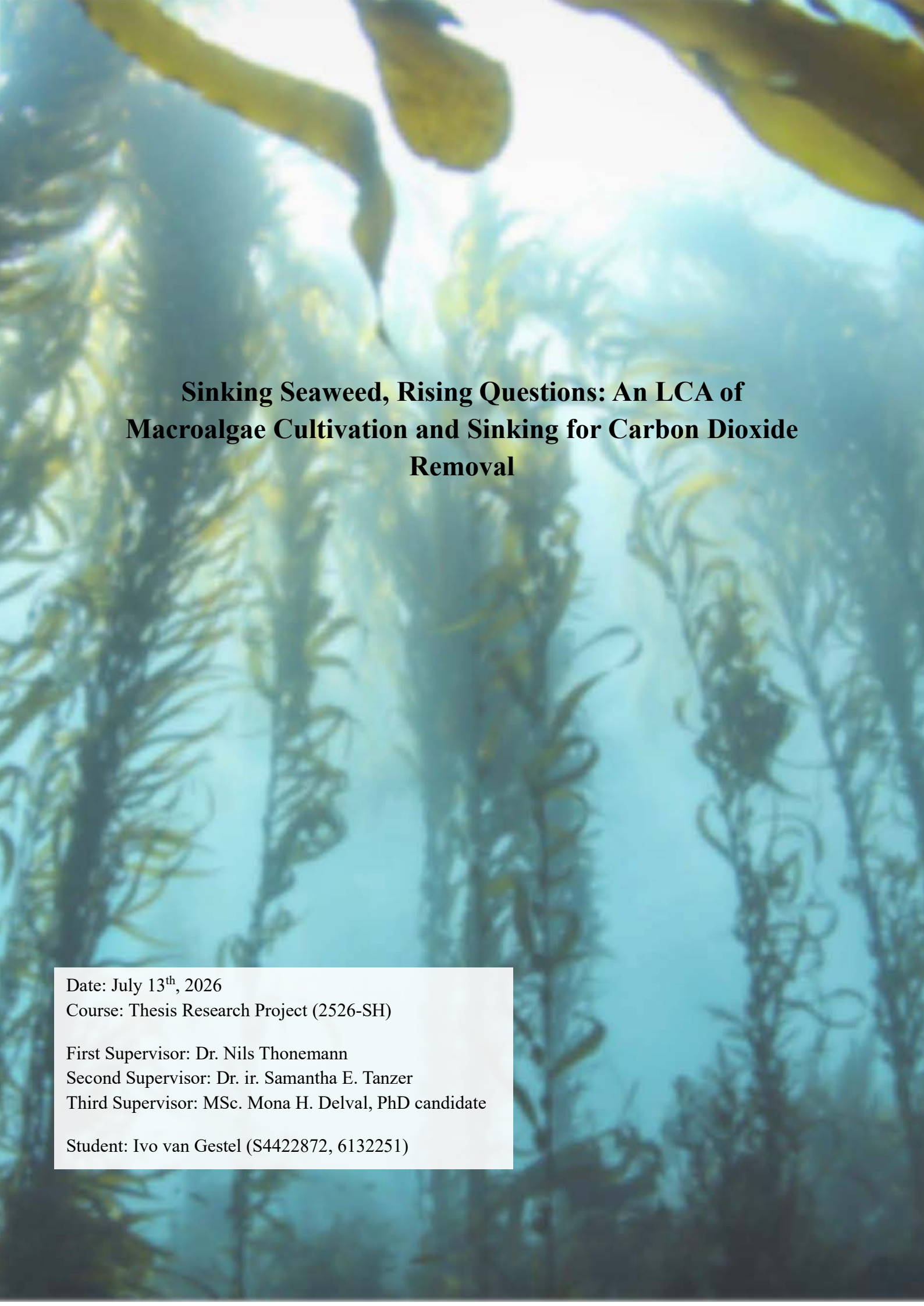


An underwater photograph showing a dense forest of seaweed. The seaweed has long, thin, feathery fronds that are yellowish-green in color. The water is a clear, light blue, and the sunlight filters down from the surface, creating a bright, slightly hazy atmosphere. The seaweed is growing in vertical columns, and some fronds are in the foreground, slightly out of focus, while others are further back, creating a sense of depth.

Sinking Seaweed, Rising Questions: An LCA of Macroalgae Cultivation and Sinking for Carbon Dioxide Removal

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Abstract

Among the portfolio of emerging carbon dioxide removal (CDR) approaches to mitigate global warming, macroalgae cultivation and sinking (MCS) has recently attracted increasing scientific, commercial, and policy interest, due to its theorised potential to enhance oceanic carbon uptake. Yet, much remains unknown about the environmental implications of adopting this technology. To address calls for more holistic assessments of the effectiveness and environmental implications of MCS, this exploratory research developed the first comprehensive cradle-to-grave life cycle assessment (LCA) of the “grow nearshore, sink offshore” MCS strategy in Northern Europe using *Saccharina latissima*. In addition to evaluating climate change impacts, the assessment quantified impacts on ecosystem quality, human health, and natural resource scarcity, while sensitivity analyses were performed to assess the influence of seven key parameters, i.e., transportation distance, biomass yield, carbon/nutrient leakage, future background conditions, seeding technique, cultivation line material, and characterisation method. Our findings suggest that MCS could, under the modelled conditions, potentially function as negative emissions technology (NET), yielding a climate mitigation potential of 227 kg CO₂-eq per tonne of CO₂ durably sequestered. At the same time, the climate change and eutrophication benefits related to this technology come paired with estimated net environmental burdens to ecosystem quality (2.03×10^{-6} species.yr), human health (1.40×10^{-3} DALYs), and natural resource scarcity (83.9 USD 2013) for every tonne of CO₂ durably sequestered. Furthermore, offshore transportation, carbon/nutrient leakage, cultivation infrastructure, and electricity usage during hatchery operations were found to be the dominant environmental hotspots, while sequestration durability as well as biomass yields present the largest uncertainties regarding MCS’s environmental performance. Given the extent of these uncertainties, as well as critical shortcomings in current LCIA methods and the limited estimated sequestration efficiency, large-scale MCS deployment remains difficult to justify.

Key words

Marine carbon dioxide removal (mCDR), macroalgae cultivation and sinking (MCS), negative emission technologies (NETs), climate change mitigation, environmental impacts, life cycle assessment (LCA), *Saccharina latissima*

Table of Contents

Abstract	2
1. Introduction	5
2. Methodology.....	8
2.1 Life Cycle Assessment	8
2.2 Goal and scope definition.....	8
2.2.1 Goal defintion.....	8
2.2.2 Scope definition.....	8
2.3 Description MCS product system and LCI analysis	10
2.3.1 Collection of fertile sporophytes.....	11
2.3.2 Spore preparation.....	12
2.3.3 Line seeding	12
2.3.4 Cultivation at sea	13
2.3.5 Harvesting of biomass	14
2.3.6 Offshore transportation and deep-sea deposition	14
2.4 Sensitivity analysis.....	17
3. Results	18
3.1 Evaluating the climate change mitigation potential of MCS	18
3.2 Environmental impacts of MCS beyond climate change	19
3.3 Assessing the sensitivity of MCS performance	22
3.3.1 Influence of transportant distance, biomass yield, and carbon/nutrient leakage.....	22
3.3.2 Influence of temporal scope, seeding method, cultivation line material, and characterisation family	24
4. Discussion	27
4.1 Towards a more holistic understanding of the environmental impacts of MCS as a mCDR approach.....	27
4.2 Implications of key uncertainties on MCS implementation.....	28
4.3 Limitations and suggestions for future research	29
5. Conclusion.....	31
References	32
Appendix.....	39
Appendix A: Detailed LCI data for MSC product system	39
Appendix B: Process contribution analysis MCS (base-case) climate change	42
Appendix C: Process contribution analysis MCS (base-case) endpoint indicators.....	43
Appendix D: Adaptations to variables for sensitivity analysis	47
Appendix E: Sensitivity analysis parameter selection	50
Appendix F: Comparison of MCS performance under different future background conditions	52

