertiliser sources (along with biofuels) (Eriksson, 2018).

On the seaside, the Baltic Marine Environment Protection Commission (HELCOM), an intergovernmental platform for environmental policy-making at regional levels to protect the marine environment of the Baltic Sea from pollution, is promoting circular bio-economy as a remedy to linear fertiliser use in agriculture (which displaces N and P from air and rock to soil and water) (HELCOM, 2007). An extensive update on the process of bio-economic development in Sweden by Bennich et al. (2020) does, however, state that “while agricultural sources of biomass have been recognised as important for the bio-based economy in Sweden, comparatively little attention has been given to the specific change processes underpinning a transition process in the agricultural sector.”

A practical action that could feed into a transition to a bio-economy while minimising eutrophication effects and contributing to nutrient circulation in agricultural practices is managing beachcast - washed-up algae and seaweed - by harvesting the nutrient-rich biomass from beaches and using it as fertiliser in agriculture (Kupczyk et al., 2019; Mainardis et al., 2021; Rudovica et al., 2021; Sinha et al., 2022; Thomas et al., 2021).

The application of bio-based fertiliser products from algae- and seaweed has been demonstrated to improve the productivity of crops, soil management, water efficiency/drought tolerance, disease management practices, and nutritional strategies - factors that can contribute to addressing future challenges in food production (Arioli et al., 2015). Although beachcast has theoretically proven a promising alternative fertiliser input, it is still practically regarded as waste rather than a resource due various challenges (Dang et al., 2023; ESSP, 2021; García & Loring, 2022; Illera-Vives et al., 2013; Madejón et al., 2022; Michalak et al., 2016; Milledge & Harvey, 2016; Nkemka et al., 2014; Rudovica et al., 2021; Walsh & Waliczek, 2020). To address challenges with resource management across land and sea with regards to food production and biodiversity in general, research suggests that collaboration cross-sectors and governance scales need to improve (Cottrell et al., 2017; Vigouroux & Destouni, 2022), and several studies on beachcast management specifically points in the same direction (Chubarenko et al., 2020; Kupczyk et al., 2019; Mossbauer et al., 2012; Woelfel & Schubert, 2021).
In turn, understanding how stakeholders view the governance structure of a particular resource management system can engage in dialogue that connect different sectors at various scales, while linking scientific work with society, which provide knowledge to improve management practices in terms of environmental impact and sustainability (UNEP, 2019). Moreover, systems thinking has been proposed as a method for scientists, policy makers and other stakeholders to "get the big picture in natural resource management" (Bosch et al., 2007).

Stakeholder engagement in beachcast management from a systems perspective that include both marine and agricultural perspectives is scarce, motivating this thesis to generate more knowledge on the topic.

1.2 Beachcast biomass – bridging land and sea

Historically, beachcast has been a valuable agricultural input in coastal areas worldwide until the introduction of chemical fertilisers essentially reduced the dependency on bio-based fertilisers, including beachcast (Illera-vives et al., 2020). However, the connection between chemical fertiliser and beachcast continued: excessive use of chemical fertiliser resulted in an overload of nutrients in waterways, seas, and oceans, which made algae and seaweed thrive – causing excessive biomass production and beachcast (Weinberger et al., 2012). Moreover, the effects of climate change, with increasing CO\textsuperscript{2} levels and temperatures in waters, may have enhanced the growth and prolonged the growth season at sea, causing in an increase in harmful macroalgal blooms (Ji & Gao, 2021). It is also long known that the anthropogenically induced displacement of nutrient flows in the form of nitrogen and phosphorus from chemical fertiliser production and use has severely affected the human environment and several ecosystems at sea and on land (FAO & SIDA, 1972).

The major consequence at sea is the cause of eutrophication and spreading of dead zones due to decay and sedimentation of the amplified amounts of organic material consisting of macroalgae and seaweed (HELCOM, 2007). The amount of biomass washed ashore has been estimated at 60,000 tons (DW) on the southern beaches of Sweden (Blidberg & Gröndahl, 2012) and 45,000 tons (DW) along the German Baltic Sea coast each year (Weinberger et al., 2012). In Resources and Society - A Systems Ecology Study of the Island of Gotland, Sweden, it was estimated that algae washing ashore accounted for a nutrient
input from sea to the land of 11.3 tons of nitrogen and 1 ton of phosphorus (whereas the flow from land in terms of runoff and sewage outlets amounted to about 2300 tons nitrogen and 330 tons phosphorus) Zucchetto & Jansson, 1985). The corresponding content of P, N, and K per kg beachcast motivate further studies on its potential role in a circular bio-economy transition (Mainardis et al., 2021; Rudovica et al., 2021; Sinha et al., 2022; Thomas et al., 2021).

The transition from bio-based to chemical fertilisers has exacerbated eutrophication, and studies have declared the need to close nutrient loops from soil to crop and back to agricultural soil to curb eutrophication and the escalation of dead zones in the Baltic Sea (Chowdhury et al., 2017; Diaz & Rosenberg, 2008).

As for the effects on land, replacing carbon-rich fertilisers (such as beachcast) in favour of chemical fertilisers in intensive agriculture has cut the supply of organic material to soils and, thereby, the ability of soils to maintain humus levels that host microbes and belowground biodiversity, wherefore sustaining healthy soil structures that retain water and nutrients is becoming increasingly difficult (Bach et al., 2020; Bardgett & Van Der Putten, 2014; Maltas et al., 2018). Adding organic material to agricultural soils also allows carbon sequestration, which is crucial in mitigating climate change (Smith et al., 2007), which beachcast could contribute to (Katakula et al., 2020). As such, re-introducing beachcast (or beachcast-derived products) to reduce chemical fertiliser use is a potential strategy and scenario for the Baltic Sea Region to decrease the nutrient input into the Baltic Sea while also improving soil properties that can store nutrients (Woelfel & Schubert, 2021). The research perspectives (and gaps), including policy aspects relating to this idea, are presented below.

1.2.1. Beachcast from research and policy perspectives (land-sea interdependency)

Seaweed-based fertiliser products have proven to be a potential alternative to conventional crop fertilisers, but it is coupled with uncertainties, such as to what degree a resource substitution would actually be feasible and what unintended consequences (i.e. trade-offs) could be expected from its production and use (Cottrell et al., 2017). In addition to these uncertainties, the sustainability challenges of future food production concerning the demand
for fertiliser include cross-sector interdependencies between land and sea that will persist in the future and need attention (Cottrell et al., 2017).

Despite this articulated land-sea connection, there is a lack of research investigating the coastal links with land and sea in the systems case of the Baltics (Vigouroux & Destouni, 2022). Most studies on coastal pressures in this area concern nutrient loads, but few comprise the sources of these loads (exceptionally long-lived legacy sources) and possible solutions and mitigation strategies. Moreover, few studies address cross-scale multi-solution management through synergies, trade-offs, and incentives for various solutions (Vigouroux & Destouni, 2022). The idea of bringing nutrients from sea to land by using mussels as fertiliser to curb eutrophication has been studied, calling for the development of composting techniques that allow for more direct use of the mussels as fertiliser to reduce the environmental impact from more advanced techniques that are energy consuming (e.g. inert storage) (Spångberg et al., 2013).

Another holistic and cross-scale multi-solution approach (to the problem with nutrient loads) was taken by the international research project Building Ecological Recycling Agriculture and Societies (BERAS), suggesting that the implementation of Ecological Recycling Agriculture (ERA) is a solution that theoretically would half the reactive nitrogen and phosphorus losses from land to sea (Granstedt et al., 2008; Larsson, 2016). ERA is defined as an agricultural system based on local and renewable resources and integration of animal and crop production on each farm or within clusters of closely located farms (to avoid nutrient excess on animal farms and deficiency on crop farms) (Granstedt et al., 2008). Realising this strategy (i.e. moving from theory to practice) includes transitioning to bio-based fertilisers (from chemical). Such a transition, however, would require support from policy management and governance structures (Larsson & Granstedt, 2010).

Beachcast biomass - a potential renewable agricultural resource that could retrieve and circulate nutrients to replace chemical fertiliser - makes beachcast harvesting and use a possible solution and mitigation strategy to relieve the coastal pressure of excessive nutrient flows from farmland to open sea. Hence, it holds the theoretical potential to contribute to a circular blue-green economy by removing nutrients and substituting chemical fertiliser (Thomas et al., 2021). However, as with most solutions, such a strategy could entail synergies and trade-offs. While posing as a potentially nutrient-rich fertiliser on land (Franzén et al., 2019; Greger et al., 2007; Michalak et al., 2017; Nabti et
al., 2017; Weinberger et al., 2019), accumulating beachcast is also problematic at sea (with accelerating eutrophication) and for coastal economies due to seized recreational opportunities (Mossbauer et al., 2012; Nelson et al., 2015; Smetacek & Zingone, 2013). This potential combination of the ‘waste-resource’ divide appears as a synergy in a circular bio-economy rather than a dilemma. However, trade-offs regarding the environmental effects on marine and horticultural/agricultural ecosystems call for further research to make beachcast management more sustainable.

A marine concern and potential trade-off is negative ecosystem effects in coastal zones from harvesting beachcast, both internationally (Griffin, 2016; Nordlund et al., 2018; Paul, 2018) and in the Baltic Sea region (Kindeberg et al., 2022; Rönnbäck et al., 2007). Due to this, the EU Habitat Directive regulates beachcast harvesting through its precautionary principle policy, recommending caution for the cause of biodiversity, in this case, bird conservation (i.e. listed species), as well as the habitat “sea cliffs and shingle or stony beaches” (Council Directive 92/43/ECC, 1992). On the other hand, the phenomena of macroalgal blooms, termed “green tides”, from nutrient overload harm marine ecosystems (Back et al., 2000; Lyons et al., 2014; Milledge & Harvey, 2016; Smetacek & Zingone, 2013; Ye et al., 2011). To mitigate the negative effects while safeguarding coastal marine ecosystems and make the management of stranded macroalgae/beachcast effective, interdisciplinary research is needed to shed light on management and governance aspects (Ye et al., 2011).

In the case of agricultural/horticultural use of beachcast, the main trade-off concerns the risk of soil contamination from heavy metal content, foremost Cadmium (Franzén et al., 2019; Greger et al., 2007; Weinberger et al., 2012), which may undoubtedly affect management decisions regarding its use and processing/treatment that require more research on beachcast as biomass and resource. When removing beachcast, it is recommended that synergies between services (by finding the use of biomass as a raw material or further processing/treatment) are obtained to achieve sustainable resource management and accommodate financing options for treatment (Woelfel & Schubert, 2021).

From an agricultural/horticultural policy perspective, there are regulatory challenges for macroalgae biomass (e.g. beachcast) and material and products derived thereof. Suggested solutions to make algae contribute to nutrient recycling and a circular economy include achieving "end-of-waste status"
(ESSP, 2021) through regulatory actions and financial support and market incentives (ESPP, 2023). According to the EU, the "end-of-waste criteria specify when certain waste ceases to be waste and becomes a product or a secondary raw material." (Directive 2008/122/EC, 2020). The current waste status and lack of market value of beachcast imply that harvesting should be generated through marked-based instruments and payments for ecosystem services from the environmental benefits of this action (Hasselström & Gröndahl, 2021).

The circular economy is expected to expand and diversify the market outlets of bio-based products, and taking/adopting holistic and integrated approaches to waste-to-resource (i.e. industrial feedstock) conversions could eventually boost a transition to a bio-economy era (Maina et al., 2017). Meanwhile, inherent tensions (e.g. trade-offs and potential rebound effects) will continue to pose challenges that are said to require transdisciplinary insights on the systemic consequences from activities and schemes - also from unintended cases and material yet not subject of attention - for us to learn how to move from theory (including policy) to practice (Schröder et al., 2019). A similar call for transdisciplinarity has been made to solve the issue of agriculture and eutrophication. Withers et al., (2014) posed the question "Where we go from here" in terms of solving the agriculture-eutrophication issue, and answered it by stating that local mitigation initiatives and activities need to connect with research that disclose the linkages between "sustainable farming practices, patterns of nutrient delivery, biological response and recovery trajectories in waterbodies".

This holistic and integrated approach is yet to be applied to beachcast - and a highly relevant and interesting case to study is the emergent beachcast system on the Swedish island of Gotland. The geographically and structurally encircled area (as an island), together with a historical knowledge of harvesting and using beachcast in agriculture, and a recent implementation of a policy programme subsidising harvesting activity to reduce the local effects of eutrophication, makes this case an opportunity to study a potential revival of a resource status for beachcast in a circular bio-economy context.

1.3 Beachcast activity on Gotland, Sweden

Like many coastal zones and islands globally, the island of Gotland, Sweden,
located in the Baltic Sea, has a long history of harvesting and using beachcast for fertilisation and soil conditioning. Research on its effects on crops on the island of Gotland dates back to the 18th century (Lythberg, 1799). Once considered an indispensable and valuable resource, farmers who violated the management rules were brought to court during the last centuries (Säve, 1938). In the documentation of farming and folk life on Gotland in the first half of the 1900s, the author wondered how anything could possibly grow on Gotland soils and attributed this miracle to beachcast (Säve, 1938).

Since then, chemical fertilisers have replaced beachcast, and the management systems for harvesting and use have changed profoundly. The Swedish government introduced a national water policy program in 2009 focusing on improving water quality through supporting local initiatives and projects through a grant scheme (Swedish Agency for Marine and Water Management, 2020). Following the implementation of this program, beachcast harvesting picked up on Gotland, and a governance system has emerged with large amounts of beachcast having been harvested, engaging various actors in the process and presenting the opportunity to reintroduce the use of the biomass as an agricultural resource input.

As such, this case of beachcast management has become an unintended incentive for a solution to curb eutrophication while potentially contributing to a circular bio-economy transition through nutrient recovery through agricultural (re)use. Thereto it represents an example of cross-scale multi-solution management to address eutrophication, which is highly relevant to connect with research, as this thesis does.

2. Research questions

This thesis aims to identify and analyse central aspects of beachcast management in a circular bio-economy context and to provide insights that can support policy development and more sustainable management practices.

To achieve the aim of the thesis, three research questions, RQ 1-3 (Table 1), were formulated to describe and analyse central aspects, considerations and measures of beachcast management and associated policy matters. The ‘central aspects’ are, to some extent, suggested by earlier studies within the field but are also identified in the early phase of the doctoral project, from descriptions
and analyses of the governance system for beachcast management and stakeholder perceptions. How the central aspects of developing more sustainable beachcast management practices could be addressed through various 'considerations' and 'measures' were identified and analysed throughout the thesis work (Table 1).

Management and governance are connected, and many challenges related to ecosystems, biodiversity and natural resources include aspects of both. Simply put, management could be described as the way natural resources are managed, while governance is the structure or network of actors governing the management activities (Larsson, 2016).

The scientific knowledge (quantitative and qualitative) provided by this thesis supports management and policy decisions that account for the multi-functionality of beachcast, requiring the involvement of the relevant actors and stakeholders in governance to a much larger degree than practised to date. Overall, the collected empirical data and knowledge (quantitative and qualitative) could contribute to the systematisation and formalisation of transdisciplinary research practices in natural resource management, as stated by Hadorn & Pohl (2007).
Table 1. Overview of the research questions, RQs (1-3), and the respective papers (I-IV), including methods and objectives that were applied.

<table>
<thead>
<tr>
<th>Research Questions (RQs 1-3)</th>
<th>Articles (including methods &amp; objectives)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Stakeholder analysis</td>
<td>Cost-benefit analysis</td>
</tr>
<tr>
<td>Semi-structured Interviews</td>
<td>Ex post analysis (CBA analysis conducted after a project is completed)</td>
</tr>
<tr>
<td>Matrix method</td>
<td>Qual.</td>
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1. *What* does the governance system for beachcast management, developed from the LOVA policy scheme on Gotland (Sweden), look like, and *why*? (Paper I)

(1) Characterizing the governance system in terms of elements and levels (including stakeholders), institutions, structure processes

N/A

N/A

N/A

2. *Which* aspects of the governance system and stakeholder perceptions of beachcast management are central to the development of more sustainable practices, and *how*? (Paper I, II)

(2) Collecting stakeholder perceptions of the beachcast governance system and organizing them around sustainability aspects; and...

By explicitly addressing trade-offs associated with beach-cast harvesting, the focus of this paper is to explore if such harvesting is economically motivated from a societal point of view. That is, are the social benefits of beach-cast harvesting likely to exceed its social costs?

N/A

N/A

3. *How* can the central aspects of developing more sustainable beachcast management practices be addressed? Considerations and measures for policy (Paper I, II, III, IV)

(3) Suggesting ways of incorporating these findings into management to improve resource management practices.

The results are used to develop recommendations for future beach-cast management.

(1) The rate of Cd accumulation in wheat crops and agricultural top soil;

(2) The changes of soil Cd fractions and Cd uptake by wheat, as affected by beachcast fertiliser treatment and chemical fertiliser (NPK); and

(3) Potential scenarios (for beachcast application) to avoid Cd soil accumulation.