List of Figures and Tables

Figure 1: Schematic overview of MCS as a mCDR approach	6
Figure 2: Flow chart of the MCS product system	11
Figure 3: Schematic representation of the near shore cultivation infrastructure	14
Figure 4: Schematic representation of the ‘quick sinking’ deposition concept	15
Figure 5: Product system stage contribution analysis of MCS climate change impact	18
Figure 6: Midpoint impact contribution analysis of MCS endpoint impacts	20
Figure 7: Product system stage contribution analysis of MCS endpoint impacts.....	21
Figure 8: Sensitivity analysis of continuous parameters	23
Figure 9: Sensitivity analysis of discrete parameters	24
Figure 10: Product system stage contribution analysis comparing characterisation families	26
Table 1: Summarised LCI of the MCS product system	16

List of abbreviations

(A)LCA	(Attributional) life cycle assessment
AoP	Area of Protection
C	Carbon
CO₂	Carbon dioxide
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
EoL	End-of-life
FU	Functional unit
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
(m)CDR	(Marine) carbon dioxide removal
MCS	Macroalgae cultivation and sinking
MOS	Macroalgae open-ocean mariculture and sinking
N	Nitrogen
NETs	Negative emission technologies
P	Phosphorus
POC	Particulate organic carbon
SSPs	Shared socio-economic pathways

1. Introduction

Over the last decades, anthropogenic carbon dioxide (CO₂) emissions to the Earth's atmosphere have been the main catalyst of climate change, resulting not only in a global temperature increase that persists for millennia, but also in widespread biodiversity loss, ecosystem degradation, and increasing risks to human health (Yoro & Daramolo, 2020; IPCC, 2023; Smith et al., 2026). Hence, urgent and collective action is required to remain within a safe operating space of the planetary boundaries (Rockström et al., 2009). While rapid and substantial emission reductions remain essential, it is increasingly recognised that carbon dioxide removal (CDR) will be a necessary complement to compensate residual emissions from hard-to-abate sectors. Accordingly, all pathways assessed by the Intergovernmental Panel on Climate Change (IPCC) that are consistent with limiting warming to 1.5°C, in line with the Paris Agreement, rely on the large-scale deployment of CDR alongside deep decarbonisation efforts (UNFCCC, 2015; IPCC, 2022; Smith et al., 2026). Despite this growing recognition, current CDR deployment remains far below levels required to meet climate targets. At present, approximately 2.2 GtCO₂ yr⁻¹ of CDR is achieved globally, almost exclusively stemming from conventional methods, such as afforestation/reforestation. In contrast, novel CDR methods contribute around 2.04 MtCO₂ yr⁻¹, accounting for < 0.1% of total CDR (Smith et al., 2026). This disparity gives rise to a substantial “CDR gap”, i.e., an additional 1.2 GtCO₂ yr⁻¹ of CDR by 2035 and 5.2 GtCO₂ yr⁻¹ by 2050 is required for pathways consistent with limiting warming to 1.5°C (Lamb et al., 2026).

Following the IPCC definition, CDR encompasses: “human activities capturing CO₂ from the atmosphere and storing it durably in geological, land or ocean reservoirs or in products” (IPCC, 2022; p.544). This definition implies three key principles: (i) captured CO₂ must come from the atmosphere, (ii) subsequent storage must be durable, i.e., while millennia may be the gold standard, currently applied thresholds range from 25 to 100 years due to a lack of scientific basis and consensus among policy makers, and (iii) removal must result from deliberate human intervention and be additional to the Earth's natural processes (IPCC, 2022; Smith et al., 2024). Consequently, CDR should be distinguished from related terms and concepts, such as carbon capture and utilization (CCU) and carbon capture and storage (CCS). Even though CCU and CCS share certain characteristics with CDR, they do not necessarily result in durable net removal of atmospheric CO₂.

Within the broader portfolio of CDR approaches, our oceans, traditionally depicted as a casualty of climate change due to acidification and warming seawater, are increasingly recognised for their potential to contribute to long-term carbon sequestration (Cooley et al., 2022; Jacobs et al., 2023; De Pryck & Boettcher, 2024). This shift in perspective is reflected in international initiatives, including the United Nations Decade of Ocean Science for Sustainable Development, which explicitly highlighted the need for negative emission technologies (NETs) in the form of marine carbon dioxide removal (mCDR) (Liu et al., 2022; De Pryck & Boettcher, 2024). Several characteristics make mCDR an attractive complement to conventional terrestrial CDR approaches, including: the scalability potential of effective solutions, i.e., oceans cover >70% of the Earth's surface area, the oceans natural sequestration capacity, storing an estimated ±50 times greater carbon (C) stock than the atmosphere and ten times more than terrestrial ecosystems; accounting for >30% of anthropogenic CO₂ uptake since the industrial revolution, and research showing that mCDR pathways offer greater durability for carbon removal (Hendriks et al., 2020; Ocean Visions, 2022). Despite these advantages, robust evidence regarding the broader environmental implications of mCDR remains markedly scant, with significant knowledge gaps concerning its environmental risks, long-term effectiveness, and associated environmental trade-offs. These challenges are particularly pronounced for marine environmental impacts, where scientific understanding remains insufficient to support robust decision-making (UNEP, 2016; Guan et al., 2023).

One mCDR method that has received considerable attention in recent years is macroalgae cultivation and sinking (MCS). MCS aims at inducing a sustained, artificial deficit in oceanic CO_2 , thereby enhancing the uptake of atmospheric CO_2 by the ocean (Alvezos & Barillé, 2023; Delval et al., 2025). Particularly, macroalgae, i.e., multicellular aquatic photosynthetic organisms (popularly known as seaweeds), convert dissolved inorganic carbon (DIC) into biomass, reducing DIC concentrations in surface waters and promoting the influx of atmospheric CO_2 to restore the original equilibrium (Choudhary et al., 2021; Delval et al., 2025). Hence, it is theorised that, when cultivated over large areas, this process could accelerate the oceanic carbon pump. Subsequently, this biomass is intentionally sunk to the deep-ocean seafloor, where carbon remineralisation can occur over expanded time-scales, thereby limiting carbon from re-entering the upper-ocean and ultimately the atmosphere (Alvezos & Barillé, 2023; Figure 1). Estimates suggest that more than half of the carbon transferred in the deep ocean remains stored for at least 400 years across most oceanic basins. However, this sequestration potential is spatially variable (Siegel et al., 2021). For instance, within the North Atlantic basin carbon ‘leaking’ is more pronounced with 33% of the carbon exported to 1000 m returning to the atmosphere within 100 years (Baker et al., 2022).

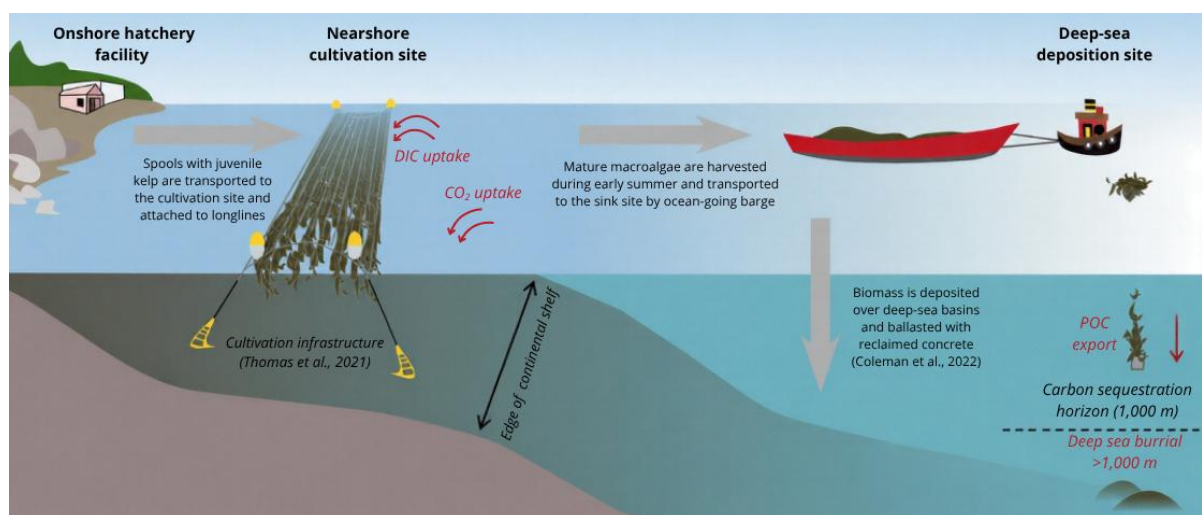


Figure 1: Schematic overview of MCS as a mCDR approach, including the sequential stages of juvenile macroalgae cultivation at an onshore hatchery facility, nearshore cultivation, and offshore deep-sea deposition below the carbon sequestration horizon (adapted from Coleman et al., 2022; see Chapter 2.3 for more details)

To inform future MCS deployment, recent studies have also begun to explore the most suitable locations and deployment strategies for MCS systems. For instance, Alvezos and Barillé (2023) advocate for a ‘Grow nearshore, sink offshore’ strategy, as an alternative to macroalgae open-ocean mariculture and sinking (MOS), noting that major macroalgae-producing countries encompass extensive open-ocean areas suitable exclusively for biomass sinking, not cultivation. Therefore, significant opportunities are lost when solely focusing on MOS. Moreover, their proposed strategy enables macroalgae to be cultivated under favourable nearshore conditions.