(1) Provide data on macronutrients, C:N ratio and Cd content on the island of Gotland, Sweden, as affected by locality, season and

(2) Map possible changes during treatment in the passive piles, in order to

(3) Consider future treatment with regards to the results.
2.3 Research design around a single case study

The research was organised around the Gotland case of beachcast harvesting and use, providing a deep and exploratory investigation and analysis to capture the complexity of beachcast harvesting and use from different perspectives. The descriptive information of a single case study alone is considered revelatory, holding the potential to stimulate further research, knowledge transfer between science and society, and future progression in policy development (Yin, 2008).

Solving sustainability issues calls for empirical research in real-life case studies and is encouraged to develop theory (Jerneck et al., 2011; Kajikawa et al., 2014). The studied case of beachcast management in this thesis incorporates "all with a stake in the product, the process, and its implications both local and global", which inevitably makes policy part of science and calls for the complex problem-solving strategy of ‘post-normal science’ (Funtowicz & Ravetz, 1993). As such, the problem-solving research of this thesis is considered post-normal instead of applied.

Within the post-normal paradigm of addressing sustainability issues, the transferability of research results has replaced the typical demand for generalisability (Flyvbjerg, 2006). Transferring learnings from one case study to another is essentially done through comparisons, e.g., naturalistic and analytical generalisation, as stated by (Stake & Trumbull, 1982).

Transferring of knowledge from a single case study onto others requires that the researcher rigorously and accurately describe their case for the reader; the contextual richness is said to allow for well-informed and sophisticated readers to make their own generalisations, which generate a broader picture that is more anchored in reality than traditional scientific inquires (Wikfeldt, 2017). It has, however, been argued that transferability through naturalistic generalization is not new to philosophers and methodologists of science (both natural and social disciplines), this type of generalisation is simply a subjective task where the "particular is somehow departicularized or translated, circumstances and all, into a new situation" (Hellstrom, 2008).

Transferability is also commonly practised for sustainability challenges, for which solutions cannot be replicated across contexts or imposed on others (Caniglia et al., 2020). One reason is that stakeholders' actions and interactions with each other should be interpreted as expressions of the contexts in which
they act (Saviano et al., 2019). As such, knowledge generation is considered context-dependent, but sharing experiences between systems and institutions can improve management practices (Giebels et al., 2016). Whether or not the ambition is to improve, it is well worth empirically investigating cases where groups of people develop and share "working knowledge" (Kloppenburg et al., 2000), which is expected to be the case for beachcast management practices studied in this thesis.

The importance of case studies, stakeholder involvement, and context dependency is well confirmed in natural resource management research, and it is especially relevant where issues can be characterised as "cross-cutting systems and stakeholder interests" and "untraded products and services" (Grimble & Wellard, 1997), which the case of beachcast management in this thesis indeed represents.

Regarding the application of circular economy as a concept, its sustainability contribution is said to require a case-by-case analysis. Although sustainable development is a global goal, circular economy-type projects (that have been implemented and that will be implemented in the near future) will always be local or regional at most (Korhonen, Honkasalo et al., 2018). This thesis contributes knowledge of a case that can provide insight into the implementation of circular economy, e.g. linking the theoretical concept of circular economy to natural resource management in practice.

### 2.1.1. Scope and scale

To capture the benefits of gaining in-depth knowledge about of the Gotland case of beachcast management, and to identify and analyse various sustainability aspects of beachcast harvesting and use in a circular economy context, the individual publications address different research questions (that provide insights that can support policy development and more sustainable management practices). Paper I addresses RQ 1, 2 and 3 by focusing on social aspects of beachcast management (including beachcast harvesting and use of the biomass), while Paper II addresses RQ 2 and 3 by concentrating on economic aspects of beachcast harvesting in the form of societal costs and benefits. Paper III and Paper IV both address RQ 3. Paper III by investigating environmental aspects of beachcast use in agriculture (focusing on cadmium...
accumulation), and Paper IV by mapping the regional variations in chemical content of beachcast (including considerations of *technical aspects*).

The four papers share the same spatial scope in the form of the geographical area of Gotland, Sweden, situated in the Baltic Sea (57 ° 28' 6" N, 18 ° 29' 12" E) (Figure 1), spanning from a regional (Paper I and II) to local (Paper III and IV) but with a consistently national and international outlook on the topic.

![Figure 1](image.png)

**Figure 1.** Map showing the location of Gotland in the Baltic Sea, sized 3100 km² and situated approximately 80–120 km east of the Swedish mainland at 57 ° 28' 6" N, 18 ° 29' 12" E.

In short, the Baltic Sea is the largest brackish inland sea in the world, characterised by its shallowness and low salinity (Strzelecki et al., 2022). The climate is semi-continental, with cold winters and mild summers. The location on the sea makes the climate milder than on the mainland but also windier (Zucchetto & Jansson, 1985), with upper layer salinities of 7 to 8 and a deeper layer with salinities of 10 to 14 ppt (Virtasalo et al., 2011). The local sea is almost tideless, and the coastal geomorphology is mainly shaped by the wave action (mean wave height of ca. 1.6 m). The bedrock consists of limestone
The focus of the thesis was set on using beachcast as an agricultural resource input. In contrast, other fates of the biomass, such as energy or material products, were not included, although the possibility of combined purposes was acknowledged. This was motivated by the fact that sustainable development of society has its base in cultivation systems, which makes food the most important form of energy or product to humanity (Gajdos, 2010). Consequently, a prerequisite for sustainable biomass management is prioritising food production when other systems (such as energy) may compete with it (Nomiyama et al., 2014).

Additionally, a more narrow focus was put on beachcast use for the purpose of fertilisation in the form of composted beachcast biomass (Paper III and IV). Other known qualities of seaweed and macroalgae (besides nutrient supply), such as micronutrient content, growth-promoting substances, and water-holding capacity of beachcast as an agricultural resource input, were not included. However, their relevance to future food production and the development of beachcast management practices were acknowledged.

In terms of the temporal scope, the time horizon stretched from stakeholder perceptions of beachcast management in the past, present, and the future (Paper I) to the present economics of beachcast harvesting (Paper II), future prediction of long-term effects on soils from the use of beachcast (Paper III), and present chemical content of beachcast in relation to seasonal variations (IV).

As such, the short time horizon of industrial society is challenged, and the temporally vast scope provides a valuable future perspective in the discussion of all four papers.

As for the scope of the thesis report, it has the following structure: relevant theories are presented in Chapter 3, followed by the methodological approach in Chapter 4, and an overview of Papers I-IV in Chapter 5. The results are presented and discussed in Chapter 6, and reflections on the potential implications of policy and beyond (including future research) are presented in Chapter 7. Concluding remarks are made in Chapter 8.
3. Theoretical and practical background

This chapter provides an overview of the conceptual background in the form of the research field – Industrial Ecology, and the practical background in the form of the research topic – beachcast.

3.1. Industrial Ecology – the research field

Industrial Ecology is a systems-based, multidisciplinary research field that emerged to improve the understanding of complex integrated human-natural systems (Allenby, 2006) and encourage action to change activities associated with environmental impacts in industrialised societies based on mimicking nature’s efficient ways of resource use (Isenmann, 2003). Since then, IE has established itself as a field mainly targeting the sustainability performance of industrial production, constituting the base for the circular economy (Korhonen, Honkasalo, et al., 2018). Yet, IE "encompasses society's use of resources of all kinds" (Graedel & Allenby, 2002, p. 19), and the conceptual width of the field makes IE a relevant field for natural resource management in varying contexts. In this thesis, the IE concepts of circular economy, systems thinking, industrial metabolism/symbiosis, and transdisciplinarity serve as the foundation.

3.1.1. Circular Economy

According to the MacArthur Foundation, the circular economy (CE) is a system for tackling sustainability challenges (such as climate change, biodiversity loss, waste and pollution) by decoupling economic activity from the use of finite resources to support the regeneration of nature, so through processes (such as composting) materials are circulated and therefore never become waste (Ellen MacArthur Foundation, 2023).

Several circular economy discourses have developed from this baseline. The discourses have different visions, strengths and weaknesses; a "cross-pollination" of their ideas and perspectives has been suggested to develop better policies, practices and research projects to make a transition to sustainable circular futures achievable. This task fits future transdisciplinary research (Calisto Friant et al., 2020).
Industrial Ecology is said to belong to the technocentric discourse (Calisto Friant et al., 2020). Still, circular resource management does not only include technological systems configurations and requires support in decision-making and effort from multiple stakeholders (Mesjasz-Lech, 2021). Therefore, this thesis interprets the CE concept as achieving circular resource management through the three basic principles of eliminating waste and pollution, circulating material, and regenerating nature (Ellen MacArthur Foundation, 2023), emphasising stakeholder engagement rather than technological innovation.

More precisely, this thesis builds on the idea that circular resource management of beachcast may minimise the eutrophying effects of macronutrients in the Baltic Sea through harvesting while contributing to future sustainable food production from agricultural use. If this system is achieved with positive ecosystem effects (or without adverse effects) in a marine and agrarian context, stakeholder engagement and environmental stewardship while also feeding into the transition to a circular bio-based economy, then the development is considered to encourage sustainable development, i.e. sustainable beachcast management.

The circular economy is compatible with the 'circular bio-economy'. However, the latter has a stronger focus on the carbon cycle (E. C. D. Tan & Lamers, 2021), wherefore both concepts will appear in this thesis.

### 3.1.2. Systems thinking

Systems thinking, a central concept of Industrial Ecology, serves as a tool for managing resources by understanding the larger context of a problem. In short, taking a systems approach means "going for the good of the whole" instead of maximising parts of a system or its subsystem and not "going through great trouble to optimise something that never should be done at all" (Shipp & Ramage, 2020). One given example of this phenomenon is optimising food production by introducing chemical fertiliser to increase food production, which resulted in today's problem with eutrophication – and from its origin, IE has related current environmental problems to industrial responses to solving perceived issues of yesterday, as a result of a lack of systems thinking (Allenby et al., pp. 18).

From a systems thinking perspective, the solution now is not only to optimise mineral fertiliser use but also to look to replacements in the forms of
substitutional materials, as well as reuse or recycle macronutrients to make the linear flows circular (targeting the core of the issue: chemical fertiliser production and use causing changes in biochemical flows that exceeding planetary boundaries). Systems thinking is an essential starting point for such solutions to be recognised and scrutinised so that they may contribute to sustainable development instead of more problems to be solved.

As formulated by Daniel (1999) and Learning for Sustainability (2022), "Systems thinking in practice encourages us to explore inter-relations (context and connections), perspectives (each actor has their unique perception of the situation) and boundaries (agreeing upon scope, scale and what might constitute an improvement)."

In the case of managing coastal zones and their resources, systems thinking serves as the foundation of Sustainable Integrated Coastal Management (ICM), sometimes applied to assess cases of resource management using The Systems Framework Approach (BaltCoast, n.d.; Hopkins et al., 2012). The inculcation of systems thinking has been deemed critical to improve problem-solving in a practical context, beginning by including the perspectives of all actors involved: researchers, policymakers, and practitioners (Cummins & Mckenna, 2010; Hopkins et al., 2012; Inácio & Umgiesser, 2019; Pezza & Pinto, 2019).

A challenge of systems thinking in this area is collaborations across scientific disciplines, combining diverse views, experience, and knowledge to define the problem, improve the understanding of systems, and achieve innovative policy alternatives (Cummins & Mckenna, 2010). Støttrup et al. (2017) evaluated the outcomes of ICM in the Baltic Sea Region. They stated that the lack of systems thinking when defining the policy issue for the problem commonly fails to be cross-sectoral (one-sectorial solutions may not be sustainable) and fails to assess the interrelation of ecological-socio-economic aspects (separate assessments may not be sustainable nor provide feasible/practical solutions).

In the above sense, beachcast management has not been researched with a systems thinking approach, and empirical studies are sought to provide insight into various practices and their effects to address the "to clean or not to clean?" dilemma (Zielinski et al., 2019). Considering the early stage of evaluation, in combination with the Gotland case not being initiated as an ICM project (although certainly resembling an example of it), this thesis
employs the core features of systems thinking as a theoretical approach. It
does not apply systems theory, nor a specific framework based on systems
thinking, such as Systems Approach Framework within ICM, which follows
a set of procedural steps (Inácio & Umgiesser, 2019; Stephenson et al., 2019).
The inclusion of interrelations (context and connections) between actors as
well as sustainability aspects (ecological, social, and economic), seen from
multiple perspectives (across sectors and scientific disciplines), made it
possible to examine the practical aspects of beachcast management and
address both the marine challenge of eutrophication and the agrarian
challenge of finding future sustainable nutrient supplies/resource inputs.
This basic interpretation of systems thinking as a theoretical approach, instead
of applying a specific framework, was also believed to allow for broader
findings, discussion, and conclusion.

3.1.3. Industrial Symbiosis

In stark contrast to linear cause-effect thinking, which has been the common
mindset in the industrial world, Industrial Ecology views resource flows from
a systems thinking perspective to detect the dysfunctions of linearity (Shipp
& Ramage, 2020; D. T. Tan et al., 2019). This thinking has generated the
concept of industrial symbiosis (or metabolism).

The concept of industrial symbiosis applies biological analogy to
anthropogenically constructed systems, for which someone’s waste becomes
someone else’s resource within a defined system (Graedel & Allenby, 2002).
As such, Industrial Ecology dismisses the concept of waste, stating that there
is no such thing, simply a failure to circulate resources within our industrial
society, as opposed to nature (Graedel & Allenby, 2002). Accordingly, waste
is merely seen as a social construction.

Subsequently, the idea of the industrial symbiosis concept is to seek symbiotic
opportunities involving water, energy, and materials, focusing on resource
reuse and how to achieve it technically, economically, and behaviourally,
sometimes realised through the construction of eco-industrial parks, EIP
(Wassenaar, 2015). The scale of symbiosis ranges from shaping local resource
use to covering global biogeochemical cycles (Wassenaar, 2015). Although not
necessarily place-specific, it can contribute to local circular economies
(Moriguchi & Hashimoto, 2015), holding potential for coastal communities managing beachcast (Thomas et al., 2021).

Beachcast has been theoretically studied from the basis of industrial symbiosis to manage a potential waste-to-resource conversion, using material flow analysis (Sinha et al., 2022), life-cycle assessment with the circular economy as a framework (Mainardis et al., 2021), valorisation of beachcast as an industrial by-product (Rudovica et al., 2021), and composting has been reviewed as a waste management method to achieve a waste-to-resource conversion of beachcast material (Han et al., 2014). From a local circular economy perspective, coastal communities managing beachcast could benefit from conversion. However, beachcast biomass is still mainly handled as waste in society, and more research is needed if this is to change (Thomas et al., 2021).

Creating EIPs is not simply equal to striving for closed-loop systems but optimising resource use. This means identifying stocks and input and output flows whose reduction is ecologically desirable and technically feasible (not only reduce resource “loss”, i.e. output to the surrounding system). Improving "metabolic pathways" in this broader sense means balancing industrial input and output to natural ecosystem capacity, which requires more integration with natural science within IE (to avoid sub-optimisation) (Wassenaa, 2015).

Moreover, the increasing pressure to reuse waste materials in society, while the ecosystem capacity to do so is not always high, makes it essential to study the actual effects of such actions (Barrow, 2000). Waste recycling from water sources to land has increased in many countries, with combined incentives to use valuable nutrient content and safeguard water quality (from nutrient overload). The theoretical potential of such a symbiosis is promising, but in practice, the application rates to land make contamination of heavy metals almost inevitable (Barrow, 2000). The risk of heavy metal contamination is highly relevant in the case of a waste-to-resource conversion of beachcast when redirecting the biomass flow from sea to land, and this central problem is addressed in this thesis by incorporating natural science.

Despite the overall comprehensive systems approach of IE, it is also criticised for failing to incorporate social aspects into methods and tools, providing overly simplistic/mechanistic representations of reality when modelling energy and material flows to create symbioses, which constitutes a gap
between theoretical principles and practical implementation of ideas for improvement in resource management (Rotmans & Loorbach, 2009).

In a review of social science in five prominent Industrial Ecology journals, Lindkvist Baumann (2014) states that many studies cover social aspects (mainly economic), although social theory is sparsely applied. Another shortcoming of social science integration in IE is the domination of organisational coverage compared to public or policy matters. This thesis applies social science theory on a resource management case of public interest rather than organisational or commercial interests, which makes it an interesting contribution to the IE research field.

The lack of research on social aspects of stranded seagrass (e.g. beachcast) and its related ecosystem services has been referred to as a "blind spot" in governance, and an integrated approach (i.e. including stakeholders) is believed to considerably contribute to holistic management and policy development in the land-sea interface (Ruiz-Fraud et al., 2019). This thesis takes such an approach.

At the founding stage of IE, Allenby (2002, pp. 329) pinpointed that future IE research could expect several policy transformations to appear (including the incorporation of environmental costs into price structures, an increased emphasis on cooperation rather than regulation, and an increasingly important role for NGOs in transitions). A research agenda for IE to address policy and management aspects was proposed by (Korhonen et al., 2004), which suggested IE research to expand beyond its industrial symbiosis/metabolism focus to descriptive analysis of flows and advice policy-makers, requesting better incorporation of social science/aspects with the natural science and engineering aspects of IE - which this thesis does. Moreover, as this thesis does, Korhonen proposed to move to more inter-organizational management (as opposed to intra-) by bridging the land/agricultural and sea/marine policy domains. On the whole, the author urges for industrial symbiosis/metabolism to be used as "a source of inspiration and creativity in the transformation of management and strategic visions towards a new sustainability culture." (Korhonen et al., 2004), which is how the concept is interpreted in this case of management and thesis. Through a broad interpretation of the symbiosis concept and integration with other scientific disciplines, IE as a research field could (re)gain recognition and consolidate its transdisciplinary science status (Wassenaa, 2015).
3.1.4. Transdisciplinarity

So far, this thesis has referred to multi-, inter- and transdisciplinarity, and although related, they are not interchangeable and need clarification. Multidisciplinarity refers to combining or involving several separate disciplines to approach a topic or problem, defined by the disciplines being applied simultaneously but independently of each other (Oxford Dictionary, 2023c). Interdisciplinarity pertains to two or more disciplines or branches of learning contributing to the topic or problem solving from two or more disciplines, defined by the disciplines interacting to work towards a common goal (Oxford Dictionary, 2023b). Transdisciplinary is an extension of the latter, defined by furthered collaboration and integration of ideas from various academic disciplines, professional specialisations, or pertinent societal actors (Knapp et al., 2019). It is defined as a logical philosophical method of studying problems (rejecting the reductionist approach of conventional scientific methods) to deal with the inherent complexity of some urgent problems of the present human situation (Oxford Dictionary, 2023a).

The core idea of transdisciplinarity research is collaboration across academic disciplines, working jointly with practitioners to solve real-world problems, and it can be applied in various fields (Klein et al., 2001). Regardless of the field, transdisciplinary research projects are defined by three overarching outcomes (Pohl et al., 2021):

- Improve the problem situation (for researchers and practitioners), such as socio-institutional change in policy, biophysical change, and reduction in resource use
- Produce and disseminate artefacts that add to stocks and flows of knowledge (accessible to researchers and practitioners), from academic papers to social activities
- Generate mutual and transformational learning for both researchers and practitioners involved in and impacted by the research

Moreover, the process of knowledge production (leading to these research outcomes) should (1) grasp the complexity of the problem, (2) consider multiple perceptions (practitioners’ and researchers’), (3) connect abstract and case-specific knowledge, and (4) develop descriptive, normative and transformative knowledge for sustainable development." (Pohl et al., 2021)
Several features of this thesis are transdisciplinary by nature, and fulfilling its aim of providing insight into beachcast management (to develop/transform practices in a sustainable direction) benefit from a transdisciplinary approach. The research topic, studying beachcast in the land-sea interface, bridges the marine and agrarian disciplines in science and interest sectors/domains in society. Thereto also contributes with the knowledge to improve the management and policy situation for beachcast harvesting and use. By considering beachcast a bio-resource and studying the effects of rearranging its flow from sea to land, it considers a replacement of chemical fertiliser that would result in biophysical change and could reduce resource use, including the finite phosphorus. On this note, sustainable phosphorus management (involving various stakeholders’ activities, needs, and interests and elaborating on feasible solutions in real-life contexts) calls for a transdisciplinary approach (Chen, 2016; Scholz & Hirth, 2015).

A transdisciplinary perspective on Industrial Ecology research is defined by a common interest in "seeing change on the ground and wanting to explore that change to work out where and how to intervene to enable its growth and development" (Mitchell, 2009). This transdisciplinary approach of this thesis opened for both the production and dissemination of artefacts that add to the stocks and flows of knowledge (accessible to researchers and practitioners), from academic papers to social activities, to allow that interest to grow, resulting in mutual and transformational learning for all actors involved. This, together with systems thinking, assisted in grasping the complexity of the problem and considering multiple perceptions, as encouraged to achieve sustainable natural resource management (Wolff et al., 2019).

Most transdisciplinary research is theoretical (addressing developing concepts or potential perspectives on challenges), and there is a pressing need to increase the number of publications focused on practising transdisciplinary research (Rokaya et al., 2017). Within IE, improving sustainability through transdisciplinary case studies has been called an innovative approach to solving complex, real-world problems (Steiner & Posch, 2006). On this note, this case study and thesis on beachcast management contribute to the empirical knowledge base for transdisciplinary research, connecting abstract and case-specific knowledge that is descriptive, normative, and transformative for the sustainable development of beachcast management.
3.2. Beachcast – the research topic

3.2.1. Comprehension of (and connections between) beachcast, compost, and biofertiliser

**Beachcast** (or beachwrack) commonly refers to a mix of marine biomass washing ashore, mainly consisting of algae and seaweed material, but also marine and terrestrial debris (shells, dead fish, and other organisms, etc.), microorganisms feeding off the piles of organic material, partly sand and possibly litter. To facilitate a discussion on processing and treatment procedures, Woelfel & Schubert (2021) suggested a distinction between beachcast and beachwrack for which the first would be the overarching term, and beachwrack the purified material consisting of only the marine organic material (originating from beachcast). The term beachcast is the pragmatically correct concept to use in this thesis. Although it may contain additional material, it should be mentioned that it, in this case, nearly exclusively consists of macroalgae and seagrass.

In the Baltic Sea regions, the natural flow of beachcast follows the seasons, commonly washing ashore during seasonal storms in the autumn and winter (Rudovica et al., 2021). If harvested for agricultural/horticultural use, the standard procedure historically in the area has been to remove the biomass and organise piles slightly offshore to decompose, resembling a passive form of the composting process (Michalak et al., 2017), requiring a minimum of human and technical resources, and thus having a low environmental impact to more technologically advanced treatments (Mainardis et al., 2021). It is only feasible to harvest beachcast fresh and from types of beaches that are accessible (excluding rocky coasts and gravel beaches) (Zucchetto & Jansson, 1985). Unless harvested, beachcast remains in naturally formed bands that are usually carried back to sea with currents and storms, with higher amounts expected in autumn and winter (Rudovica et al., 2021). The rate at which beachcast is formed and its retention time on the beach depends on the oceanographic processes that transport it, the geomorphological conditions of the coast, and morphological characteristics of the macrophyte material (the source of the beachcast) (Hyndes et al., 2022). Hence, spatial and temporal variations influence the beachcast composition and chemical content (e.g. nutrients and heavy metals). These variations affect the use of beachcast compost as a fertiliser, and according to the European Sustainable
Phosphorus Forum, the inconsistency is identified as a challenge for algae- and seaweed-derived fertiliser products to contribute to a circular economy (ESSP, 2021).

**Compost**, decayed organic/bio-based material used as a fertiliser for growing crops, is a valuable option for resource conversion as it can serve to maintain and improve soil structure in areas of intensive agriculture (counteracting the decrease of organic matter from chemical fertiliser use, or stabilise the scarcity of traditional manure) (Barrow, 2000). However, the presence of heavy metals (including Cd) in waste materials is the main bottleneck, as these can accumulate in the upper soil layer (and eventually crops, animals, and humans) or leach through the soil profile and pollute groundwater (Barrow, 2000). On the other hand, the contamination risk in a soil-plant system can be reduced by continuous application of clean organic/bio-based fertilisers as heavy metal concentrations decrease (Sun et al., 2021).

The composting process is critical to obtain a fertiliser or product for soil amendment from bio-waste, and several studies explore composting treatments to improve and measure the qualities of compost, e.g. anaerobic and aerobic digestion (de Guardia et al., 2010; Pace et al., 2018), maturity and stability (Cáceres et al., 2018; Mahapatra et al., 2022). Several studies have experimented with composting beachcast, but further research is required to master the process (Michalak et al., 2017; Mossbauer et al., 2012; Walsh & Waliczek, 2020).

'Biofertiliser' is vaguely defined in the EU Fertilising Products Regulation, "generally used to mean a fertiliser derived from bio-based materials" (ESSP, 2021). At the same time, bio-based material in the form of organic waste has been recognised as valuable for agricultural application because of its fertilising qualities, which, together with a need to protect water quality to avoid further eutrophication, has become an incentive to recycle waste streams to land in several countries worldwide (Barrow, 2000). Turning nutrients and carbon from sewage sludge into a benefit to the Baltic Sea area has received attention in the name of circular economy and was assessed in an international collaboration between universities (Stockholm Resilience Institute, 2020). However, organic waste, in general, needs attention, either for

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2 ESPP brings together companies, scientists and stakeholders for sustainable phosphorus management and nutrient recycling
recovery of its valuable content (as a resource) or for safe disposal (as waste material) (Barrow, 2000).

Common challenges with using organic waste as agricultural resource input, in general, include treatment (to make the material usable) and application techniques (suitable farm equipment), logistics chains (from treatment/production site to farmland), acceptance (by farmers, wholesales, consumers, and other stakeholders), and economically feasible (Case et al., 2017a). This may also be true for beachcast, but further research is needed.

However, research on agricultural applications of algae and seaweed-based biomass has predominantly focused on derived products (extracts, liquids, powders, concentrates). In contrast, knowledge regarding using drift seaweed and algae as beachcast compost is less known (Illera-Vives, 2020). However, case studies on beachcast management in a land-sea context have addressed the practical implications of beachcast compost application in agriculture, horticulture, and other alternative treatment processes (Cocozza et al., 2011; Cole et al., 2016; Garcia & Loring, 2022; Greger et al., 2007; Kupczyk et al., 2019; Michalak et al., 2016, 2017; Walsh & Waliczek, 2020)

### 3.2.1. Case studies on beachcast management and treatment (in a land-sea context)

A review of research addressing the global problem of macroalgae blooms and beachcast (including social, environmental, and economic aspects) concluded that developing its use in the circular economy is a promising solution. In this systematic review, most studies applied life cycle or techno-economic methods to assess potential pathways to a waste-to-resource conversion in a circular economy context, and only 3% of studies specifically focused on social and/or economic aspects. It is also noted that many economic costs associated with beachcast management are underestimated, as the actual cost often extends beyond the time and machinery used to clear and dispose of the material. Coming closer to the actual figure would be of value, although collecting and processing such data is time-consuming and difficult (Joniver et al., 2021).

Composting or co-composting of beachcast material has been studied as a sustainable managing option for waste management in the occurrence of macroalgae blooms, providing a reasonably straightforward treatment process that could allow for small local composting facilities outdoors without
advanced and significant economic investment, and several studies experiment with treatment processes to improve fertiliser and soil amendment qualities (Cole et al., 2016; Greger et al., 2007; Han et al., 2014; Kupczyk et al., 2019; Madejón et al., 2022; Michalak et al., 2017; Mossbauer et al., 2012; Walsh & Waliczek, 2020).

Other cases have a more market-oriented approach than an alternative to waste management and, instead, study the valorisation of marine waste. One study (including cases from Norway, Scotland, and the Baltic Sea area) proposes that new value chains and business models should be developed to change the outlook on beachcast (from a cost-intensive to a profitable activity) and obtain a waste-to-resource conversion (Rudovica et al., 2021).

Other treatments besides composting are being explored, such as biochar (Dang et al., 2023; Macreadie et al., 2017) and biogas production (Barbot et al., 2016), ecological restoration of dunes (Kupczyk et al., 2019; Williams & Feagin, 2010), and development of insulation construction material (Bouasria et al., 2021; Kuqo & Mai, 2022). The option of producing biochar has been researched as a means of purifying the material from heavy metal content while providing benefits to agricultural production, and although promising, the multiple and costly technological steps and their associated difficulties have yet to be practically solved (Katakula et al., 2020; Macreadie et al., 2017; Wen et al., 2022). Another option is biogas production, which faces similar challenges as those of biochar, such as the high moisture, minerals, and salt content of beachcast (Barbot et al., 2016; Mainardis et al., 2021; Nkemka et al., 2014; Risén, 2014; Vincevica-Gaile et al., 2022), although expected to be solved by technological development and pre-processing of the biomass (Vincevica-Gaile et al., 2022). Beachcast harvesting and use have also been of interest as a carbon sequestration measure and, thereby, climate change mitigation (Joniver et al., 2021).

The particular case of harvesting and using composted beachcast on Gotland has been presented as an opportunity to contribute to a bio-economy by closing the loop on phosphorus in a resource-efficient manner (i.e. the composting treatment has a relatively low cumulative energy demand and low carbon and nutrient footprints) (Thomas et al., 2021). Similarly, a comparative case study of alternative treatment strategies in a circular economy framework (from the Mediterranean Sea/Italy) found that composting was preferred due to low investment and operating costs in relation to the value of the produced compost as fertiliser (Mainardis et al.,
2021). While composting is a promising treatment to make beachcast an agricultural resource input and a contribution to the bio-based circular economy transition in society, more research is needed on its heavy metal content (Franzén et al., 2019; Michalak et al., 2017; Weinberger et al., 2012) and uncertain waste-resource status (Chubarenko et al., 2020). It has been suggested that more comprehensive assessments incorporating economic aspects should assist decision-making and improve management practices regarding beachcast (Risen et al., 2017).

Beachcast management and treatment approaches involve multiple stakeholders, both private and public (CONTRA, 2021), who should be given attention when adopting management strategies for treatment solutions (Mainardis et al., 2021). A study on stakeholder perceptions of beachcast management strategies carried out by Ruiz-Frau et al. (2019) on the Balearic Islands off the Spanish coast demonstrates that stakeholders' empirical evidence on related ecosystem services and associated negative impacts can deepen the understanding and provide public support of financial investments.

In a review on composting beachcast, it is suggested that research on beachcast management should be interdisciplinary to discover ways of lowering the economic costs of massive beachcast harvesting/removal and use (García & Loring, 2022). Similarly, an economic perspective of natural resource utilisation and bio-economics points to the need for multidisciplinary efforts to develop cost-effective management (Palatnik & Zilberman, 2017). So, while research suggests that processes are viable and environmentally sustainable, the current absence of capital spending to achieve a waste-to-resource conversion of beachcast calls for a systematic review of the viability and challenges surrounding its utilisation (Joniver et al., 2021)

Accordingly, the approach of this thesis provides a transdisciplinary and systematic review of beachcast in the form of an in-depth case study.

### 4. Methodology

"The methodological platform of studies on material and energy flows related to environmental impacts, and to these flows closely related
aspects such as their management, share similar borders to research usually gathered under the term IE (cf JIE 2010)." (Lindkvist & Baumann, 2014)

Overall, the thesis was constructed by applying the IE concepts and principles of systems thinking, industrial symbiosis, and transdisciplinarity to a single case study, and a suitable mix of methods and tools, and a research team were selected to fulfil the aim and objectives (through the research questions).

4.1. Multidisciplinary approach

The theoretical concepts of systems thinking (Chapter 3.1.1.) and industrial symbiosis (Chapter 3.1.2.) call for transdisciplinarity (chapter 3.1.3.) that encourages integration of scientific disciplines and the inclusion of practitioners' knowledge (to co-produce descriptive, normative, and transformative knowledge) as a means for sustainable development (Klein et al., 2001). This inevitably integrates different epistemics (ways of knowing about what exists) (Buizer et al., 2011; Chen, 2016).

On the principles of the sustainability science-policy interface (to achieve transformation), Chiu et al., 2020 state that "solutions can be found by combining rigorous physical basis in Natural Sciences with managing real-life complications best seen via the lens of the Social Sciences.". This is the methodological approach of this thesis. The combination of natural-social science disciplines and epistemological stances was applied: "by recognising that human beings act in response to their perception of ecological impact rather than to that ecological impact per se" (Howard-Grenville & Boons, 2009). This form also motivates the strong focus on perceptions in the qualitative phase of the thesis consisting of Paper I and the proceeding quantitative phase (answering the questions raised in Paper I) consisting of Papers II, III, and VI - all of which served to answer RQ 2 (which are of both qualitative and quantitative character). The RQs (1-3) and the respective methods applied in the papers (I-IV) that were used to answer them are listed in Table 1 (Chapter 2).

During the research and thesis process, knowledge production, dissemination, and communication of the results also took place beyond scientific articles, bridging science and society. This resulted in the creation of
artefacts and social activity on the topic of beachcast management parallel to (or following) the papers (I-IV). As this could affect perceptions and impact decision-making and, ultimately, policy for resource management, these are presented and discussed in the thesis (Chapter 6).

A multidisciplinary research team of engineers, ecologists, economists, and agrarians associated with different research institutes conducted the research for this thesis, studying the case from various scientific disciplines/angles and exchanging knowledge outside of academia. University collaborations cross-sector is confirmed to contribute to local or regional sustainability transitions, and connecting research agendas to real-world sustainability issues is supported by scholars (Trencher et al., 2014).

4.2. Mixed-methods approach

Systems thinking, as a means of understanding and management (incl. policy development), calls for combining different types of methods and tools, i.e. generic specific and deductive inductive and qualitative quantitative (Shipp & Ramage, 2020), with the challenge of finding a balance between holistic and atomistic thinking about the system (Shaked & Schechter, 2017).