Although these developments represent recent progress towards practical implementation, considerable uncertainties remain which could affect the mitigation effectiveness and environmental implications of MCS as a mCDR pathway. Particularly, whereas most studies focus on carbon fixation (55%), the fluxes more directly contributing to carbon sequestration, such as carbon export to the deep ocean and burial in marine sediments, remain poorly understood (Pessarrodona et al., 2023). Hence, relatively little is known about the fate of artificially sunk macroalgae. Furthermore, uncertainties extend beyond sequestration pathways, including but not limited to the effects of specific operational and design choices, such as transportation distances, cultivation infrastructure, and consequences of varying

macroalgae yields (Slegers et al., 2021; Thomas et al., 2021; Zhang et al., 2022; Alevizos & Barillé, 2023; Delval et al., 2025). Therefore, despite the surge in commercial and political interest, already resulting in the issuance of mCDR credits, calls for a moratorium on the sinking of macroalgae into deep-ocean ecosystems are increasing, pending evidence of its effectiveness and robust assessments of its environmental impacts (Boyd et al., 2022; Hurd et al., 2022; Rickart et al., 2022; Chopin et al., 2024; Delval et al., 2025).

In order to assess the environmental impacts of technologies, uncover hotspots among process stages, and identify opportunities for improvement, life cycle assessment (LCA) is widely employed as a systemic methodology to quantify the environmental impacts of a product, service, or process from raw material extraction (“cradle”) to manufacturing, use, and final disposal (“grave”) (Curran, 2023). In recent years, a growing body of LCA literature has examined macroalgae-based supply chains in the context of blue growth strategies as part of a wider bioeconomy, including applications in food and feed, bio-based polymers, and biofuels (Alvarado-Morales et al., 2013; Taelman et al., 2015; Melara et al., 2020; Koesling et al., 2021; Slegers et al., 2021; Thomas et al., 2021; Nilsson et al., 2022; Zhang et al., 2022; Alaya et al., 2023; Li et al., 2023). In contrast, LCA studies specifically addressing MCS remain scarce (Delval et al., 2025). To date, only two cradle-to-grave LCA studies have been conducted (Coleman et al., 2022; N’Yeurt et al., 2012). Specifically, Coleman and colleagues (2022) assess the net sequestration for a system deployed in the US, whereas N’Yeurt et al. (2012) investigate the efficiency of a conceptual MSC system with combined biogas production, without a specified geographical scope. While both studies suggest that MCS could lead net carbon removal, the authors solely investigate the contribution of their product system to climate change, overlooking broader environmental implications, potential trade-offs, and leaving a potential risk for unintended environmental consequences unaddressed. Moreover, neither study addresses uncertainty regarding parameters or modelling choices, despite the considerable uncertainties surrounding this technology (Delval et al., 2025).

To address the research question, “*How environmentally sustainable is the implementation of MCS as a mCDR approach, considering its broader environmental performance and key sources of uncertainty?*”, this research develops and analyses a state-of-the-art cradle-to-grave LCA model of MCS. It encompasses the implementation of the ‘grow nearshore, sink offshore’ strategy within Northern Europe, a region considered particularly suitable for MCS deployment (Alevizos & Barillé, 2023; Chapter 2.2). The LCA spans the complete *Saccarina latissima* supply chain, from the onshore hatchery up until offshore transportation and deep-sea deposition based on the ‘quick-sinking’ concept proposed by Coleman et al. (2022). *S. latissima* was selected because it is one of the most extensively cultivated macroalgal species in Northern Europe, and, as a native seaweed, is well adapted to the regional conditions, contributing to its rapid growth and high biomass yield (Dhakal et al., 2024). The model explicitly accounts for biochemical flows by incorporating C, nitrogen (N), and phosphorus (P) uptake associated with biomass growth, thereby capturing the bioremediation function of the system (Thomas et al., 2021). The contribution of this research is twofold. First, whereas existing studies on MCS are scarce and have been fairly limited in scope, solely focusing on climate change impacts, this study provides the *first cradle-to-grave LCA of MCS, identifying hotspots and trade-offs pertaining to ecosystem quality, human health, and natural resource scarcity, in addition to climate change*. Hence, resulting in a more holistic understanding of the implications of adopting this mCDR technology. Second, given the considerable uncertainties surrounding MCS, this study evaluates the *sensitivity of its environmental performance to seven key parameters that were identified as particularly uncertain and influential in determining the overall environmental impacts* (see Chapters 2.4, 3.3, and Appendix F for further details). Ultimately, these findings contribute to ongoing debates regarding the environmental sustainability, risk, and feasibility of MCS, offering evidence to guide more informed decision-making about its role within the emerging portfolio of mCDR strategies.

2. Methodology

2.1 Life Cycle Assessment

This study employs LCA as its primary methodology. LCA is widely recognised as the most comprehensive framework for assessing the environmental impacts of a defined product system by accounting for the resource consumption and emissions across different life cycle stages (Guinée et al., 2002). Specifically, the research is structured around the four phases of conducting an LCA. The first phase, goal and scope definition, establishes the purpose of the study and outlines the system boundaries, functional context, level of detail. Subsequently, the life cycle inventory (LCI) phase, entails compiling and quantifying all relevant inputs and outputs associated with the product system, including material and energy flows, as well as environmental emissions. During the third phase, life cycle impact assessment (LCIA), these flows are translated into environmental impacts across various impact categories using established impact assessment methods. The final phase, interpretation, involves analysing and evaluating the results from the inventory and impact assessment stages, using subsequent analysis such as contribution and sensitivity analysis, to draw conclusions about the environmental impact of MCS beyond solely climate change and the influence of key parameters (Guinée et al., 2002; Baumann and Tilmann, 2004; Thomas et al., 2021).

2.2 Goal and scope definition

2.2.1 Goal definition

This exploratory study seeks to evaluate the environmental sustainability of implementing the “grow nearshore, sink offshore” MCS strategy as a mCDR approach deployed in Northern Europe, considering its broader environmental performance and key sources of uncertainty. To achieve this, a state-of-the-art cradle-to-grave LCA model was developed and analysed. Moreover, apart from capturing long-term carbon sequestration, by accounting for CO₂ uptake and losses, local nutrient bioremediation was also explicitly accounted for by considering N and P flows. To better understand the implications of adopting this technology as a means to address global warming, outcomes were investigated pertaining to climate change impacts, specifically, and three ‘areas of protection’ (AoPs): ecosystem quality, human health, and natural resource scarcity, more broadly, expanding the current knowledge on the holistic implications of adopting this mCDR approach. Specifically, apart from the assessment of the overall environmental impacts associated with the MCS system, detailed contribution analyses for product system stages and processes were conducted to identify the main impact drivers, providing insight into critical opportunities for improvement of MCS system design and deployment. Furthermore, considering that this technology remains at the pilot-phase, substantial uncertainty surrounds its operational performance and environmental impacts. Therefore, this study also investigates the impact of key parameters on the MCS system’s performance, which so far has not received any attention in the LCA literature. Thereby, this research provides insights into the conditions under which MCS may deliver improved or reduced environmental benefits, while highlighting key sources of uncertainty that should be prioritised in future research and technological developments.