The inclusion of a quantitative phase and a qualitative phase in an overall research study is referred to as a mixed-methods approach (Johnson & Onwuegbuzie, 2004), which contributes knowledge beyond what could be provided by either approach alone and allows for philosophical assumptions to be made while applying theory (John & David, 2017).

The value of a mixed methods approach to resource management in marine social-ecological systems has been praised by Murray et al. (2016), stating that approaches featuring qualitative and quantitative elements may provide a step towards the need to distil complex systems (making them observable, measurable, that can expose inevitable trade-offs involved in resource management). Meanwhile, the mixed-methods approach deploys holistic thinking that can depict diverse values, attitudes and conceptions of 'what should be' in marine systems (paying attention to scale and context). This thesis has been structured methodologically to provide such a combination.

Paper I constitutes a stakeholder analysis (qualitative), Paper II cost-benefit analysis (qualitative and quantitative), Paper III cultivation experiment
Stakeholder analysis, as a qualitative method in natural resource management, recognises different actors involved in utilising or conserving natural resources, including their engagement, influence and perceptions (Prell et al., 2009). Such an approach can help identify and resolve trade-offs and conflicts of interest and engage stakeholders on multiple levels of decision-making (Prell et al., 2009). In this case, the stakeholder analysis was conducted in the form of semi-structured interviews.

Cost-benefit analysis (CBA), in a natural resources management context, serves to quantify the net monetary costs and benefits of a management activity, policy development or projects that have a deliberate aim of improving the provision of ecosystem services (or actions that may indirectly affect it, sometimes adversely) (Boardman et al., 2018). This is done before (ex-ante), after (ex-post) or during a project (in medias res) by subtracting the monetary costs of the activity from the monetary value of all the generated benefits, and if the benefit exceeds the cost, there is the economic justification for the project to proceed (Boardman et al., 2018). When data scarcity precludes monetisation, an activity's consequences can be assessed qualitatively (Boardman et al., 2018). In this case, the CBA was of both quantitative and qualitative character.

Field experiments reflect the notion that research is best in settings that most closely mimic the domain in which knowledge is to be applied (Green & Gerber, 2004). In this case, a crop cultivation experiment was conducted to predict the long-term soil accumulation of cadmium from beachcast application.

Chemical samples of a natural resource could be used to monitor and improve management practices. In sampling for natural resource monitoring, any prior information on variation should be utilised as well as possible to search for an efficient sampling design to improve management schemes (de Gruijter et al., 2006). In this case, prior analyses of beachcast from the national policy and grant scheme were combined with new sampling to obtain data and advice on further monitoring.
The research design developed during the study, for which the qualitative phase (Paper I) led the way, with its findings further developing research questions of both qualitative and quantitative character (Paper II), and quantitative (Paper III, and VI), serving to answer the research questions that are qualitative and quantitative, RQs 1-3. Consequently, the thesis consists of an initial qualitative phase (Paper I), followed by a transition from qualitative and quantitative one (Paper II), a quantitative (Paper III and IV), and finally, the qualitative compilation of this thesis, i.e. Qual -> Quan -> Qual).

Treating qualitative work as equal to quantitative work within Industrial Ecology is an opportunity to create change toward sustainable futures (Mitchell, 2009). This thesis does this through its design, i.e. the Qual -> Quan -> Qual combination. According to the mixed methods typology by Leech & Onwuegbuzie (2009), this thesis/research project could be defined as a thoroughly mixed - concurrent - equal status design. In this design, the quantitative and qualitative phases are mixed concurrently at one or more stages, combined in the research questions and analysis, and given approximately equal weight.

### 4.3. Ethics

Science addressing sustainability issues transdisciplinary will involve ethics as "it delves into how a particular scientific finding is 'good for' ecological sustainability; whether it 'ought' to be transformed into policy; and, whether such is the 'right' thing to do" (Joaquin & Biana, 2020). Such a task inevitably entails moral reasoning and value-based normative judgments (ethics) necessary to consider during decision-making processes when scientific findings/results should be translated into relevant policies. The result may be a “philosophical” gap in science-policy interfaces unless discussed. This thesis bridges this philosophical gap by discussing its results (from Paper I-IV) and decision-making about relevant philosophical policy and sustainable development stands.
5. Overview of Papers I-IV

The background, content, and general findings in Paper I-IV are summarised in this section. The summaries are abstracts of respective papers.

5.1. Paper I. Using stakeholder perceptions to deepen the understanding of beachcast governance and management practices on Gotland, Sweden

Paper I investigated and provided insights into the beachcast governance system on Gotland, Sweden, from a sustainability perspective using stakeholder perceptions of the emergent policy-based management system that subsidises beachcast removal to mitigate eutrophication. The system has come to connect land and sea by awakening the interest in using beachcast in agriculture and involving multiple actors. This case study confirmed the importance of an integrated approach to coastal management, considering a diverse set of actors and governance levels, and showed how cross-level communication and collaboration have enabled such integration, although improvements could be made. The case-specific ways of incorporating the findings included assuring the financial stability of the grant scheme, simplifying the administrative process, adapting strategies for feedback on the effects of management actions, and developing science–society collaboration. These are related to issues that could be expected in similar settings elsewhere. For example, questions about whether or not to subsidise a coastal management system for beachcast and whether such a subsidisation would result in the intended outcome are coupled with the ongoing debate regarding decentralised versus centralised governance and, thus, at what level the managerial responsibility should lie within an integrated system. Moreover, the acclaimed importance of an integrated management approach (which this study confirms) needs to consider actors’ varying agendas and different motivations for a waste-to resource conversion of beachcast in the land–sea interface through valorisation or other means in order to avoid indefinite reliance on subsidisation in this form and a debate on who should carry the costs. In theory, stakeholders commonly agreed on an improvement in making beachcast management more sustainable: to achieve a system for
circular resource management. In practice, however, they perceived it challenging to combine interests across domains. As such, future studies need to direct attention to and determine whether varying interests can be combined, and thus, if stakeholders can collaborate to solve the challenges of beachcast management or if the interests are considered too divergent, and alternative solutions should be sought and researched. This highlights the need to embrace and combine diverging interests within a governance system (beyond solving conflict or negotiating values) in order to be able to incorporate the whole spectrum of sustainability, i.e. practice systems thinking.

The systems thinking approach of the paper allowed for the inclusion of land and sea aspects as well as human components of a mitigation and management response to coastal eutrophication, displaying important aspects and conditions for successful implementation. Conceptually, this study provided additional support for applying systems thinking to provide an in-depth understanding of coastal zone resource management, in this case targeting beachcast, but potentially of value to similar ocean and coastal management cases. Moreover, the study shed light on the waste-resource dilemma of beachcast and the complexity of managing ‘ambiguous resources’—i.e., ones that lack market value as a resource but are not necessarily considered waste— and thus coupled with dubious legislation and ownership (e.g., commons, ancient rights, or even private property). The attention to the waste-resource dilemma could serve to develop management practices to ensure environmentally sound and sustainable management.

While this study addressed a site-specific case, the analysis and discussion of coastal resource management expands the empirical knowledge of governance and ocean and coastal management, tackling management issues to secure the future of coastal resources and should be of interest to those interested in the implications of governance arrangements. This is especially pertinent in tackling ‘ambiguous resources’, which fall between management sectors, legislative institutions, and the economic instruments intended to promote sustainable resource use (e.g., blue bio-based economy), as well as appearing to fall between the cracks of different theories for assessing sustainability. This calls for further applied and conceptual research on beachcast management and other “ambiguous resources” in coastal zones worldwide.
5.2. **Paper II. Cost-benefit analysis of beach-cast harvest: Closing land-marine nutrient loops in the Baltic Sea region**

Based on the idea that harvesting beachcast can help mitigate marine eutrophication by closing land-marine nutrient loops and provide a blue biomass raw material for the bio-economy, Paper II assessed ecosystem effects and social trade-offs with beachcast harvesting, exploring if harvesting is economically motivated from a societal point of view by conducting a cost-benefit analysis (CBA) on beachcast harvest initiatives. The cost–benefit analysis was applied to harvest activities during 2009–2018 on the island of Gotland in the Baltic Sea. Ecosystem services included N & P removal vs. return including estimated scale of nutrient removal; change of recreational opportunities on land; habitat change on land; GHG emissions; physical function change; harvest costs; transaction costs; and other consequences such as positive social relations.

The results indicated that the activities entailed a net gain to society, highlighting benefits such as nutrient removal from the marine system and improved recreational opportunities as well as costs of using inputs necessary for harvest. This lent substance to continued funding for harvests on Gotland and assessments of upscaling of harvest activities to other areas in Sweden and elsewhere. The lessons learnt from the considerable harvest experience on Gotland should be utilised for developing concrete guidelines for carrying out sustainable harvest practice, paying due attention to local conditions, but also to what can be generalised to a wider national and international context.

However, the content of heavy metals in beachcast adds some uncertainty concerning its use in agriculture and calls for more research on the variations of heavy metal concentrations with regards to agricultural use. A wider system boundary would also motivate the accounting of carbon flows and net greenhouse gas reduction potential resulting from different use options, which might give additional motivation for funding beachcast management or give direct financial income through carbon trading. In-depth assessments of post-harvest greenhouse emissions from beach-cast storage and use, and of various use options (e.g. biogas, biochar, and insulation), and their financial viability are key aspects to explore to optimize future beachcast management. The benefits of nutrient removal and improved recreational opportunities...
could also be monetized more precisely by carrying out local valuation studies that are designed specifically for Gotland.

5.3. **Paper III. Future trends in soil cadmium concentration from applying beachcast to agricultural land on Gotland, Sweden**

Although using beachcast compost as a fertiliser has multiple positive effects on agroecosystems, there are uncertainties regarding the risk of Cadmium (Cd) accumulation in soil. To estimate potential risks, Paper III consisted of a field experiment and Cd mass balance was conducted to predict the rate of Cd accumulation, changes in soil Cd fractions, and potential beachcast application methods that avoid Cd soil accumulation. With a time horizon of up to 2090, the long-term accumulation and adsorption of cadmium were predicted and analysed.

Considering the scenario of applying beachcast compost yearly at a rate of 20 ton ha\(^{-1}\) compost with a Cd content of 1.5 mg kg\(^{-1}\) dw, the EU threshold for biofertilisers (EU Fertilising Products and Amending Regulations, 2019), the soil Cd would increase with 25% by the year 2023, and approximately 100% by the year 2070.

In the scenario where the maximum Cd input from beachcast compost was set to the same threshold as the level established for sewage sludge, 0.75 g ha\(^{-1}\) year\(^{-1}\), beachcast compost with a Cd content of 1.5 mg kg\(^{-1}\) DW (the EU threshold for biofertilisers) could be applied in an amount of approximately 2000 kg ha\(^{-1}\) per year (one-tenth of the amount applied in this study).

Long-term effects from the continuous application of beachcast as fertiliser cannot be disregarded, and management strategies must adapt accordingly. Strategies to minimise cadmium in the input may consider careful application regarding the Cd content of the beachcast compost, amounts applied, and co-application with other fertilisers to minimise the Cd input. More knowledge of variations in cadmium levels of beachcast compost is required before recommendations can be provided.
3.3. **Paper IV.** Regional variations in chemical composition of fresh and composted beachcast on the island of Gotland, Sweden – considering future treatments

Paper VI mapped regional variations in chemical composition of fresh and composted beachcast on Gotland, Sweden. The excellent resource potential of beachcast in a bio-based circular economy is partly withheld by uncertain chemical properties, e.g. macronutrient content, C:N ratio, and Cd content, and more research is required to explore feasible treatment strategies and techniques that can compensate for such uncertainties. To expand the knowledge in this area, we compiled and analysed samples of fresh beachcast from a database within the marine policy scheme, LOVA, on Gotland, Sweden, to study local and seasonal variations in macronutrients, C: N ratio, and Cd content. This data set was complemented and combined with additional samples of fresh and composted material from passive pile treatment, measuring macronutrients, C: N ratio, ammonium, nitrate, and Cd content, and maturity index.

The results confirm that regional variations of the abovementioned parameters would most likely require investments in treatment techniques and strategies to make beachcast usable. The N and P content between two localities containing approximately ⅕ of the N and ⅓ of P than the other could exemplify the magnitude of the local variation. Seasonal variations show that the average N value is the highest in spring samples (5.6%) compared to summer samples (1.5%). Significant differences were also found for the C: N ratio, where the highest ratio was found in the summer samples (14,13) compared to the lowest for spring (7,05). The behaviour of the compost in passive pile treatment, only one out of three piles matured (to an index of 0.08) in approximately the same period. As for the cadmium content, the LOVA scheme samples contained, on average, 1.24 mg /kg DM Cd, which is below the EU limit for bio fertilisers at 1.5 mg/kg DM. However, Cd's ‘within-locality’ variation is significant and individual samples exceed the legal limit.

Further data collection could be facilitated by extending the LOVA scheme sampling to include (1) additional sampling post-composting and documentation of the composting time, (2) calculating C: N ratio and maturity index (ammonium-nitrate ratio), and (3) continuous documentation of the Cd content for each harvesting location, and (4) supporting experimentation with
co-composting using locally available biowaste. This knowledge could eventually assist policy in supporting context-specific treatment strategies that can bolster the waste-to-resource conversion of beachcast in the best way possible from a systems perspective.

6. Results & Discussion

This thesis aims to identify and analyse central aspects of beachcast management in a circular bio-economy context and to provide insights that can support policy development and more sustainable management practices.

It does so by first answering three research questions: What does the governance system for beachcast management look like, and why? Secondly, it identifies which aspects of the governance system and stakeholder perceptions of beachcast management are central to developing more sustainable practices and how. Thirdly, based on the results, it identifies and analyses how the central aspects of developing more sustainable beachcast management practices can be addressed, articulating considerations and measures for policy.

Finally, and separately from the posed research questions, the results beyond scientific articles, in the form of other artefacts, are presented.

6.1. What does the governance system for beachcast management, developed from the LOVA policy scheme, look like, and why? (Paper I)

Over a decade ago, Ostrom (2008) suggested that "institutional theorists move from touting simple, optimal solutions to analysing adaptive, multi-level governance as related to complex, evolving resource systems" to make natural resource management sustainable. Considering that few empirical studies of governance across land-sea has been completed (Pittman & Armitage, 2016), the descriptive knowledge of the governance system for beachcast management on Gotland, developed from the LOVA policy scheme, provides valuable insights. In a stakeholder analysis (Paper I), the governance
structures, processes, and institutions were discovered, and based on stakeholder perceptions of the system, the essential aspects for the development of more sustainable management practices were disclosed, including: (1) a strong stakeholder engagement/social capital, (2) the difficulty of a split land-sea vision, (3) seeking to solve the contamination issue, and (4) disruption of management responsibility (including financial and technological development) across governance levels and sectors.

**Governance institutions, structures, and processes**
The governance system for beachcast management consists of institutions (laws, policies, rules, and norms), structures (decision-making bodies, formal organizations, informal networks), and processes (decision-making, policy creation, negotiation of values, conflict resolution), which were mapped in paper I (Figure 2).

**Figure 2.** Map of the institutions (laws, policies, rules, and norms); structures (decision-making bodies, formal organisations, informal networks); and processes (decision-making, policy creation, negotiation of values, conflict resolution) for the beachcast governance system. Lines illustrate relationships between actors, where arrows represent actions that are part of the grant scheme, and dashed lines show independent activity.

**Institutions.** The LOVA grant scheme co-funds beachcast harvesting to mitigate local eutrophication effects. This has increased the beachcast activity
on Gotland, which makes the LOVA scheme a central institution in the governance system for beachcast management on the island (Fig. 1). Depending on the course of beachcast from harvesting to use, various legislations and rules apply, for which the Gotland County Administrative Board are responsible for pre-harvesting laws and regulations. For a detailed description of legislation from harvesting to use, see Paper I.

**Structures.** As such, two major public decision-making bodies of the governance structure are the Swedish Agency for Marine and Water Management (SwAM) at the national level and the Gotland County Administrative Board, which represents the national government of Gotland. While the former has a national responsibility for the LOVA scheme, the latter handles applications for LOVA projects on Gotland (Fig. 1). Although several areas for water quality improvement are eligible for LOVA funding, the Gotland County Administrative Board has almost exclusively allocated LOVA funds to beachcast harvesting projects (Paper I).

The governance system also comprises other formal organisations and networks. Gotland Municipality has legal responsibility for beachcast handling (post-harvesting), and NGOs apply for LOVA grants and organise beachcast harvesting activities, typically at “their bay” (commonly stretching a couple of hundred meters and consisting of varying-sized groups of permanent and part-time residents living within visiting distance from the beach), by contracting entrepreneurs for harvesting, as well as farmers to dispose of/use the beachcast material (HaV, 2022). Several NGOs consult marine interest organisations informally for knowledge exchange. On occasion, farmers have contacted the Agricultural Advocacy Group for advice on using beachcast as a fertiliser, but harvesting and using beachcast independently of the LOVA scheme is rare.

Gotland’s advocacy group for tourism is detached from the LOVA scheme, although the group acknowledged beachcast removal as crucial to the tourism industry. The private sector, representing business owners operating within the tourism industry, occasionally engages in local NGOs at the location of their businesses and are thus actors within the LOVA scheme. The explorative phase of discovering stakeholder relationships showed that several stakeholders represented multiple roles: individual members of NGOs being farmers; a group of farmers within the agricultural advocacy group having formed an NGO to harvest beachcast within the LOVA scheme; a representative of the agricultural advocacy group being a farmer and active
in an NGO; and members of NGOs having formed a marine interest organisation.

The social network connected actors across marine and agricultural domains, bridging land and sea interests and breaking the land-sea silos at a local level.

**Processes.** The NGOs’ financial and administrational reporting (e.g., of retrieved nitrogen and phosphorus from the sea) is reviewed by the Gotland County Administrative Board and subsequently transferred to SwAM, which consequently reports LOVA project results to the Swedish Government, which in turn updates the yearly national LOVA budget based on the results. Hence, LOVA’s prolongation relies on fulfilling and prioritising its environmental protection incentives. SwAM has national responsibility for handling the LOVA scheme with an ordinance as a legal basis. Still, the County Administrative Boards can adapt processes to regional conditions and applicants. In the case of Gotland, these have partly been changed to suit beachcast by requiring and collecting chemical samples of harvested beachcast (keeping cadmium in mind), adjusting the administrative planning requirements upon request from NGOs, and requiring agricultural use of the harvested biomass. Farmers were, however, not consulted in the decision-making process. Instead, the responsibility of complying with this rule was put on LOVA applicants—i.e., NGOs—to contact and communicate with farmers, which proved complicated due to farmers’ lack of interest in using beachcast. Hence, farmers are formally required to be a part of the LOVA scheme at the level of execution but, in practice, operate informally within the governance system shaped by the scheme.

As of today, harvesting beachcast is subsidised, but processing/treatment of the biomass to facilitate agricultural use as fertiliser or for soil amendment is not, although authorities now require agricultural use to finance harvesting (Paper I). However, the link to the agricultural sector has been established by NGOs and stakeholders operating as part of civil society (at ground-level planning, Figure 2) and not by authorities, and was thus created bottom-up instead of top down.
6.2. Which aspects of the governance system and stakeholder perceptions of beachcast management are central to the development of more sustainable practices, and how? (Paper I, II)

**Strong stakeholder engagement and social capital**

Already two decades ago, Allenby (2002) predicted that the public and NGOs would have a significant role in shaping policy for sustainable development. Such a development is now desired to bridge the land-sea interface in the Baltic Sea region as it gives more authority to the local level in planning (Pikner et al., 2022). The governance system for beachcast management on Gotland displays this development through the prominent role of NGOs, reflected in the number of NGO run projects that reached 40 in less than a decade from when the grant scheme was introduced (2009–2018) (Paper II).

A shared culture among stakeholders has proven to stimulate bottom-up actions from within and outside disciplinary silos, which have a bridging role in creating change (Saviano et al., 2019). This is also displayed in the case of Gotland, where a shared culture of caring for the local surroundings may stimulate stewardship across landscapes and seascapes that fosters sustainability (Paper II). Despite varying interests among stakeholders (i.e. reasons to be involved in beachcast activity), there is a shared notion of what would constitute an improvement for beachcast management, i.e. including both marine and agricultural ecosystem effects, which has served to bridge land and sea in this case, although with some difficulty (Paper I).

**Difficulties of applying a split land-sea vision in practice**

All sectors of society must be involved in developing long-term sustainable solutions to the complex issue of agriculture and eutrophication, and nutrient reduction strategies should range from "catchment-to-coast" (Withers et al., 2014). Paper I shows that local stakeholders applied this type of split land-sea vision on beachcast management by seeing and seeking to combine marine and agricultural interests and sustainability aspects (i.e. applying systems thinking). Accordingly, local stakeholders were largely on the same page regarding what they considered an improvement of the governance system: curbing eutrophication and creating a circular resource flow through
agricultural use of beachcast\(^3\), displaying a split land-sea vision. Stakeholders did, however, perceive it difficult to pursue this vision in practice (Paper I).

One reason for the difficulty was the contradictory (marine) policy incentives. On the one hand, the EU Habitat Directive to conserve ecosystems to protect species, and on the other hand, the environmental policy scheme LOVA to curb eutrophication by removing beachcast material from the coast. Local authorities struggled with the dilemma of choosing between the two policies, causing what was referred to as a "harvest-hesitation" at the level of management (Paper I). Local NGOs and other stakeholders on ground-level, on the other hand, shared personal observations with authorities of marine ecosystem improvements such as fish species returning (Paper I).

Another aspect of the split land-sea vision was the main difficulty of engaging the agricultural sector due to the concern for cadmium contamination of soils and crops, as well as fluctuating nutrient content and crop availability, infrastructure and logistics, and processing techniques for treatment options (Paper I). This was perceived to prevent further use in agriculture, and the possibility of solving this problem. In theory, the societal benefits of including the agricultural sector in the economic equation, may make beachcast an even more cost-efficient measure to curb eutrophication (Paper II), but the challenge of Cd content remains.

**Seeking to solve the contamination issue**

In line with previous research that proclaims the agricultural qualities of beachcast, while also articulating concern for potential contamination (Franzén et al., 2019; Greger et al., 2007; Katakula et al., 2020), Paper I shows that stakeholders perceived beachcast to hold multiple benefits as an agricultural resource input, but its use being withheld by the risk of cadmium contamination (of soils and crops) and waste status. The waste-resource ambiguity, highlighted in Paper I, entails the catch of refraining from applying beachcast due to the risk of cadmium soil accumulation (referring to threshold regulations/policy recommendations for biofertilisers), although seeking agricultural benefits (e.g. nutrient supply, increased organic content

\(^3\) Interviewees were not familiar with the aim of the thesis, and independently argued for/motivated their statements, wherefore a potential influence from the research project could be dismissed.
and water holding capacity) and achieving the international circular bio-
based economy vision/policy. Following this, the term "ambiguous resource"
was coined to shed light on material lacking a clear waste or resource
definition or classification, consequently falling between legislative and
regulatory cracks - receiving little attention for treatment (as hazardous
waste), nor for its potential to contribute to a circular bio-economy transition
(as it holds no current resource value) (Paper I).

In a perspective on ambiguities around waste and waste prevention,
Wiprächtiger et al. (2021) suggest a clearer and more narrow definition of
waste, meaning that waste has to be treated as a resource unless 'hopeless'.
Regardless of the definition (waste or not), the common contamination risk of
biofertilisers calls for risk assessments and management strategies, including
treatment options (Corden et al., 2019). This is also true for beachcast, and
Paper I shows that stakeholders sought knowledge on the same topics: the
environmental risk of cadmium contamination from agricultural application
of beachcast, treatment options (before or during agricultural use), as well as
management strategies (including sectoral and financial).

To address the environmental risk of cadmium contamination, the long-term
cadmium soil accumulation in a local context was modelled in Paper III, and
the cadmium content of the beachcast material in relation to local variations
and passive pile composting (the common processing technique/treatment)
was mapped in Paper IV. The last paper, Paper IV, also covered the topic of
nutrient availability to crops by measuring the macronutrient content,
maturity index and C:N ratio of fresh and composted beachcast. These studies
provided results that include potential measures to develop more sustainable
beachcast management strategies. Essentially, the results on management
responsibility are relevant to the present.

Distribution of management responsibility (including financial and
technological development) across governance levels/scales and
sectors
Effective symbioses emerging from new solutions that aspire to close
biological loops and develop the concept of circular economy at the regional
level (e.g. beachcast management) need regulatory support (e.g. such as end-
of-waste status for beachcast), but they also need to safeguard the
environment and human health, and stakeholder-based approaches (as to
how) has shown to be crucial (Vanhamäki et al., 2020). This case study disclosed stakeholder preferences regarding the distribution of management responsibility (including financial and technological development) across governance levels (local vs. regional) and sectors (marine, agricultural, and tourism).

Like a previous study by Risén (2014) no single stakeholder or sector proved willing to bear the whole cost for beachcast management (harvesting and use), causing a reluctance to accept or acquire managerial and financial responsibility for maintenance and development of the existing beachcast governance system (Paper I). This reluctance was found to jeopardise the longevity of the governance systems and attempts at improving management practices (Paper I). In line with Risén (2014), Paper I showed that one reason for the reluctance was that the benefits of beachcast activity are perceived to be unevenly distributed between stakeholders at various governance levels/scales and their representative sectors, either marine, agricultural, or tourism-related. In this case, tourism and even agricultural sectors were perceived as "free-riders" for not carrying a financial responsibility (Paper I). This phenomenon in natural resource management risks results in public underinvestment in resource management, or over-exploitation (Van Laerhoven & Barnes, 2014). It appears to be a risk in this case, since the marine policy sector was discontent with financing beachcast harvesting for beach cleaning purposes, possibly withdrawing their funding in the future for this reason. Such a withdrawal could provide stronger incentives for private investments to valorise beachcast in the future, with over-exploitation as a possible and undesirable outcome.

The fact that the system also spans several sectoral and policy/legislative areas, e.g. eutrophication mitigation policies, waste, and agriculture, makes it difficult to practically apply systems thinking and fully combine the varying interests of different sectors (Paper I). If the marine sector transfers the managerial responsibility (perhaps including financial) to tourism, the environmental focus, e.g. interest in the marine ecosystem effects from beachcast harvesting might fade, as Griffin (2016) also found likely in a thesis on beach management strategies in Scotland. Likewise, the need to involve the agricultural sector is critical to consider the potential effects on soil and crops from beachcast use to safeguard environmental and human health (Papers III and IV).
Stakeholders and/or sectors wishing to be relieved of the subsidy scheme (either for the responsibility or dependency) resulted in an intense search for other means of financing. These included changes in existing management structures from decentralised to centralised management, and changes in financial structures such as funding a bailiff, charging tourists a fee, and finding uses of beachcast as part of a circular and blue economy through market mechanisms/valorisation/product development, although no such options are currently within sight (Paper I). The costs and benefits of beachcast harvesting were researched in Paper II, providing similar suggestions to secure financial support in order to develop more sustainable beachcast management practices, which could be considered in policy development.

Stakeholders’ quest to find financial incentives for using beachcast was coupled with technological development, confirming the statement by Chubarenko et al., (2020) that cost-efficient technology is key if beachcast is to have a future as a resource in local economies (Paper I). Furthermore, Paper I displayed different preferences between governance levels regarding the development of technological solutions to beachcast treatment and management: large-scale, centralized, and more advanced technical solutions to treat beachcast (such as biogas) were commonly proposed by top-level planning, whereas stakeholders at the execution level sought more small-scale and immediate/logistically simple options requiring less investment (such as on-site composting).

6.3. How can the central aspects of developing more sustainable beachcast management practices be addressed? Considerations and measures for policy (Paper I, II, III, IV)

Three central aspects that affect the development of sustainable management practices, as found in Paper I are: harvesting-hesitation considering coastal ecosystem effects (1), waste-resource ambiguity considering the risk of soil accumulation of cadmium (2), and reluctance to accept or acquire managerial and financial responsibility for beachcast activity (3). These aspects are coupled with policy considerations, and potential measures to address these aspects are presented in the results from Paper I, II, III, and IV.
Continued experimentation and monitoring of marine ecosystems to handle the harvest-hesitation (1)

The precautionary principle exists to allow decision-makers to adopt precautionary measures when scientific evidence about an environmental or human health hazard is uncertain and the stakes are high (European Parliamentary Think Tank, 2015). However, an international policy cannot always consider or adapt to local contexts, wherefore precaution may be the least risky option to protect ecosystems, but perhaps not the best (Dupuy, 2009; Powell, 2010). In the case of beachcast harvesting on Gotland, applying the precautionary principle of the international EU Habitat Directive could put beachcast harvesting on hold although positive marine ecosystem effects are being observed (Paper I). For this reason, Paper I encouraged carefully rethinking and challenging the precautionary principle to enable experimentation with beachcast in this particular case.

This was motivated by the uncertainty of preserving the current state of marine ecosystems, together with positive stakeholder reports and observations. The reported return of fish species (Länsstyrelsen & Martinsson, 2015) was mentioned (but not monetized) in Paper II as a marine ecosystem benefit, and local stakeholders shared observations of several other positive effects such as fish returning to local bays (Paper I).

Further support of such knowledge documentation (e.g. of the recovery of water-bodies) through citizen science projects (e.g. extending the continuous sampling of beachcast) is suggested to make the sampling feasible, and provide information to decision-makers on the marine and coastal ecosystem effects, while also maintaining the strong stakeholder engagement/social capital that can foster environmental stewardship (Paper I). Stakeholders expressed doubts of a continuation of the subsidy scheme due to the known ambivalence associated with beachcast harvesting, which was said to cause a hesitation to invest in local beachcast harvesting activity (Paper I), e.g. equipment, information and observation of ecosystem effects. As such, the harvesting-hesitation may result in a loss of social capital.

Another argument for continued experimentation with harvesting, and monitoring of its effects, is that complete knowledge regarding how much beachcast is ecologically safe to harvest/remove cannot be produced, wherefore continued experimentation and monitoring of marine ecosystem effects is encouraged (Paper I). This is in line with Bruckmeier (2014) stating:
"Managerial decisions cannot be made merely by acquiring more and more data: there is not sufficient time for that. Choices have to be made with insufficient knowledge and informed guesswork."

**Consistent sampling of composted material and careful agricultural use to remedy the waste-resource ambiguity (2)**

Withers et al. (2014) insisted that experiments that aspire to address agriculture and eutrophication simultaneously need to be highly site-specific and connect with research to disclose the linkages between farming practices and responses with regard to soil and water mediums. Accordingly, Paper I compared the LOVA policy intervention of projects for beachcast harvesting to a large-scale (although local/regional) experiment in need of follow-up on its effects.

Policy decisions regarding cadmium risks from agricultural use of beachcast need to be made, and either the decisions are made with the target of avoiding Cd accumulation in soils (i.e. zero added risk), or based on avoidance of adverse effects on human or ecosystem health. The first could be considered safer since it requires detailed knowledge of Cd behaviour in the soil-plant system, which involves complex process that make the behaviour difficult to predict (Barrow, 2000; Grant & Sheppard, 2008; Hanc et al., 2009; Römkens et al., 2018). For this reason, Paper III focused on soil contamination and accumulation of cadmium, rather than cadmium transfer from soil to crop.

Scenarios were generated to discern patterns for which beachcast compost could potentially be applied long-term while avoiding Cd soil accumulation; e.g., sustainable use. Considering the crop rotation constant, scenarios were modeled with the following variables: combining a lower (i) Cd content of the beachcast compost than applied in the experiment (i.e. the experiment averaged 1.9 mg Cd kg⁻¹), and (ii) frequency of application. The three generated scenarios were:

(1) Beachcast compost with a Cd content of 1.5 mg kg⁻¹ DW, the EU threshold for bio-fertilizers (EU Fertilising Products and Amending Regulations, 2019) applied yearly

(2) Beachcast compost with a Cd content of 1.5 mg kg⁻¹ DW applied in 7–9 yr. intervals
(3) Beachcast compost with a Cd content of 1.0 mg kg\(^{-1}\) DW applied in 5–7 yr. intervals

The fractional Cd increase from each scenario is presented in Table 2.

Table 2. Scenario modelling, showing changes in soil Cd fractions when applying beachcast compost with a lower Cd content than the beachcast compost in the cultivation experiment, in which the model contained 1.0 and 1.5 mg kg\(^{-1}\) DW, respectively) at different time intervals (ranging from 1–9 years) to investigate when Cd would not accumulate in the soil (Paper III).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Interval</th>
<th>Change in soil Cd(_{2030}) (%)</th>
<th>Change in soil Cd(_{2050}) (%)</th>
<th>Change in soil Cd(_{2070}) (%)</th>
<th>Change in soil Cd(_{2090}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beachcast compost 1.5 mg kg(^{-1}) DW</td>
<td>Every yr.</td>
<td>19</td>
<td>51</td>
<td>81</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>7 yrs.</td>
<td>−0.068</td>
<td>+1.6</td>
<td>+3.3</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>9 yrs.</td>
<td>−0.068</td>
<td>−0.11</td>
<td>−0.04</td>
<td>2.0</td>
</tr>
<tr>
<td>Beachcast compost 1.0 mg kg(^{-1}) DW</td>
<td>5 yrs.</td>
<td>−0.72</td>
<td>0.29</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>7 yrs.</td>
<td>−0.72</td>
<td>−0.91</td>
<td>−0.93</td>
<td>−0.83</td>
</tr>
</tbody>
</table>

The results show that Scenario 1 (applying beachcast compost with a Cd content of 1.5 mg kg\(^{-1}\) DW every year) would double the soil Cd level (109% increase). Scenario 2 (applying beachcast compost with a Cd level of 1.5 mg kg\(^{-1}\) DW) displayed a turning point at an application rate of 7–9 years, for which a slight decrease in soil Cd levels could be expected. A decrease in soil Cd from Scenario 3 (beachcast compost with a Cd content of 1.0 mg kg\(^{-1}\) DW) could be expected if beachcast is applied every 5–7 years. Details are presented in Table 2, where the fluctuating numbers (percentages) are due to fluctuating Cd output.
In the thought experiment and scenario of setting the maximum Cd input from beachcast compost to the same threshold as for sewage sludge at 0.75 g ha\(^{-1}\) year\(^{-1}\), beachcast compost with a Cd content of 1.5 mg/kg DW (EU threshold for biofertilisers) could be applied in the amount of approximately 2,000 kg ha\(^{-1}\) per year (a tenth of the applied amount in this study). This corresponds to a tenth of the applied amount in this study, when using beachcast biomass with a relatively high Cd content, averaging 1.9 mg Cd kg\(^{-1}\). Despite the considerably high Cd content, the long-term effects on agroecosystems from Cd soil accumulation from continuous application of beachcast as fertilizer cannot be disregarded, and careful use is recommended.