2.2.2 Scope definition

2.2.2.1 MCS Product system and system boundary

This study applies an attributional life cycle assessment (ALCA) approach, focussing on the environmental burdens associated with the sequestration of 1 tonne of CO₂ for at least 100 years through the cultivation and controlled sinking of brown algae (Phaeophyceae), specifically *S. latissima*. The assessed system represents a MCS pathway with one annual growth cycle, consisting of six main stages:

(i) the collection of fertile sporophytes, (ii) spore preparation, (iii) line seeding, (iv) cultivation at sea, (v) biomass harvesting, and (vi) offshore transport and deep-sea deposition. (van Oirshot et al., 2017; Thomas et al., 2021; Coleman et al., 2022; Nilsson et al., 2022). A detailed description of the product system is provided in Chapter 2.3. The system boundary follows a cradle-to-grave perspective, including all relevant upstream and operational processes required for biomass production and transport, as well as the final deep-sea deposition stage to ensure durable carbon storage. This approach aligns with recent recommendations by Delval and colleagues (2025), emphasising that all processes from resource extraction to long-term carbon storage must be included to accurately assess the net carbon removal potential and associated environmental impacts of mCDR strategies.

2.2.2.2 Temporal, geographical and technological scope

The *temporal coverage* of this study reflects contemporary conditions, i.e., both the adopted foreground and background LCI data represents the period from 2020-2025. This time frame reflects the present technological maturity and operational performance of MCS and therefore serves as the basis for evaluating the environmental hotspots, trade-offs, and key uncertainties associated with implementing this mCDR approach.

The *geographical coverage* is limited to Northern Europe, a region identified as highly suitable for MCS deployment. This selection is supported by the global spatially explicit suitability assessment of Alevizos and Barillé (2023), which considers critical factors such as bathymetry, distance to port infrastructure, nutrient availability, and spatial conflicts with shipping activities, submarine infrastructures, and ecologically significant areas. According to these authors, Norway and Denmark exhibit the largest potential for MCS deployment, estimated at 593.616 km² and 453.805 km², corresponding to $\pm 20.9\%$ and $\pm 17.2\%$ of their exclusive economic zones, respectively. These findings position Northern Europe as a key region for MCS development and reinforce the need for a more complete assessment of the environmental impacts associated with its implementation and the influence of key parameter variability.

The *technological coverage* encompasses the primary onshore nursery infrastructure, including aquaria and filters, as well as energy use associated with temperature control, lighting, aeration and stirring, and seawater source and filter systems, near-shore cultivation infrastructure (see Chapter 2.3 for a detailed description), sea-going transportation vessels, and the fast-sinking disposal concept proposed by Coleman and colleagues (2022).

2.2.2.3 Function, functional unit and reference flow

As described in Chapter 1, the MCS method for mCDR involves the cultivation of macroalgae, during which DIC is captured via photosynthesis. This process increases the uptake of atmospheric CO₂, by causing a seawater deficiency in DIC, allowing more carbon to be drawn out of the atmosphere and into the ocean waters. Following cultivation, the biomass is harvested, and intentionally sunk to the deep-ocean, where a fraction of the biomass is then presumed to be durably sequestered (NASEM, 2022; Coleman et al., 2022; Delval et al., 2025). Within this context, the system's function is defined as: “the provision of durable removal of atmospheric CO₂ through macroalgae cultivation and intentional deep-ocean deposition below the carbon sequestration horizon”.

For mCDR technologies, Delval et al. (2025) recommend defining the functional unit (FU) in terms of the amount of atmospheric carbon stored, the storage duration, the storage medium, and the storage location. Accordingly, the FU of this research is defined as: “one tonne of atmospheric CO₂ stored for at least 100 years via macroalgae biomass below the deep-ocean carbon sequestration horizon (>1,000 m).” Particularly, the storage duration is consistent with currently applied thresholds for durable carbon

sequestration (Smith et al., 2024), while carbon sequestration horizon depth is based on the value reported by Coleman et al. (2022).

Consequently, the reference flow pertaining to the studied product system is defined as: “one tonne of atmospheric CO₂ stored for at least 100 years via macroalgae biomass below the deep-ocean carbon sequestration horizon (>1000 m) in Northern Europe by adopting the MCS mCDR approach.

2.2.2.4 LCIA methodology

To transform the inventory flows pertaining to the FU into potential environmental impacts, this study employs an endpoint-oriented approach, whereby impacts are aggregated into three AoPs, namely: (i) ecosystem quality, expressed as local relative species loss in terrestrial, freshwater, and marine ecosystem (species.yr), (ii) human health, measured by healthy life years lost due to disease or incidents (DALYs), and (iii) natural resource scarcity, capturing the cost increase for future resource extraction (USD 2013) (Hauschild and Huijbregts, 2015). Endpoint indicators build on midpoint indicators by translating impacts along the environmental cause-effect chain into their ultimate consequences, yielding a more concrete and decision-relevant assessment of the product system's performance (Hauschild and Huijbregts, 2015). Moreover, by evaluating endpoint damage, all midpoint indicators are converted into ultimate consequences, enabling more direct comparison of their relative contribution (see Chapter 3.2). The resulting impact scores, together with additional contribution analyses at process and midpoint-level, enable the holistic evaluation of the environmental performance and trade-offs associated with the MCS system. Additionally, because climate change mitigation constitutes the primary objective of MCS, the climate change midpoint indicator is analysed separately, enabling a direct assessment of the system's carbon removal performance and climate impacts. All LCI data were compiled in *Activity Browser* where, subsequently, calculations were performed to quantify the inputs, outputs, and environmental impacts.

For the characterisation of LCI results, this study adopted the ReCiPe 2016 v1.03 (H) impact assessment method, a widely applied LCIA framework in European and Dutch environmental assessments (Huijbregts et al., 2016). ReCiPe 2016 was selected due to its comprehensive coverage of environmental impact pathways and its more detailed coverage of marine environmental impacts and N flows compared to alternative LCIA methods, which is particularly relevant for assessing the bioremediation effects associated with MCS. It is assumed that the uptake of N during macroalgae growth contributes to reduced marine eutrophication. This assumption is based on the cultivation of *S. Latissima* in nutrient-rich nearshore environments due to nutrient runoff, which is nitrogen-limited in nature (Howarth & Marino, 2006; UNEP, 2026). Additionally, following the recommendations of Deval et al. (2025), a second LCIA method family was included as part of the sensitivity analysis, i.e., IMPACT World+, to evaluate how variable the results are to changes in underlying characterisation models (See chapter 2.5).

2.3 Description MCS product system and LCI analysis

The MCS product system assessed in this study comprises six sequential stages, distributed across three locations: an onshore hatchery facility, a nearshore cultivation site, and a deep-sea deposition site beyond the continental shelf (Figure 2). The process begins with the collection of fertile sporophytes, followed by spore preparation and the seeding of juvenile kelp onto string that can be deployed on the nearshore cultivation infrastructure. Subsequently, the biomass undergoes a grow-out stage at sea, after which mature *S. latissima* is harvested. The final stage involves offshore transport and deep-sea deposition of the carbon-rich biomass to enable long-term sequestration.

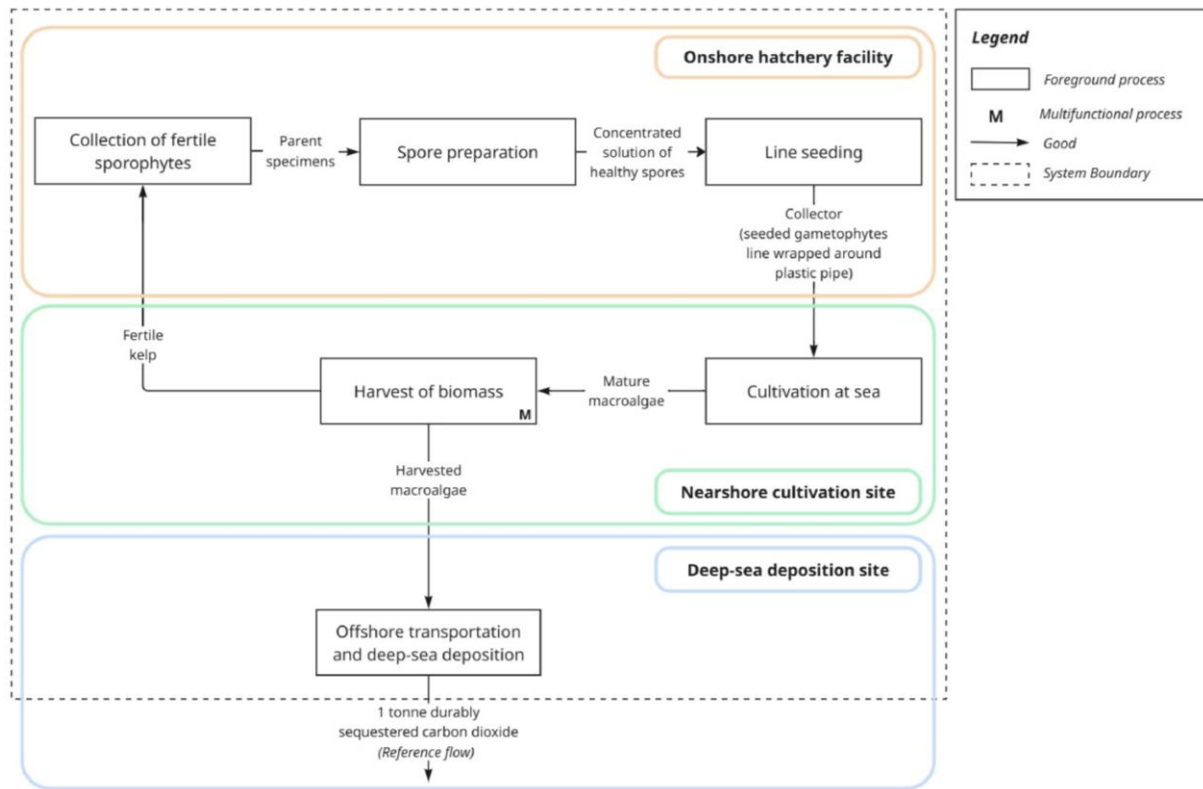


Figure 2: The MCS product system showing all stages and intermediate goods for the production and deposition of *S. latissima* biomass (where possible, LCI data from Thomas et al. (2021) and Nilsson et al. (2022) is adopted for stages 1-5, while the final stage is based on Coleman et al. (2022)).

The LCI data used in this study are, to the extent possible, derived from Thomas et al. (2021) and Nilsson et al. (2023), who conducted detailed assessments of macroalgae cultivation under Northern European conditions. These datasets are extended by incorporating the additional product system stage of macroalgal biomass transport and deep-sea deposition, based on the sinking concept and data of Coleman et al. (2022), and supplemented with own calculations (Appendix A). Background data was sourced from the ecoinvent v3.12 - cutoff database, a widely recognised source for environmental modelling (Wernet et al., 2016; Wu & Wang, 2022).

A summarised LCI of the product system stages is presented in Table 1, while Appendix A presents a complete overview as well as the underlying calculations and modelling assumptions. In the following sections, a more detailed description of each stage is provided.

2.3.1 Collection of fertile sporophytes

Seedling breeding starts with the collection of local fertile *S. latissima* at the cultivation site, using plastic (polypropylene) bags and fabric cloths (Taelman et al., 2015; Nilsson et al., 2022; Li et al., 2023). Selection focuses on mature individuals bearing reproductive tissues, which are required for subsequent spore release. Specifically, this selection is performed manually on-board harvesting vessels, where suitable thalli (i.e., the vegetative body of seaweed (Titlyanov et al., 2017)) are separated from the bulk biomass. Moreover, as the collection of fertile sporophytes occurs alongside routine harvesting activities, vessel use is accounted for in the harvesting stage (v), since the share attributable solely to sporophyte collection is considered negligible. While some studies suggest that collection is typically performed using small workboats, a standard barge is assumed in this model due to data limitations (Nilsson et al., 2022). Following collection, the biomass is transported to a land-based hatchery facility,

involving short-distance marine transport (barge), again accounted for in stage v, followed by road transport (lorry) (Nilsson et al., 2022).

Material inputs for the sporophytes collection stage that require end-of-life (EoL) treatment include: polypropylene for the plastic harvesting bags and woven cotton for fabric cloths. These materials are assumed to be treated via the ecoinvent v3.12 - cutoff 'market group for municipal solid waste' process, representing waste management within the European region (RER), which in ecoinvent denotes an aggregated geography using averages from multiple European countries to create a regional proxy dataset (ecoinvent, 2023).

2.3.2 Spore preparation

The spore preparation process encompasses the processes required to obtain a concentrated solution of healthy spores from parent specimen. Initially, spore development is induced by removing the basal portion of the blade (meristem) from the collected specimens. The remaining tissue is then cleaned and maintained for 6-10 weeks in a controlled flow-through system, with regulated temperature and artificial lighting, containing filtered, aerated, and stirred seawater. During this incubation period, reproductive tissue develops, after which spores are released and collected in a bucket containing sterilised water (Thomas et al., 2021).

Material inputs for the spore preparation stage that require EoL treatment include polyethylene for the buckets as well as chromium steel for seawater filters. These materials are assumed to be treated via the ecoinvent v3.12- cutoff 'market group for municipal solid waste' process taking place within the RER.

2.3.3 Line seeding

As described in the case study of Thomas et al. (2021), the seeding process comprises the processes required to produce strings covered with juvenile kelp (i.e., seeded line) which are wound around a plastic pipe to facilitate deployment at sea (together referred to as collectors). Specifically, the conventional submersion seeding method involves putting the collectors in a concentrated spore solution, allowing spores to directly settle onto the cultivation string (Thomas et al., 2021; Bolderskov et al., 2021). Following settlement, the collectors are transferred to controlled aquaria, where the organisms develop into juvenile kelp over a period of 3-5 weeks under regulated conditions, including extended photoperiods (16 hours of light), controlled light intensity ($\sim 100 \text{ mmol photons m}^{-2} \text{ s}^{-1}$), and the addition of a nutrient-enriched medium.

Similarly as the previous spore preparation process, activities are carried out in a laboratory environment designed to provide the optimal conditions for attachment and early growth into juveniles that are large enough to thrive at sea. The medium in which the seeding takes place, referred to as the nutrient mix, is made in the laboratory and follows the modified ES medium nutrient mix (similar to Ayala et al. (2023)).

Material inputs for the line seeding stage that require EoL treatment include: polymethyl methacrylate for the aquaria, polyethylene for the buckets and seawater filters, polyvinylidenechloride for the collector, and chromium steel for seawater filters. These materials are assumed to be treated via the ecoinvent v3.12 - cutoff 'market group for municipal solid waste' process taking place within the RER. Additionally, the nutrient mix is assumed to be treated via the 'market for wastewater, average' process, with as regional scope Europe without Switzerland.

2.3.4 Cultivation at sea

This process encompasses deployment and cultivation of juvenile kelp at sea. Deployment is carried out by unwinding the seeding lines from the collectors and attaching them to the longlines of the cultivation infrastructure. In addition, stage 4 accounts for the inputs and outputs required for the installation, maintenance, and decommissioning of cultivation infrastructure, as well as routine monitoring activities while the kelp matures, along with the associated transportation (Thomas et al., 2021; Nilsson et al., 2023; Slegers et al., 2021). The nearshore cultivation infrastructure design is illustrated in Figure 3 (adapted from Thomas et al. (2021)); and also included in the study of Koesling et al. (2021)), while the corresponding LCI is presented in Table 1 and Appendix A.

During this cultivation period, the uptake of nutrients from the water, commonly referred to as bioremediation or bioextraction, and the fixation of carbon through photosynthesis, referred to as carbon capture, are explicitly accounted for. The values for the bioremediative uptake of nutrients and the capture of C are based on the composition of *S. latissima* (C: 26.2% of dry matter; N: 2.7% of dry matter; P 0.24% of dry matter) (Thomas et al., 2021). Moreover, to align with the FU of this study and characterisation models behind ReCiPe 2016 v1.03 and IMPACT World+, the values for the uptake of carbon in the cultivated kelp are converted to CO₂ and all environmental flows pertaining to carbon capture and bioremediation are treated as negative emissions, following the same method as Seghetta et al. (2017) and Thomas et al. (2021).

Material inputs for the cultivation stage that require EoL treatment include: concrete for anchors, polyvinyl chloride for buoys, steel, low-alloyed for chains and shackles, and polyethylene for anchoring buoys, and longlines. These materials are assumed to be treated via the ecoinvent v3.12- cutoff 'market group for municipal solid waste' process taking place within the RER. It should be noted that, the material inputs for the main longline (c1 in Figure 3) are excluded in the waste treatment, as they are part of the deposition system and are ultimately sunk to the deep-ocean (Coleman et al., 2022). This reflects the dual function of the longline within the MCS system, where it not only supports cultivation but also serves as part of the sinking mechanism (see Figure 4). Unlike conventional cultivation systems in which longlines are reused across multiple cycles, this MCS approach involves sinking the longlines together with the attached biomass. Therefore, biodegradable materials are considered more appropriate for this application (Coleman et al., 2022). Accordingly, the main longlines are modelled using as flax fibre rather than polyethylene (as adopted by Thomas et al. (2021)), considering equivalent functional performance by accounting for the tensile strength to density ratio and the reduced mechanical properties of flax fibres due to prolonged exposure to marine settings (Moudood et al., 2019; Appendix A).