As Paper III shows, the Cd content of the input material strongly affects long-term accumulation, and as for all biomass and biofertilisers, the chemical content of beachcast (fresh or composted) is prone to large variations (Paper IV). However, (Weinberger et al., 2012) compiled several cases of sampling from the Baltic Sea Area and concluded that "[...] the reported heavy metal content in Baltic Sea seaweed varies widely and several studies show relatively low cadmium content. This was confirmed by Paper IV which mapped the local and seasonal variations of cadmium content of beachcast biomass on Gotland to a larger extent than previous research has thanks to the LOVA scheme that has been, and is, conducting continuous sampling for a decade (the samples used was fetched from yr. 2012-2023).

Although the average Cd level of the LOVA scheme samples at 1.24 mg Cd kg\(^{-1}\) DM is below the EU threshold for biofertilisers at 1.5 mg Cd kg\(^{-1}\) DM, there are single samples that exceed the level, which causes uncertainty regarding its use (Paper IV). The local significance is also coupled with a large “within-locality” variation, increasing the unpredictability and further complicating management decisions regarding its use (Figure 3, Paper IV).
Figure 3. Overview of the LOVA scheme samples of beachcast, showing the content of total Cadmium (Cd) in relation to locality (Sandhamn, Kvarnåkershamn, Nisseviken, Norebod, Sandviken, Vitviken South, Vitviken North, Kyrkviken, and Alnäsaviken) (Paper IV). The box-plot shows median, quartiles, mean and max values, and outliers.

The unpredictability of chemical content (cadmium and macronutrients) is inevitable due to natural variations that are impossible for humans to control in advance, and it will undisputedly affect management (Paper IV). Some of the biomass may be used while some should not, or at least needs treatment, which calls for consistent sampling as a management measure. This process could also enable separate treatment for “batches” that exceed assigned thresholds, and combine different treatments of the biomass, e.g. construction or insulation material (Paper IV). Over time, his process could also result in somewhat better predictions of the chemical content, which could simplify treatment.

However, as Paper I states, anticipating precise knowledge is deceptive, as these gaps will never be filled to a satisfactory level (at which the chemical content of the biomass becomes predictable), and management decisions will have to be made. This leaves us with "engineering" a satisfactory product, e.g. fertilizer or soil amender, depending on the sought quality (Paper IV).
So, given the unpredictability of the chemical content of beachcast, co-application with manure (Paper III) or an engineered compost (Paper IV) are two types of measures that may make beachcast management more sustainable. Co-composting would lower the Cd levels (i.e. "dilution principle") and help to control the composting procedure to obtain a more optimal NPK and C:N ratio (Paper IV). Eventually, an engineered soil/compost product could be developed according to industry standards that comply with agricultural policy and regulations for biofertilisers (Paper IV).

To conclude the results: regardless of the definition or classification of beachcast material/biomass (waste or not), beachcast entails issues with contamination risk and fluctuating nutrient Cd content and availability (Paper III, and IV). This is a common issue with biofertilisers (Corden et al., 2019), mirrored in farmers' perceptions and concerns (Case et al., 2017b), just as this case of beachcast use illustrates (Paper I). This calls for safe management strategies in the form of careful use and consistent sampling and possibly treatment before application to make it useful (Papers III, and IV). A pressing question is if any stakeholder group or actor will take the lead on such a development that also would bring about huge costs.

Continued subsidy and cross-sectoral collaborations to abide by managerial and financial responsibility for beachcast activity – and realize an example of a bio-based circular economy (or regenerative resource system) (3)

Paper II concluded that the benefits of beachcast harvesting (excluding a potential use) within the current case of beachcast management exceed the costs. The benefits from nutrient removal were estimated at 11.5 million USD2018 and the change of recreational opportunities on land was deemed likely to be a clear benefit. The habitat change on land was inconclusive but deemed small considering the conditions. As for the costs, the net effect of GHG emission change from bands to piles was difficult to ascertain, although Björk et al. (2022) shortly after assessed the difference to the advantage of piles. The cost of GHG emissions from harvest machinery and associated transports was estimated to be 0.24 million USD2018, harvest costs to 1.1 million USD2018, transaction costs to 0.39 million USD2018, and physical...
function change was deemed a potential cost in the future. The net effect of local cooperation and knowledge building taking place in the LOVA projects (e.g. other consequences) was difficult to ascertain, yet acknowledged (Table 3). As such, the cost-benefit relation for harvesting alone (excluding the potential use of beachcast) motivates a continued subsidy.

**Table 3.** Summary of cost and benefits associated with beachcast harvest in the LOVA projects (2009-2018), presented in Paper II.

<table>
<thead>
<tr>
<th>Type of consequence</th>
<th>Benefit, million USD$_{2018}$</th>
<th>Cost, million USD$_{2018}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient removal from the marine system</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Change of recreational opportunities on land</td>
<td>Net effect likely to be a clear benefit</td>
<td></td>
</tr>
<tr>
<td>Habitat change on land</td>
<td>Net effect inconclusive, but probably small</td>
<td></td>
</tr>
<tr>
<td>GHG emissions change from bands to piles</td>
<td>Net effect difficult to ascertain</td>
<td></td>
</tr>
<tr>
<td>GHG emissions from harvest machinery and associated transports</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>Physical function change</td>
<td>A potential cost in the future</td>
<td></td>
</tr>
<tr>
<td>Harvest costs</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Transaction costs</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Other consequences</td>
<td>Net effect difficult to ascertain</td>
<td></td>
</tr>
</tbody>
</table>

A continuation of the subsidy would provide financial stability that can maintain and support the governance system that has created cross-sector collaborations - a setup that holds the potential for stakeholders (public and private) to combine interests and financial investments, i.e. carry costs based on the retrieved benefits (Paper I and II).

If the tourism sector could take financial responsibility (without becoming the main managing sector, nor remaining a "free-rider", Paper I), the existing governance system with its collaborative setup holds great potential in connecting marine, coastal, and terrestrial social-ecological systems (Paper II),
and may become a long-lived statute/example to enable the development of sustainable beachcast management (Paper I). In practice, a measure to consider (for tourism to take financial responsibility) could be the introduction of a tariff. According to the results of Paper II, the total monetized costs of beachcast at 1.73 million USD2018 could be covered by a fee of USD 0.79 per passenger to and from Gotland for one year.

Additional benefits and funding could also be bolstered by sustainable use(s) of beachcast biomass, through the expansion of the system boundaries to include agricultural and/or other sectors (Paper II). Quantification of more ecosystem services (benefits) from its use could motivate further funding, and/or valorisation of beachcast could provide direct financial income, such as carbon trading, biogas or biochar, insulation material, and compost/soil production (Paper II), given that environmental and human health is not at risk (Paper III and IV). This is in line with Milledge & Harvey (2016) who suggested that commercial exploration of the beachcast biomass for food, fuel, and/or pharmaceutical products could fund harvesting and offset the economic impact of "golden tides".

However, due to the currently low market viability of beachcast, coupled with the associated ecosystem services provided by harvesting, Hasselström & Gröndahl (2021) consider beachcast management (in the context of nutrient update and the blue bio-economy) more suitable for subsidization, taxpayer-funded schemes or market-based instruments (such as cap & trade, compensatory mitigation, and payment for ecosystem services) because of their ability to internalize positive externalities. Papers I and II came to a similar conclusion, although referring to the risk of failing the existing governance system, which supports cross-sectoral collaborations that could serve as a platform to address or solve the central aspect of stakeholders/sectors abiding managerial and financial responsibility for beachcast activity. A situation without strong stakeholder involvement could self-evidently not render a waste-to-resource conversion.

Moreover, maintaining and developing the current governance system with its cross-sectoral collaboration could result in an agreement or consensus regarding the direction for the development of more sustainable management practices and combined use(s) in a circular economy context (Paper I). As a first step, measures to improve current management practice could consider the knowledge produced in Papers, I, II III, and IV, such as continued experimentation with harvesting and monitoring of coastal ecosystem effects,
and consistent sampling of beachcast biomass (e.g. Cd) and careful use (e.g. low application rate) to avoid soil accumulation of cadmium. Future cross-sectoral collaboration would most likely also incorporate science-society collaborations, between academia and other stakeholders. Such knowledge generation and exchange, as encouraged in Paper I, could serve to fill knowledge gaps that cause "harvest hesitation", which withholds experimentation and the opportunity to develop management practices.

To conclude, a continued subsidy of beachcast management and its cross-sectoral collaborations is key to let the "policy window for a bio-based circular economy" for beachcast biomass stay open so that management can develop in a sustainable direction (Paper I).

6.4. What knowledge production, dissemination, and communication has taken place during the conduction of this thesis (beyond scientific articles, bridging science and society)? Possibly affecting perceptions and ultimately policy for resource management

There are inevitable results in the form of activities beyond written scientific outputs that come with place-based research (Horlings et al., 2020). The communication between the research group and practitioners established during the process of conducting this thesis ventured into the production and dissemination of knowledge and artefacts (e.g. written work and social activities). Knowing that these activities added to the stocks and flows of knowledge that may improve the problem situation (for researchers and practitioners), affect perceptions, and ultimately policy, they are presented in their section to feed into the discussion later (and for transparency). These include a theatre play, photo exhibition, book chapter, articles in the local/regional paper, as well as. All of this together lays the foundation for mutual and transformational learning for both researchers and practitioners involved in and impacted by the research.

Following Papers I and III, a theatre manuscript and play with a plot about beachcast harvesting and use was arranged at the art gallery Körsbärgsgården, Sundre, Gotland. The work was organized in collaboration with a local school on the topic of 'Konst och kunskap' (Eng. Arts & Science), setting up the play
Släkens liv - en tur i kretsloppet (Eng. The life of beachcast - touring the natural resource cycle), engaging students in a pedagogically transdisciplinary form of teaching that included the art of acting, writing, drawing, history, natural sciences (biology and chemistry) and technology. Behind the manuscript and play, the students had hours of classroom teaching in each subject, conducted cultivation experiments, and produced material for an art exhibition (Figure 4). The process also engaged local farmers to explain the practicalities of using beachcast in agriculture, historically and today.
**Figure 4.** Newspaper magazine covering the local collaboration on beachcast harvesting and use initiated by the art gallery Körsbärsgården, in collaboration with a local school, involving farmers behind the scenes.
Following Paper I and II, a photo exhibition showing historical photographs of beachcast harvesting and use from the Riksarkivet (Eng. National Archives) was arranged by an active member of a local NGO harvesting beachcast within the LOVA policy scheme (Figure 5).

![Photo exhibition](image)

**Figure 5.** Mattias Klintberg/Riksarkivet (Landsarkivet i Visby/Mattias Klintbergs arkiv). From the archives, arranged by a member of an NGO harvesting beachcast in a local church.

Moreover, a popular science article briefing Paper II was published in the magazine Havsutsikt (Havsmiljöinstitutet, 2022), summarising the cost-benefit analysis of beachcast harvesting as a result of the implementation of the LOVA policy scheme on Gotland.

Furthermore, this thesis work was featured in a chapter of the book Vår del av Östersjön (Eng. Our part of the Baltic Sea) (Jakobson, 2020), which tell of (and praise) the local engagement and stewardship for the Baltic Sea on Gotland. The author of the book, Hanna Mi Jakobsson, also published two articles on the research work in the local paper Gotlands Allehanda (Jakobsson, 2019).

Before and during the production of Paper III and IV, a Master’s thesis was conducted from a cultivation experiment set up at a commercial horticultural garden (Vamlinbo prästgård). Following this, a collaboration formed between the garden and the farmer who had delivered the composted beachcast to our experiment. The farmer initiated co-composting experiments for product development to deliver and develop beachcast compost to the garden.
regularly. Simultaneously, a newsletter from ESSP reading Algae and the Circular Economy: Regulatory Challenges, informed of a company (Olmix group) working on the valorisation of beached seaweed (ESSP, 2021), who presents themselves as "The preferred partner of farmers for agroecological transition" (Olmix Group, 2023).

Following Paper IV (which encouraged sharing experiential knowledge of treating and using beachcast in agriculture) and a completed cultivation experiment (growing corn) at a demonstration farm (for which the data has been analysed but not complied in an article), an information session was held by the Gotland County Board, intended for knowledge sharing among farmers (Länsstyrelsen Gotland, 2023). The activity was partly financed by ‘Europeiska jordbruksfonden för landsbygdsutveckling’ (Eng. European Commission, Common Agricultural Policy, Agriculture and Rural Development).

Other commercially related communication took place during the conduction of this thesis. One experience includes being contacted by a company investigating the possibility of initiating a climate compensation program (in line with carbon-offset schemes,) off beachcast harvesting, counting carbon credits for each ton of carbon being removed from the sea and sequestered in the soil through agricultural use.

Another experience include being contacted by an entrepreneur and philanthropist group in the tech industry (following a national Baltic Sea conference) who had acquired a farm with an ambition to develop a form of model for sustainable agriculture that would host research projects. Their motivation was a combination of having become familiar with regenerative agriculture and having heard of the historical importance of beachcast as a resource in agriculture, but also the contamination risk, wherefore they wished to support research to experiment with treatment options, also onsite (Personal communication, 4 October 2021).

"We want to create a model farm for future sustainable agriculture, which is not intensive but based on permaculture and similar full-scale circular thinking around the use of resources... and we want to bring in beachcast because it is a local resource that we understand has been very significant, but is problematic today. We want to support research to use beachcast for cultivation again, or find sustainable ways to use it; we heard about alternatives such as construction insulation or cement building materials.” (Entrepreneur/farmer)
Other unofficial (but for the thesis work significant) comments/quotes include one by top-level planning (i.e. local authorities) that expressed concern for the unstable geopolitical state and the vulnerability that comes from being dependent on chemical fertilizer supply (Personal communication, Government official). The same actor criticized international politics for not being brave enough to make decisions that radically change policy so that a transition to a bio-based circular society can become a reality.

"I would like to see an increased degree of self-sufficiency for Gotland... the fertilizer dependence, yes, everything is imported today, and it makes us vulnerable. Perhaps even more considering Gotland’s location as an island... There is a fear from the political side, they don’t dare to raise the tax on commercial fertilizer. It’s difficult, but it’s also a lack of courage! What happens is that politics puts a ban on knowledge. We know better."

(Government official)

Another significant quote was by a farmer expressing a disappointment in the research community mainly focusing on exceptionally high-yield land for its return on investment while neglecting huge areas of less fertile land although there is talk of a lack of farmland (which could be managed sustainably, e.g. increasing biodiversity) and its global contribution to food production is still significant. As a result, the actor raised a concern for a lock-in with highly intensive agricultural practices (if other production does not receive the same attention).

"Agricultural research on seeds, plant breeding, and fertilizers focuses on high-yielding land only. For me, and many others, it makes no sense to listen to the 'latest' news; it only applies to that type of land and those conditions. I will soon be unable to get hold of a suitable seed here. At the same time, there is talk of a lack of agricultural land, but there is a lot of land not being used today because it does not pay off, even if sustainable farming on that land could contribute to biodiversity and so on."

(Farmer)

The above-mentioned activity resulted in informal communication in the form of a presentation at the Nobel Prize Museum on the topic of food tech (Nobel Prize Museum, 2023). The occasion served as a discussion ground for whether food tech actors (in academia or the industry) will consider a material like beachcast attractive enough to invest in, for example, to develop
management strategies and treatment methods to achieve a waste-to-resource conversion.

Lastly, part of a scientific poster presented in the last phase of the thesis was also printed and put up in different locations on Gotland where the research had taken place, including contact information (Figure 6). The poster briefed the four articles of the thesis and presented a main message that could be considered a compact formulation of the conclusions drawn from the discussion of these results.

**Figure 6.** Part of a scientific poster that was put up in the locations where research was taking place, together with contact information (excluded in the figure).

All of the above knowledge production, dissemination, and communication that has taken place during the conduction of this thesis (beyond scientific
articles) could be considered "co-production" of knowledge, serving to bridge science and society. Qualitative knowledge co-production for sustainability should be context-based, pluralistic, goal-oriented and interactive (Norström et al., 2020). These features are displayed and could be developed further from the foundation built in this process.