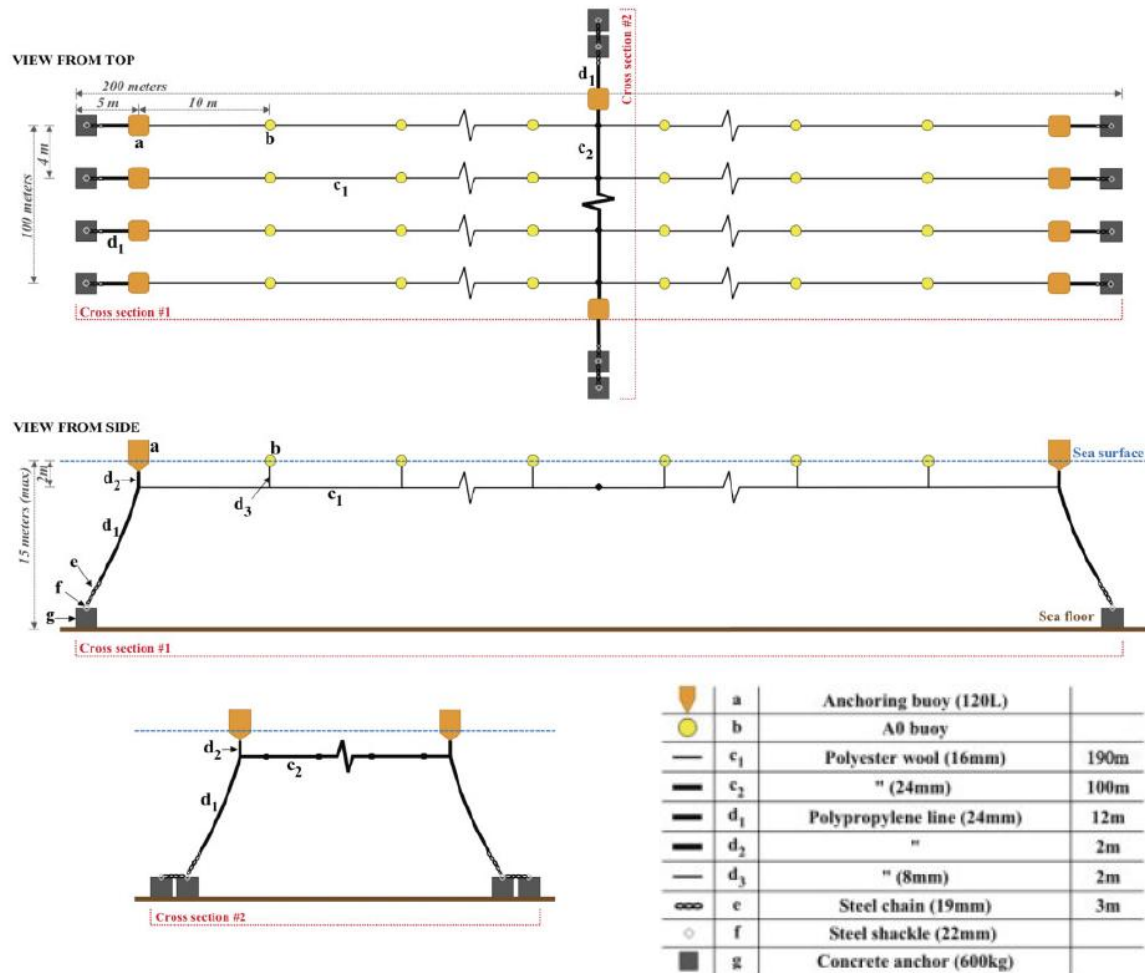


Figure 3: Schematic representation of the nearshore cultivation infrastructure, as seen from above and from two cross-sections. The system comprises anchoring buoys (a), longline buoys (b), longline ropes (c₁-c₂), anchoring ropes (d₁-d₃), chains (e), shackles (f), and concrete anchors (g); adapted from Thomas et al. (2021). This design represents a rope-based cultivation system, which is typical for nearshore mariculture and the preferred medium in European macroalgal aquaculture (Amponsah et al., 2024; Taelman et al., 2015).

2.3.5 Harvesting of biomass

Sugar kelp (*S. latissima*) is cultivated from early winter to early summer, during which it reaches a typical length of 1-2m before harvest (Thomas et al., 2021). The harvesting operation involves a vessel accessing the cultivation site to retrieve the longlines bearing the mature biomass. Concurrently, fertile individuals are selectively collected for use in subsequent cultivation cycles, following the procedure outlined in stage 1. Although the described process is multifunctional, i.e., yielding two functional flows (mature macroalgae and fertile kelp), it does not require physical or economic allocation, since both remain within the system boundary (See Figure 2; Guinée et al., 2002).

2.3.6 Offshore transportation and deep-sea deposition

The cultivation lines are prepared for the deposition stage according to the deposition concept of Coleman et al. (2022). Specifically, recycled concrete weights are attached to the grow line (0.000741 m³/m of longline), as well as temporary floats to support the concrete weight and the longline. Specifically, these are assumed to be the buoys (b in Figure 3) which are also part of the cultivation infrastructure (Thomas et al., 2021; Coleman et al., 2022).

Subsequently, the grow lines are towed out beyond the edge of the continental shelf. The transportation distance is assumed to be 582.4km, equivalent to the average distance from ten studied *S. Latissima* cultivation sites in Northern Europe to water depths exceeding 1000 m (Taelman et al., 2015; Koesling et al., 2021; Slegers et al., 2021; Thomas et al., 2021; Nilsson et al., 2022; Zhang et al., 2022; Ayala et al., 2023; EMODnet, n.d.) After the temporary floats are removed, the carbon-rich macroalgal biomass will sink below the carbon sequestration horizon (>1.000 m), where it is deposited on the deep seafloor and may become incorporated into the sediments. This method adopts the principle of ‘fast sinking’, assuming harvested biomass could be engineered to sink to the seafloor in a rapid and efficient manner with no remineralization along the way (Wu et al., 2023). Finally, the temporary flotation buoys are transported back to the cultivation site.

The sequestration timescales of macroalgal POC and dissolved organic carbon (DOC) exported to the ocean interior will depend on the depth and location where it is respired back to CO₂, as ocean circulation and ventilation rates vary spatially (Pessarrodona et al., 2023). For the North Atlantic basin, which is the best available a proxy for modelling MCS in Northern Europe, it was found that 33% of the carbon exported to 1.000 m returns to the atmosphere within 100 years (Baker et al., 2022). Due to a lack of specific data, similar leakage rates have been assumed for the N and P remediated by the macroalgae.

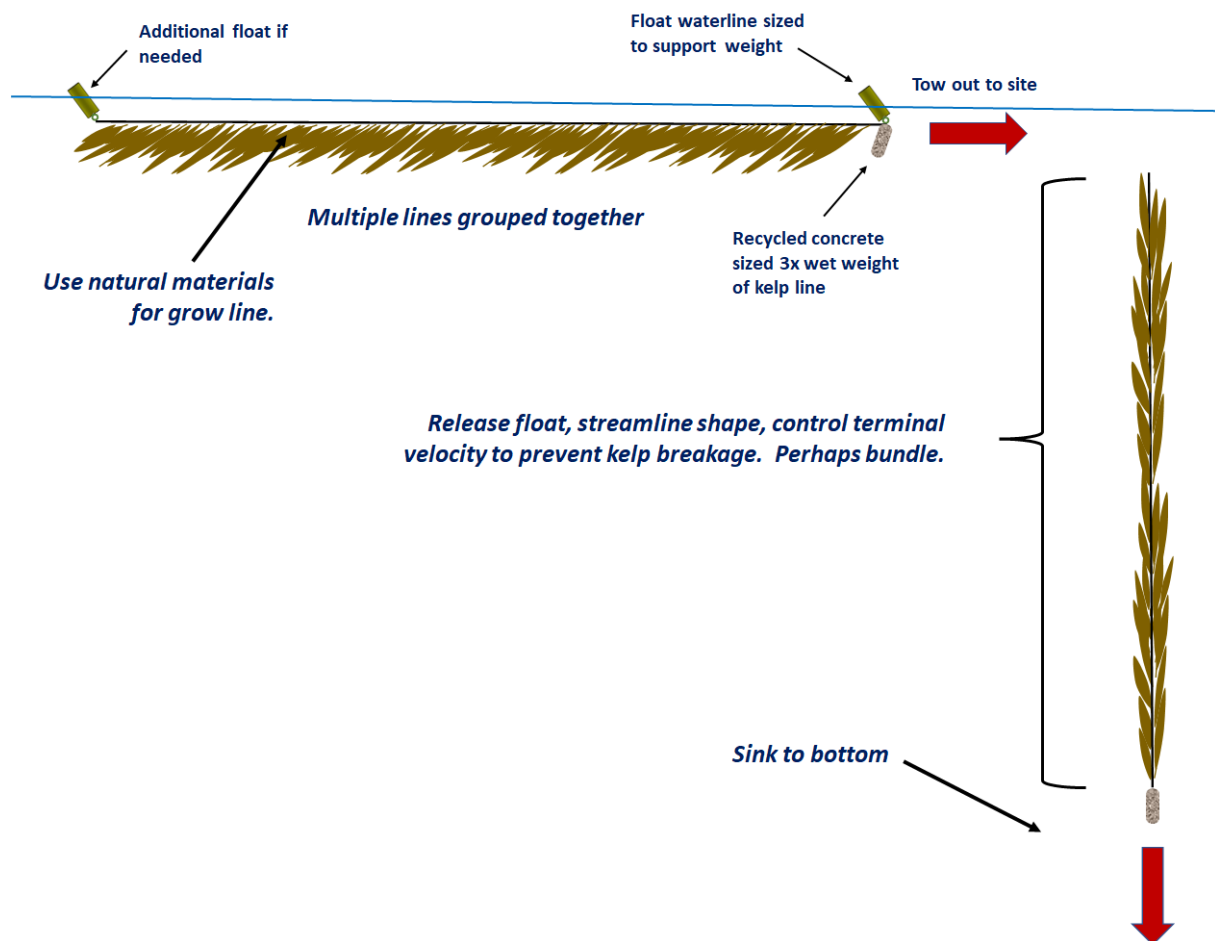


Figure 4: Schematic representation of the ‘quick sinking’ deposition concept from Coleman et al. (2022). The system consists of grouped cultivation long-lines composed of biological fibres, temporary flotation devices, which are assumed to be the buoys (b in Figure 3), and recycled concrete weights to induce sinking. The lines are towed to the sink site, after which the floats are removed to initiate quick sinking of the biomass to the deep seafloor; preventing intermediate remineralisation (Wu et al., 2023)

Table 1: Summary of foreground inventory inflows (↑) and outflows (↓) for each product system stage, specifying aggregated amounts required to durably sequester one tonne of CO₂. The complete LCI, including linkedecoinvent v3.12 background processes, biosphere 3 flows, and more detailed inventory flows is provided in Appendix A, as well as an overview of the assumptions, calculations, and data sources.

Inventory flows and unit processes	Amount	Unit	Inventory flows and unit processes	Amount	Unit
Collection of fertile sporophytes (i)			Cultivation at sea (iv)		
Fertile kelp (↑)	1.00E+00	kg	Collectors (↑)	1.00E+00	item
Polypropylene, granulate (↑)	1.00E-02	kg	Concrete block (↑)	2.87E-02	kg
Woven cotton (↑)	1.00E-02	kg	Stretch blow moulding (↑)	1.24E+00	kg
Lorry freight transport (↑)	1.00E-02	t*km	Polyethylene high density, granulate (↑)	6.66E-01	kg
Parent specimens (↓)	1.00E+00	kg	Polyvinyl chloride (↑)	5.77E-01	kg
Municipal solid waste (↓)	2.00E-02	kg	Steel, low-alloyed, hot rolled (↑)	2.74E+00	kg
Spore preparation (ii)			Fibre, flax (↑)	7.64E+00	kg
Parent specimens (↑)	1.00E+00	kg	Fleece, polyethylene (↑)	1.03E+00	kg
Electricity, medium voltage (↑)	6.54E+00	kWh	Diesel barge transport (↑)	3.92E+00	t*km
Extrusion, plastic pipes (↑)	5.67E-03	kg	Nitrogen (↑)	4.08E+00	kg
Fleece, polyethylene (↑)	1.51E-02	kg	Carbon dioxide (↑)	1.45E+02	kg
Steel, chromium steel 18/8 (↑)	1.68E-03	kg	Phosphorus (↑)	3.62E-01	kg
Concentrated solution of healthy spores (↓)	1.00E+00	l	Mature macroalgae (↓)	1.00E+03	kg
Municipal solid waste (↓)	2.25E-02	kg	Municipal solid waste (↓)	5.04E+00	kg
Line seeding (iii)			Harvest of biomass (v)		
Concentrated solution of healthy spores (↑)	1.00E+00	l	Mature macroalgae (↑)	1.00E+03	kg
Electricity, medium voltage (↑)	1.87E+01	kWh	Diesel barge transport (↑)	1.27E+00	t*km
Polymethyl methacrylate (↑)	2.91E-01	kg	Harvested macroalgae (↓)	1.00E+03	kg
Injection moulding (↑)	2.91E-01	kg	Fertile kelp (↓)	1.00E+00	kg
Extrusion, plastic pipes (↑)	2.86E-01	kg	Offshore transportation and deposition (vi)		
Fleece, polyethylene (↑)	3.02E-02	kg	Harvested macroalgae (↑)	1.03E+04	kg
Steel, chromium steel 18/8 (↑)	3.36E-03	kg	Diesel barge transport (↑)	7.10E+03	t*km
Nutrient mix (modified ES medium) (↑)	2.53E-01	l	Durably sequestered carbon dioxide (↓)	1.00E+00	t
Nylon 6 (↑)	1.58E-01	kg	Waste concrete (↓)	7.61E-01	m ³
Collector (seeded line) (↓)	1.00E+00	item	Nitrogen (↓)	1.38E+01	kg
Municipal solid waste (↓)	6.11E-01	kg	Carbon dioxide (↓)	4.92E+02	kg
Wastewater, average (↓)	2.53E-04	m ³	Phosphorus (↓)	1.23E+00	kg

2.4 Sensitivity analysis

In reality, there are numerous parameters and uncertainties that affect the environmental impacts of adopting the MCS strategy described in this study, none of which have been assessed in the current body of LCA literature. Therefore, to evaluate the robustness of the presented results and quantify the extent to which selected parameters influence the environmental impacts of the mCDR technology, a sensitivity analysis was conducted. Parameters were selected based on (i) their susceptibility to data variability and uncertainty reported in literature, and (ii) their contribution to total environmental impacts across one or more impact categories, as identified through the contribution analysis or concluded by previous research. Based on these criteria, seven parameters were included in the assessment: transportation distance to the sink site, biomass yield, carbon and nutrient leakage before the sequestration time horizon, future background conditions, line seeding technique, main cultivation line material, and LCIA characterisation method. A rationale for the selection of each parameter is provided in Appendix E, and model adaptations to reflect changes to these parameters are shared in Appendix D.

Among the selected parameters, the assessment of future background conditions required a distinct approach, i.e., whereas the remaining parameters were evaluated by modifying foreground model variables or the LCIA set-up, future scenarios were reflected by relinking the foreground model to prospective LCI databases. To this end, the software *premise* was used, which enables the representation of future systems by transforming background processes within the ecoinvent database using projections from integrated assessment models (IAMs) under selected socio-economic shared pathways (SSPs) for a specified future year. In this research, three SSPs were considered, spanning a spectrum from sustainability-oriented development (SSP1-M), to a continuation of current trends (SSP2-M), to a fragmented world characterised by limited technological progress and high emissions (SSP3-H), for the year 2050 (Riahi et al., 2016). Moreover, the IAM model IMAGE was selected due to its comprehensive representation of interactions between energy, land-use, and environmental systems, as well as its detailed sectoral coverage, making it particularly suitable for capturing the broader biophysical and socio-economic dynamics relevant to MCS (Stehfest et al., 2014).