7. Implications for Policy and Beyond

This thesis aims to identify and analyse central aspects of beachcast management in a circular economy context and to provide insights that can support policy development and more sustainable management practices. As an extension of the results and discussion (section 6.1-6.3), it is therefore relevant to discuss potential implications for policy in a broader sense. I do so by relating the previous results and discussion (on the specific case of beachcast management) to philosophical stances on policy and sustainable development in resource management - bringing out three main topics (which may apply to other cases of managing natural resources or bio-based materials, although I refrain from generalizing):

- Development of sustainable beachcast management practices - theoretical and practical incongruity
- Future scenarios for agricultural systems - and their suitability for beachcast (and biofertilisers alike)
- The 'sparing or sharing' debate (on future agricultural systems) - bridging land and sea

Thoughts on Industrial Ecology as a research field and future research on the topic of beachcast are also discussed.

7.1. Development of sustainable beachcast management practices - theoretical and practical incongruity

In theory, beachcast harvesting and use appear a promising contribution to a circular bio-based economy with its N and P content, but this thesis and other literature show the difficulty of accomplishing a system for resource management in practice, i.e. management responsibility, financial means, and treatment options, that require waste-to-resource conversion. In theory, all
organic waste can be treated for recovery of nutrients and pollution control, while producing economic returns that can pay for treatment, but implementation of systems is tricky and requires a holistic view (Gajdos, 2010).

Vaneekhaute et al. (2018) suggested a roadmap towards setting up an optimal treatment train for nutrient recovery from waste to speed up the transition to a bio-based circular nutrient economy (from fossil-based). Intended as a decision-support guide to adjust strategies of nutrient recovery to local fertilizer markets, the suggested process consisted of identifying local fertilizer markets, determining the initial feasibility of the nutrient recovery solutions, and integrating processes in a treatment train. This thesis has touched upon all three steps, which are of interest to discuss in the same order.

Paper I showed that stakeholders at all management levels (of the governance system) and scales (marine and agricultural) were on a hunt to identify local fertilizer markets with a circular economy as a model and incentive. However, despite the stakeholder interest (perceptions disclosed in Paper I), there are no local fertilizer markets currently within sight, as previous studies on beachcast management in a circular economy context confirm (Chubarenko et al., 2020; Rudovica et al., 2021; Van Hal et al., 2014; Vaneekhaute et al., 2017). Optional markets that may provide a higher value for compost, in general, are fertilizer for organic crops and farms, commercial fruit and vegetable production, commercial nurseries, forestry, publicly owned flower beds/green spaces, home garden fertilizer and soil amendment products, and landscaping (Corden et al., 2019). All of these alternatives were mentioned by stakeholders in Paper I, and should certainly be researched in a transdisciplinary manner.

Regardless of the market, however, managing the risk of soil accumulation and crop contamination from cadmium (Paper III) and fluctuating chemical content (including cadmium and macronutrients) would most likely require investments in treatment techniques and strategies, and apart from being theoretically promising, they need to be practically anchored (Paper IV).

Generally, the economic and technical feasibility of nutrient recovery from waste is determined by the N and P content and N:P ratio of the material, i.e. the expected product value of the produced fertilizer (Vaneekhaute et al., 2017). So far, however, several market-oriented technological experiments of beachcast treatment (to develop agricultural resource inputs) have not proven
economically feasible, (Chubarenko et al., 2020; CONTRA, 2021; Hasselström et al., 2020; Joniver et al., 2021; Mainardis et al., 2021; Rudovica et al., 2021; Thomas et al., 2021; Van Hal et al., 2014; Vaneckhaute et al., 2017), and therefore remain theoretical. This suggests that future studies on beachcast management should investigate the feasibility of nutrient recovery solutions by better matching the N and P content of untreated (i.e. fresh) beachcast material with existing technological options, to calculate a threshold for return-of-investment (ROI) for an engineered fertilizer product.

However, as Papers I, III, and IV concluded, beachcast does not appear as a substitute for chemical fertilizer products if N and P (and N:P ratio) input alone constitutes the comparison and competition. Therefore, it would be interesting to research the local marketability of other beachcast qualities (beyond N and P, such as soil amendment to improve soil quality), which could expand the possibilities of paying for treatment of the biomass.

Improved soil quality from beachcast compost application (as soil amendment or conditioning), including micronutrient content, is an unvalued contribution today, although acknowledged (Katakula et al., 2020; Kumari et al., 2013; Nabti et al., 2017; Walsh & Waliczek, 2020). Soil quality increases the macro- and micronutrient and water-holding capacity of soils, and the microbial activity that benefits soil/belowground biodiversity that in turn serves to reduce agrochemical use (Bünemann et al., 2018) and more holistically it improves soil health or fertility (Patzel et al., 2000). Value-added products such as soil conditioners that improve soil quality for sustainable agriculture have received little attention in comparison to fertilizers and chemical inputs, although the market is considered vast (Babla et al., 2022). In a critical review of the topic of soil quality, Bünemann et al. (2018), argue that soil quality improvement cannot be achieved simply by adapting management strategies in existing agricultural systems is insufficient since their short-term economic thinking does not value such long-term effort. Consequently, the focus should be on fundamental system re-design “summarized as regenerative agriculture in the framework of circular economy” (Bünemann et al., 2018).

In contrast to explicitly seeking valorisation and marketability, however, this case of beachcast management argued that the current lack of market incentives for harvesting and use makes a continued (and perhaps extended) subsidy a more realistic option (than market-based financing) to make the multiple benefits of beachcast harvesting and use feed into a circular economy.
transition (Paper I and II). So if valorisation of beachcast remains unsuccessful, subsidization could provide ecologically sound waste management that also allows exploring areas of use to obtain circularity. As Gajdos, (2010) put it, ecologically sound waste management should be in the interest of the whole of society.

However, deciding on fertilizer subsidies or taxes commonly comprises a trade-off between societal scale/level (Scholz & Geissler, 2018); what may economically benefit an agricultural business may not serve a higher system's overall sustainability goals, and reversely so. So if subsidies would also incorporate investments in treatment techniques for fertilizer production (not only harvesting the beachcast biomass), it would be of interest to widen the concept of circular economy to circular society to realize a waste-to-resource conversion of beachcast biomass. To think beyond growth, existing technology, and market-based solutions, the term Circular Society has been introduced as an alternative to Circular Economy (Jaeger-Erben et al., 2021). Circular economy as a policy practice has been contested partly because of the challenges of governance and management of the circular economy-type of material flows that are inter-organizational and inter-sectoral (Korhonen, Honkasalo, et al., 2018). As a response, circular society frames transitions to circularity as a social-ecological and transdisciplinary undertaking that requires cooperation between all areas and levels of society (Jaeger-Erben et al., 2021), which is required to improve beachcast management (Paper I).

The circular society debate is in many parts more visionary than practical (Jaeger-Erben et al., 2021), but if used and implemented in the case of beachcast management, it could perhaps disclose its multiple values to society, which could generate funding to develop more sustainable practices. Moreover, the transdisciplinary focus of Circular Society could expand the scope to incorporate more sectors (than marine and agricultural). Similar to the industrial symbioses concept of Industrial Ecology (e.g. eco-industrial parks), expanding the system boundaries to explore various uses of beachcast in other sectors could result in an integration of various processes in a treatment train (Paper II). This could solve the issue of managing batches of beachcast that are not suitable for direct use in agriculture due to exceeded cadmium thresholds for biofertilisers (Paper IV), i.e. by including the building sector to use beachcast in construction material (Paper II). Possibly, this type of treatment train could qualify beachcast management for carbon offset schemes and the carbon removal certificates produced under the EU
framework, through carbon farming and product storage (European Commission, 2022).

In the case of sewage sludge, a waste-resource conversion (e.g. moving from theory to practice) is said to be hindered by the search for an optimal technical solution, wherefore feasible alternatives and/or combining feasible areas of use is encouraged (e.g. return of sewage sludge to agriculture, extraction of phosphorus and/or garden soil production). As such, policymakers and researchers are encouraged to put equal emphasis on what the material becomes as discussing technological development to realize a waste-resource conversion of sewage sludge in a circular economy framework, and thus take management decisions along the road instead of seeking to find one solution once and for all (Burgman, 2022). Similar conclusions were made in some of the thesis papers: Paper I by concluding that management decisions will have to be made without complete knowledge and answers, Paper II by encouraging synergies between possible applications for beachcast, and in Paper IV by opting for an exploration of treatment options that could result in a combination of use of beachcast.

A mixture of various treatment systems was also suggested in an extensive assessment of sustainability aspects of bioenergy and nutrient recovery from marine biomass by Risén (2014). It was concluded that it could serve to support multiple needs (food production, energy, and materials) while also avoiding severe technological lock-ins from investing in only one system.

The above discussion points to the difficulty of beachcast (like other types of bio-based fertilizers) to find its way into the current industrialized/intensive agricultural system (despite its qualities and potential contribution to bio-based circular society), and thereby a theoretical and practical incongruity associated with the development of sustainable beachcast management practices, which policy need to solve. Perhaps such a development requires systems changes to our current agricultural system, wherefore future scenarios for agricultural systems and their suitability for beachcast (and biofertilisers) are of interest to discuss.
7.2. Future scenarios for agricultural systems - and their suitability for beachcast (and biofertilisers alike)

The conditions for agricultural practices are changing, and new agricultural systems and paradigms are expected (Rundgren, 2022), urging us all to rethink the evolution of agricultural production in which the scenario of regenerative agriculture or agroecology are proposed as new ways forward (Garcia-Oliveira et al., 2021; Gowdy & Baveye, 2018; Kassam & Kassam, 2020). The principles of Ecological Recycling Agriculture (ERA), proposed as a necessary transition of agricultural practices in the Baltic Sea drainage area to curb eutrophication of the Baltic Sea (Larsson, 2016), are fundamentally the same as the principles of regenerative agriculture or agroecology: increasing biodiversity, enriching soils, improving watersheds, and enhancing ecosystem services through the exclusion of chemical fertilizers, and a change in land use in terms of less intensive local organic agriculture (Tittonell et al., 2022). Regenerative agriculture has been roughly referred to as "agroecology without politics" (Tittonell et al., 2022). Considering that a transition to bio-based fertilizers, required to curb eutrophication of the Baltic Sea, is said to need “support from policy and governance structures” (Larsson & Granstedt, 2010), the involvement of politics could be considered inevitable. Tittonell et al. (2022) call it unrealistic to not include politics in transformative approaches to agriculture altogether, considering the effects of decontextualized farming, a dependency on external inputs and financing, and degradation of resources, biodiversity, and the environment. Considering the social and policy-related findings/results in this study (see Chapter 6), agroecology also comes across as a highly relevant area to discuss in relation to a potential local (re)introduction of beachcast in agriculture to contribute to future sustainable food systems.

The concept of agroecology has developed into both a science and a set of practices (Garcia-Oliveira et al., 2021; Kassam & Kassam, 2020; Kremen et al., 2012; Milestad, 2020; Pereira et al., 2018; Porter & Francis, 2016). The general term ‘agroecological practices’ commonly denotes ecological science or principles being applied to agriculture (regardless of the actors' discourse or agenda), whereas ‘agroecology’ entails a wider transformative purpose (through and for such practices) (Levidow, 2015).

Apart from agricultural intensification (e.g. a continuation of industrialization and intensive land use, but with an expected minimization of negative
ecosystem effects through technological innovation), agroecology is recognized by the UN expert panel HLPE as a future trajectory for sustainable agriculture and food systems that enhance food security and nutrition (HLPE, 2019). Among several other features, HLPE (2019) has identified the following principles (extracted), which apply to beachcast as an agricultural resource input, and relate to topics raised in this thesis:

- Ensure a regenerative use of natural resources and ecosystem services
- Encourage recycling systems by supporting the reuse of waste in the forms of compost, and mulch
- Enhance biological and ecological processes in agricultural production to reduce the use of purchased inputs that include fossil fuels and agrochemicals
- Improve soil structure and health/fertility (i.e. soil quality) and recycling of nutrients
- Redirect subsidies and incentives that at present benefit unsustainable practices, to support the transition towards sustainable food systems
- Encourage locally appropriate strategies for maintaining soil fertility that are environmentally sustainable at the same time as being economically viable for farmers
- Take into account farmers’ access to diverse, traditional, and locally adapted resources

Sustainable utilization of beachcast as fertilizer is expected to play an important role in agroecosystems in coastal areas in the near future with regards to food security (as the elimination of chemical fertilizers will be necessary) and nutrition (restoring essential plant nutrients to the soil) (Emadodin et al., 2020). The stakeholder interest disclosed in the transdisciplinary findings of this thesis (section 6.4) could be said to reflect this expectation. The thesis also indicates that beachcast management could be an example of regenerative use of a natural resource and associated ecosystem services (marine and agricultural) if a sustainable recycling system for reuse of the material (currently considered waste) could be treated for use as compost (or mulch) in agriculture (Paper I, II, III and IV). However, beachcast is unlikely to serve as an input substitute in our current intensified agricultural system, although it may come to reduce the use of fossil fuels and agrochemicals (Paper I, III, and IV, and the findings of this thesis as a whole). From an agroecological perspective, however, beachcast (as an agricultural resource) could contribute to nutrient recycling and improvement of soil structure and health/fertility, qualities that have no market value today (provided that the risk of cadmium contamination is managed, potentially through consistent sampling to "clear" batches, or treatment).
Identifying the resource potential of beachcast is thus a matter of the context in which it is evaluated/assessed, and the concept of agroecology appears as an opportunity for beachcast to be re-introduced as an agricultural resource input by acknowledging and valuing the multiple qualities of beachcast (besides N & P supply). The potential of regenerative agriculture to improve soil health on Gotland, Sweden, has been assessed and due to the context dependency of the approach, further research on Gotland is encouraged (Daverkosen et al., 2022). Including the contribution from a local resource such as beachcast in coming analyses of such systems would be highly interesting.

Agroecological principles also suggest that subsidies that currently benefit unsustainable practices are redirected to support transitions to sustainable food production instead, in favour of local strategies that maintain soil fertility while being economically feasible for farmers (HLPE, 2019), and by the means of taking into account farmers’ access to a diverse, traditional and locally adapted resource. Considering the findings of this thesis, subsidizing or financially supporting an environmentally safe reintroduction of beachcast compost as a local agricultural resource input on Gotland appears to match agroecology.

Globally, fertilizer subsidies stand a major share of subsidizing that has led to over-fertilization and problems with soil fertility and contamination (e.g. of macronutrients and cadmium) (Scholz & Geissler, 2018).

The cost efficiency of different measures to reduce the agricultural load of nitrogen and phosphorus to the Baltic Sea has been researched, but systems change such as the one to regenerative agriculture (deemed feasible or not) has not, and it should be studied further before the direction of future agriculture or Baltic Sea policy is set (Larsson, 2016). Researching the cost efficiency of a systems change consisting of an agroecological transition In the Baltic Sea Region (including redirection of subsidies) that incorporates a reintroduction of beachcast as a resource input would be highly relevant for future studies in the land-sea interface, and Gotland could serve as a case study.

Tittonell et al. (2022) state that it is a common misconception that including social and political dimensions of farming is only relevant when working with “smallholder farmers in the global South” since social and political dimensions influence practices (processes) and outcomes also most advanced
economies”. Regarding the topic of the cadmium content of chemical fertilizers, and dealing with trade-offs on fertilizer subsidies to secure a future sustainable fertilizer supply, Ulrich (2019) argues for taking hindsight and systemic perspective. The author considers it "unavoidable for anyone seriously concerned with the topic", stating that the only rational option now is to switch to a green transformation because "The interests of future generations, who do not have a voice, stand at risk of being played against the interests of a growling industry minority that aims to keep the status quo." (Ulrich, 2019). The author predicts that directing financial support and research funds towards 'decadmiating' technology for phosphate rock or acid will make farmers suffer from price increases that would come with the cost of implementing such technology on an industry-wide scale would. Considering this, redirecting subsidies to finance the development of a 'decimating' beachcast could be a local strategy that would maintain soil fertility while being economically feasible for farmers.

The IE idea of incorporating environmental costs into price structures may very well support the idea of redirecting subsidies, as the external costs of chemical fertilizer production and use would become internalized, allowing for a fair comparison of the cost efficiency between alternative fertilizer inputs such as beachcast. Future research that directly compares beachcast macroalgae as biofertiliser with commercial fertilizer products has been directly encouraged (Joniver et al., 2021; Pardilhó et al., 2023), and despite multiple attempts at finding ways to its use in the circular economy (Joniver et al., 2021), a waste-to-resource conversion of beachcast has not been put to practice. As such, a continued focus on the product development of Beachcast within the current food regime appears futile. Product development at any cost may also infer a development that may not benefit local farmers, nor provide positive effects at scale.

Agroecology is also considered a knowledge-intensive concept focused on techniques that are not delivered top-down, but developed from farmers’ traditional knowledge and experimentation of locally adapted resources, community involvement is highly valued, and trusting the capability of local communities to experiment, evaluate, and create synergies and scale-up innovations through farmer-to-farmer research (Altieri & Toledo, 2011). Such an approach was encouraged in Papers I and IV to improve beachcast management and mirrored in the knowledge quest among stakeholders of the governance system for beachcast management on Gotland, and its strong
social capital that could serve to conduct citizen science (Paper I). The learning and social cohesion that comes with “co-innovation processes” may be more important in fostering long-term sustainable transitions than targeting specific outcomes in terms of soil, water, carbon, and biodiversity (Tittonell et al., 2022).

Policy changes supporting a transition to agroecological practices, and perhaps paradigm, involve substantial policy changes that are currently underway (Ajates Gonzalez et al., 2018; Gemmill-Herren et al., 2023; Gliessman, 2019, 2021), and researching the potential facilitation of a waste-resource conversion of beachcast biomass could provide valuable knowledge that connects theory with practice in this quest. Many local examples of regenerative resource use in agriculture come from practice rather than research, and they are not always well-documented in the scientific literature (Tittonell et al., 2022). Hence, viewing and researching beachcast from the perspective of agroecological science could perhaps help to solve its waste-resource ambiguity and contribute to sustainable resource management.

The incipient policy changes towards systems changes, transition, and perhaps paradigm shifts of food systems (intensification or alternatives such as agroecology) have initiated a discussion of the underlying philosophical stances of policy within natural resource management, which future direction, which also strongly relate to beachcast management.

7.3. The 'sparing or sharing' policy stance/debate (on future agricultural systems) - bridging land and sea

The two contrasting response pathways to unsustainable food systems, scenarios of intensification or agroecology directly relate to the philosophical policy divide regarding land and resource use and management in agricultural production into either 'sparing or sharing' to ensure biodiversity and thereby future sustainable food production, as it "underpins sustainable food production" (FAO, 2019). 'Sparing' refers to intensifying agriculture to release other land for protection/conservation without human interference, whereas 'sharing' refers to developing alternative biodiversity-friendly (i.e. agroecological) farming practices over larger areas (due to expectedly lower
yields\textsuperscript{4}) (Dudley & Alexander, 2017). However, to achieve the sustainable development goals (SDGs), green deal policy strategies (e.g. EU) should encourage the return of agricultural land that has been abandoned as a result of policies, initiatives, and subsidies (e.g. EU common agricultural policy, CAP) having reduced the area of cultivated soils in the EU (increasing in food importation and agricultural pressure in other parts of the world) (Vara Prasad et al., 2023).

HLPE (2019) pinpoints this 'sparing or sharing' dilemma by asking if biodiversity should be conserved in agriculture or only in the wild, referring to it as a critical dimension and controversial barrier to transitions towards sustainable food systems (SFSs). This dimension also appears present in beachcast management and the development of sustainable practices in the sense of being safe as well as contributing to sustainable development in terms of a bio-based circular society.

Firstly, Papers I questioned the good in applying the precautionary principle for the conservation of marine ecosystems at this stage (to protect biodiversity) in this particular case of beachcast management, since the human-induced eutrophication has caused excessive production of beachcast with negative (or even unidentified ecosystem impacts). The same debate on conservation applies to agricultural sustainability, particularly soil, “[…] the ultimate source that sustains us humans”, raising "the thorny question of what is ‘natural’ and when human disturbance actually began", as Janzen et al. (2021) put it. This thorny question is also one to address for beachcast management (Paper I).

Secondly, the debate raises the question of whether or not ecosystems can remain unaffected by us humans. Especially regarding sourcing food that for the most part involves the manipulation of some sort and degree (positive or negative), one excellent example being the connection between terrestrial and marine ecosystems through agricultural production and eutrophication that beachcast research so clearly displays. In the case of beachcast management, policy development will need to deal with the fact that sustainable agro-ecological systems frequently demonstrate higher LERs (Land Equivalent Ratios), and FAO states that "Agroecology thus promotes agricultural systems with the necessary biological, socio-economic and institutional diversity and alignment in time and space to support greater efficiency" (FAO, 2023).

\textsuperscript{4} Integrated agroecological systems frequently demonstrate higher LERs (Land Equivalent Ratios), and FAO states that "Agroecology thus promotes agricultural systems with the necessary biological, socio-economic and institutional diversity and alignment in time and space to support greater efficiency" (FAO, 2023)
governance of the Baltic Sea cannot be achieved while simultaneously intensifying agriculture production in the area (Larsson, 2016). This speaks for the need to think in terms of ‘sharing’ in policy development (perhaps also achieving greater systems changes/paradigm shifts/transitions) that take into account that the nutrient load to sea has to significantly decrease for beachcast management to contribute to sustainable development. Otherwise, an action like nutrient recovery through circular resource management of beachcast (harvesting and use), and other relatively small-scale bio-based resource inputs to agriculture, may become more or less negligible - a spit in the ocean.

7.4. Thoughts on IE and future research

In a transdisciplinary perspective on Industrial Ecology research, Mitchell (2009) states and suggests that "we’ve come to the view that life is far too messy to throw up ‘problems’ that can be ‘solved’. So rather than seeking problem solutions, we wonder if we might be seeking ‘problem resolutions?’ This is a question that beachcast, with its history and documented qualities, may be an example of, although indeed facing challenges. The challenges closely resemble those of a "wicked problem" in ecosystem management and policy; no single answer or solution exists, only a better understanding of a problem and how challenges may be processed. (Defries & Nagendra, 2017; Head, 2019, 2022).

This thesis shows that the challenges with beachcast are largely the same or similar as for other biowaste, i.e. treatment (to make the material usable), application techniques (suitable farm equipment), logistics chains (from treatment/production site to farmland), acceptance (by farmers, wholesales, consumers, and other stakeholders), and economic feasibility (Paper I).

However, practical implications of biowaste use need to be appreciated by stakeholders to make biomass flows enter the circular economy, or else resource management will remain unsustainable and so will society (Sherwood, 2020). To accomplish this, it may be necessary to uncouple the petrochemical industry and biomass production with renewable fertilizers and enhance stakeholder cooperation with the help of policy to support this task (Sherwood, 2020).
In a large study and survey of farmer perceptions and use of organic waste products in the journal Agricultural Systems, Case et al. (2017b) found that improved soil structure was chosen as the most important advantage or reason to use organic fertilizer, followed by low cost to buy or produce, and ease of availability. To increase the availability and farmer use, a mix of government and industry-led measures was suggested, which brings us to discuss subsidy schemes and market-based mechanisms with regards to appreciating beachcast in a bio-based circular economy.

This thesis discussion indicates that beachcast appears to have a better chance of being appreciated for its qualities in an agroecological context rather than within the currently dominant paradigm (or possible future intensification of agricultural practices), and thereby contribute to a transition to a sustainable food regime. A major challenge then, is how beachcast, and perhaps other ambiguous resources, are to receive attention to address the facing challenges, such as the Cd content of beachcast. Especially when knowledge production technological innovation, economic competitiveness, skills, and institutional resources have been, and are, foremost focused on the dominant food regime (Levidow, 2015), a situation that this thesis could be said to confirm (e.g. chapter 6.4 with statements from stakeholders). This is where IE comes in and could make a difference.

It has been claimed that the circular economy paradigm is the foundation that facilitates the planetary agro-ecological transition (necessary to avert from linear production systems and achieve sustainable resource management) (Zarbà et al., 2021). On the other hand, the inclusion of biomass in the 'circular economy' is yet not significant, and this is partly due to the fact that smaller cycles (e.g. repair, recycling) retain more value than larger cycles (e.g. biochemical flows). This means that "restorative material flows that return a resource to nature" in practice become neglected by the circular economy (Sherwood, 2020). At this point in time, beachcast is a "terrific" example of such a resource, and Industrial Ecology may assist in addressing this problem. The finding of this thesis encourages it, although with caution, i.e. not seeking valorisation at any cost. Future researchers (and IE researchers) must be cautious about what the result may be. The fast development of wetland management is an interesting example.

As a consequence of incorporating wetland restoration in a carbon credit system, wetlands have gone from being viewed as useless to becoming a "gold mine" for investors for climate compensation. The banking interest has raised
the value of wetlands, while scientific and local voices are raised concerning
the risk of only concentrating on carbon sequestration, which inflicts on local
stakeholders' agricultural livelihood and holistic thinking (Bergstedt, 2023).
The critique is directed at the absence of systems thinking (not wetland
restoration as a measure), which inflicts on the more diverse agricultural
practices in the area that incorporate local ecosystem knowledge. Research
has also identified the scale of wetland restoration to be critical in order to
manage tradeoffs and synergies (Hambäck et al., 2023). A lack of systems
thinking and local anchoring in natural resource management is deemed to
become unsustainable, and unfortunately, the idea of trying to support
sustainable development employing compensation through natural resource
management is assisted by the policy stance of 'sparing'. This wave could very
well hit beachcast (the interest is there) and the potential consequences of such
a development should be critically researched so that it is not automatically
sought simply because it could welcome beachcast into the circular economy
(i.e. through technical-economic assessments).

As noted early in this thesis, Industrial Ecology has been criticized for not
bringing about change or transformation, and instead becoming a tool to
'optimize' resource management within current paradigms, e.g. seeking
valorisation without long-term consequential thinking (Chapter 3.1
Theoretical background). IE researchers have criticised the development of
CE, as an extension of the Industrial symbiosis concept, for feeding into this
development (Korhonen, Honkasalo, et al., 2018; Korhonen, Nuur, et al.,
2018).

The issue is not one of Industrial Ecology alone, "the new ecology" founded
by the mid-21st century applied economic theory to nature, (Worster, 1996),
an approach that lives on, although economic principles applied to resource
management are questioned from the perspective of systems-wide strategies
for sustainable resource management (Crane et al., 2011; Hofmann, 2022;
Schröder et al., 2019). Hofmann (2022) calls for the concept of Circular
Economy can shift baselines from unconditional growth to degrowth, and
urges academia to scrutinize the classical approaches and instruments of
strategic resource management that are mostly based on assumptions of the
latter. In the book *Impossibilities of the Circular Economy - Separating Aspiration
from Reality*, Semertzidis (2022) suggests the concepts of 'Degrowth' and
'Resource Nexus' could assist in improving the Circular Economy.
This critique is reflected in the key message from the European Green Deal, which calls for wider systems thinking in resource management (to go beyond value chain-based approaches) through applying the Resource Nexus concept (European Environment Agency, n.d.). Resource Nexus specifically looks at resource interlinkages, for instance between food and water resources to increase biodiversity and soil fertility (European Environment Agency, n.d.). According to the EU, applying Resource Nexus to policy interventions generates important information about synergies and trade-offs across resource-related goals, contributing to more effective management strategies. It has proved useful for identifying knowledge gaps, imbalances in policy focus, and potential "winners and losers" among stakeholders, and as a basis for informed discussions (European Environment Agency, n.d.). If combined with other methods, such as governance approaches, when applied to case studies, Resource Nexus assessments could add to the systemic understanding of sustainability challenges and help strengthen policy coherence and integration (European Environment Agency, n.d.). Considering the above features, this thesis fits the Resource Nexus concept very closely.

Additionally, this case of beachcast management illustrates the criticism of CE and also IE (trying to 'optimize' resource management within the current agricultural paradigm, see Chapter 3, Theoretical and practical background) through its waste-resource ambiguity that remains unsolved (as beachcast holds no market value). Not changing the way of thinking may slow the sustainable development of beachcast management practices. On this note, however, applying the basic principles of IE in this thesis (instead of specific quantitative tools) served to highlight this issue, which shows the strengths of applying IE theory in this broad sense. It also served to indicate that the field could benefit from venturing further into new paradigms and areas such as agroecology to spark a transition to more sustainable resource management and a circular bio-based society. In turn, this back-to-basics approach could also bring about a wider system-thinking perspective, reflection, and transparency among IE researchers on the human-nature relationship, as these aspects inevitably affect resource management and policy development, as shown in the 'sparing or sharing' debate. This may go as far as reflecting on how we humans perceive ourselves in relation to nature, and thereby its resources.
The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES, divides our relation to nature into four categories, where we perceive ourselves to either live from, with, in, or as nature (IPBES, 2022), which affect policy for resource management. Similar to how Isenmann persuasively two decades ago made a "Plea to Employ Nature as a Model in a Reflective Manner", this could encourage Industrial ecologists to dig and dive even deeper (than reflecting on nature as a model) by encouraging us to reflect on our relation to nature. Perhaps this would mean returning to the roots where the economy is subordinate to ecology and an establishment of the next "new ecology" where economic principles and theory do not rule policy, which results in "ambiguous resources" such as beachcast that possess great resource qualities but hold no value.

8. Conclusions

This thesis aims to identify and analyse central aspects of beachcast management on Gotland, Sweden, in a circular economy context and to provide insights that can support policy development and more sustainable management practices.

Firstly, the results show that subsidising beachcast harvesting to mitigate the local effects of eutrophication has generated a governance system consisting of institutions, structures and processes in a network of actors at different management levels.

Secondly, the analysis of the governance system and stakeholder perceptions revealed that strong stakeholder engagement and social capital are central to developing more sustainable beachcast management practices. Another identified central aspect of the governance system is the difficulty of applying a split land-sea vision in practice, i.e. combining marine and agricultural interests and societal domains. Moreover, from a marine point of view, there is a harvest hesitation due to perceived uncertainties regarding potentially negative impacts on biodiversity in coastal zones from beachcast harvesting, which may hold back the development of beachcast management. From an agricultural perspective, this thesis confirms the concern for cadmium contamination and solving this issue is undoubtedly a central aspect of improving beachcast management. Due to these challenges and the waste-
resource ambiguity associated with beachcast, the distribution of management responsibility (including financial and technological development) across governance levels/scales and sectors is problematic. It should be addressed if developing more sustainable beachcast management is to continue.

Thirdly, in order for science, society and policy to address these central aspects, the following considerations and measures are suggested: experimentation and monitoring of marine ecosystems to handle the harvest-hesitation; consistent sampling of chemical content in composted material and careful agricultural use to remedy the waste-resource ambiguity; and a continued subsidy and cross-sectoral collaborations to abide by managerial and financial responsibility for beachcast activity (and realise an example of a bio-based circular economy or regenerative resource system). A continued subsidy of beachcast management to support the established cross-sectoral collaborations is crucial in letting the "policy window for a bio-based circular economy" for beachcast biomass stay open so that management can develop sustainably.

Lastly, considering the implications for policy and beyond, beachcast is found between land and sea, where it also falls through the cracks. By minimising the eutrophying effects of water from its removal and providing much-needed qualities as an agricultural resource input to soils, it could contribute to the transition to a bio-based circular economy in society. Yet, this symbiosis is not happening. The insights into beachcast management on Gotland, Sweden, in this thesis, provide a perspective on this waste-resource ambiguity from an Industrial Ecology viewpoint. By identifying and analysing different aspects of harvesting and use, it can be concluded that beachcast (and potentially bio-based fertilisers alike) struggle to find its way into the current intensive agricultural system. This points to a theoretical and practical incongruity associated with realising a waste-to-resource conversion of beachcast, displaying the distance between ambition and reality in the attempts to valorise beachcast. Realising the theoretical resource potential of beachcast is thus a matter of looking beyond trying to valorise beachcast in a context in which it is unlikely to be able to compete, the current agricultural paradigm.

Instead, agroecology (the counter track to intensified agriculture, according to FAO) appears as an opportunity for beachcast to be re-introduced as an agricultural resource input by acknowledging and valuing the multiple
qualities of beachcast (besides N & P supply). Among other principles, agroecology suggests that subsidies currently directed at unsustainable practices (such as chemical fertiliser use) are redirected to support transitions to sustainable food production in favour of local strategies that maintain soil fertility while being economically feasible for farmers.

On the broader perspective, for beachcast (and perhaps natural resources alike) to contribute to the circular economy and sustainable development, this thesis points to the need for policy within natural resource management to be formulated based on the philosophical stance of 'sharing' (i.e. agroecology) rather than 'sparing' (intensification). The strong land-sea connection of this resource (connected by chemical fertiliser use causing macroalgae blooms and thereby excessive beachcast) highlights the need for 'systems thinking' (i.e. sharing') within natural resource management in general, as it is impossible to isolate biochemical flows - waterways and soils will remain connected (wherefore 'sparing', i.e. intensified agriculture becomes unsustainable).

Research and the field of Industrial Ecology could assist this development if it avoids operating within the present paradigms (as it has been criticised for) and instead develop the connection with concepts such as Agroecology, Degrowth, and Resource Nexus. Perhaps this would mean returning to the roots where the economy is subordinate to ecology, and establishing the next "new ecology" where economic principles and theory do not rule policy. This could perhaps make "ambiguous resources" (such as beachcast), which possess great resource qualities but hold no value in our current way of thinking, acknowledged and can support sustainable development.
References


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Stockholm, November 2023
EN DOKTORSÅTHANDLING

Han som sitter därborta hade en doktors-avhandling
som vinden tog hand om
ja, bokstavligen bläste den bort
(någonstans i Tyrolen, tror jag).
Tålmodigt hade han arbetat på den
och säkert kändes det svårt
några år framöver, men numera
tar han det stillsamt och filosofiskt.
– Vi behöver nog lite till mans en doktors-
avhandling
som blåser bort, säger han.

Och det krävs inte mer än ett öppet fönster.

Nils Ferlin
Ur Kejsarens papegoja