Two complementary one-at-a-time sensitivity analyses were adopted. First, the continuous parameters (i.e., transport distance, biomass yield, and carbon/nutrient leakage) were evaluated by individually varying each parameter between 50% and 150% of its base-case values in 25% increments. For each scenario, all model variables affected by the parameter under investigation were adapted accordingly, while the remaining parameters were held constant (Chapter 3.3.1; Appendix D). Second, the discrete parameters were evaluated by comparing alternative scenarios against the base-case, including future instead of present-day LCI background data, spray-seeding instead of submersion seeding, polyethylene instead of flax-fibre main cultivation lines, and the IMPACT World+ LCIA method instead of ReCiPe 2016 (Chapter 3.3.2). For all scenarios, impacts were assessed pertaining to the climate change midpoint indicator and the three endpoint indicators.

3. Results

The following chapter presents the results of the cradle-to-grave LCA of the MCS system. First, the climate change impacts and net carbon removal potential of the mCDR approach are assessed (Chapter 3.1). Second, the environmental implication of MCS are evaluated more broadly using endpoint indicators, including detailed contribution analyses to identify the main environmental hotspots and trade-offs (Chapter 3.2). Third, the influence of key continuous and discrete parameters is assessed through sensitivity analysis (Chapter 3.3).

3.1 Evaluating the climate change mitigation potential of MCS

Calculating the climate change impacts associated with the durable sequestration of one tonne of atmospheric CO₂ for at least 100 years through MCS reveals that a net uptake of 227 kg CO₂-eq is achieved when accounting for both removal and emissions within the product system. Particularly, the gross GHG emissions of the mCDR technology are equivalent to 1269 kg CO₂-eq, whereas gross uptake amounts to 1496 kg CO₂-eq. Figure 5 depicts the net contributions of each product system stage to the overall climate change impact.

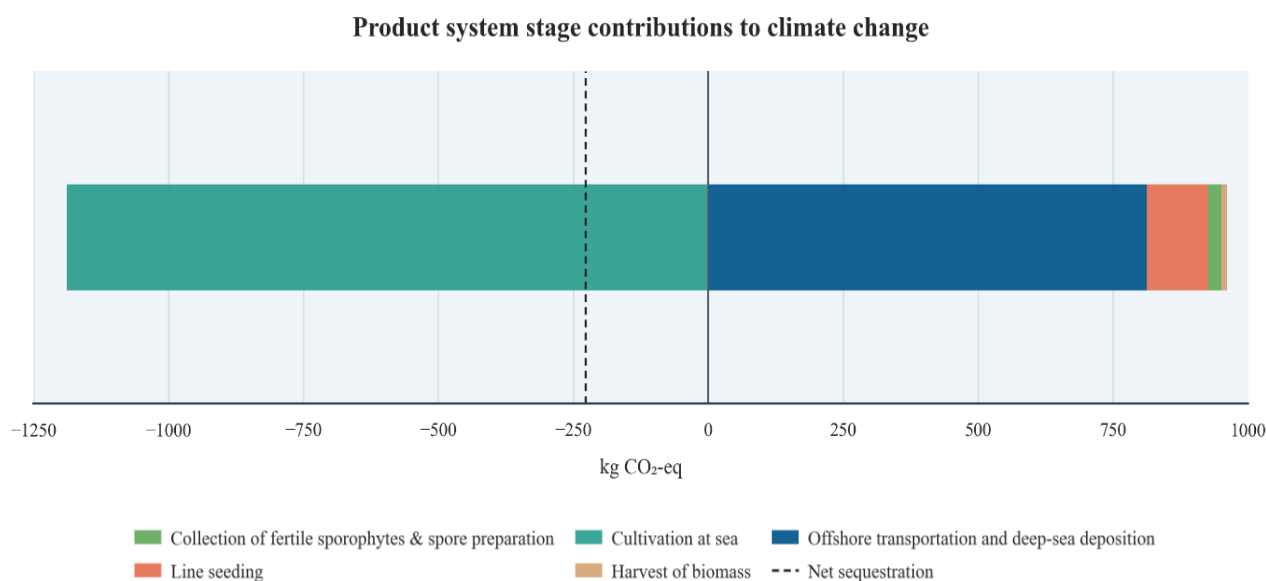


Figure 5: Absolute net contributions of individual product system stages to the climate change impact of MCS, assessed using the ReCiPe 2016 v1.03 midpoint (H) characterisation method.

The offshore transportation and deep-sea deposition stage (vi), constitutes the largest source of GHG emissions, i.e., 813 kg CO₂-eq (corresponding to 54% of the gross GHG emissions). Moreover, a more detailed process contribution analysis (Appendix B) indicates that this is primarily driven by carbon leakage occurring before the end of the 100-year time horizon and transportation of the biomass to the deposition site, respectively emitting 492 kg CO₂-eq (33%) and 305 kg CO₂-eq (20%). Line seeding (iii) represents the second largest net emitting stage, 113 kg CO₂-eq emitted (7%), which can be traced back mainly to the electricity consumption during hatchery operations, responsible for 68 kg CO₂-eq emissions (5%). On the other hand, the GHG emissions resulting from the collection of fertile sporophytes and spore preparation (i & ii), as well as harvesting of the biomass contributes only marginally, accounting for 35 kg CO₂-eq (2%).

Although the net climate benefit can be traced back to the cultivation stage (iv), due to the uptake of CO₂ by the macroalgae during growth, further contribution analysis that considers the gross climate change impacts of processes rather than the net product system stage outcomes, shows that this stage is also associated with substantial GHG emissions (Appendix B). In particular, the cultivation infrastructure leads to non-neglectable emissions, i.e., 269 kg CO₂-eq (18%). Nevertheless, the uptake of 1496 kg CO₂-eq achieved during the macroalgal growth substantially exceeds these emissions, resulting in the net reduction of -1188 kg CO₂-eq shown in Figure 5. Ultimately, while the current results indicate that MCS can provide net carbon removal, the magnitude of emissions associated with offshore transport and premature remineralisation of sunk biomass demonstrates that the overall effectiveness of this technology is highly dependent on both the sequestration longevity and transport requirements.

3.2 Environmental impacts of MCS beyond climate change

Shifting our attention beyond the assessment of climate change impacts, the broader environmental performance of the MCS system was evaluated using the ReCiPe 2016 (H) endpoint methodology (Figure 6). Particularly, the results of sequestering one tonne of atmospheric CO₂ for at least 100 years via MCS indicate a potential net impact on ecosystem quality of 2.03×10^{-6} species.yr, reflecting the potential loss of biodiversity over time due to environmental pressures. Additionally, the net human health impacts amount to 1.40×10^{-3} DALYs, representing the potential loss of healthy life years associated with the product system-related emissions. Lastly, the future additional extraction costs that can be linked to MCS, caused by the depletion of mineral and fossil resources, equals 84 USD 2013.

Ecosystem quality is most severely impacted by terrestrial acidification, water use, and photochemical oxidant formation, contributing 25%, 17%, and 19%, respectively. Moreover, additional process contribution analysis shows that terrestrial acidification is primarily related to the flax fibre production for the cultivation infrastructure (i.e., 33%) and biomass transportation to the deposition site (31%) (Appendix C, Figure 1). Similar trends emerge for the other two indicators with water use impacts shaped for 83% by flax fibre production and retting, and photochemical oxidant formation for 68% by offshore transportation. The results below also indicate that climate change impacts on terrestrial ecosystems and marine eutrophication have a combined mitigating effect of 20% on the ecosystem damage caused by MCS, with additional process analyses for terrestrial ecosystem climate change impacts showing similar trends as discussed before, i.e., carbon leakage and offshore transportation limit the mitigating potential of the mCDR system the most.

As for human health, on the other hand, the endpoint results are most shaply affected by particulate matter formation (i.e., 46%), followed by carcinogenic and non-carcinogenic human toxicity (i.e., 18% and 19%, respectively). Additionally, process contribution analyses indicate that whereas the former stems primarily from offshore transportation (i.e., 33%) and electricity generation from lignite and hard coal (i.e., 20%), the latter two impact categories are the result of various waste treatment processes (Appendix C, Figure 2). Similar as for ecosystem quality, a positive impact is observed pertaining to the climate change impact on human health, reducing the overall damage on human health by 12%. Lastly, futher analysis of resource scarcity, highlights that non-renewable energy resource use, primarily linked to petroleum and gas production (i.e., 90%), is the primary driver, with a smaller effect related to material resource depletion, which is for 87% related to rare eath element extraction and treatment (Appendix C, Figure 3).

Contributions of midpoint impact categories to endpoint impacts

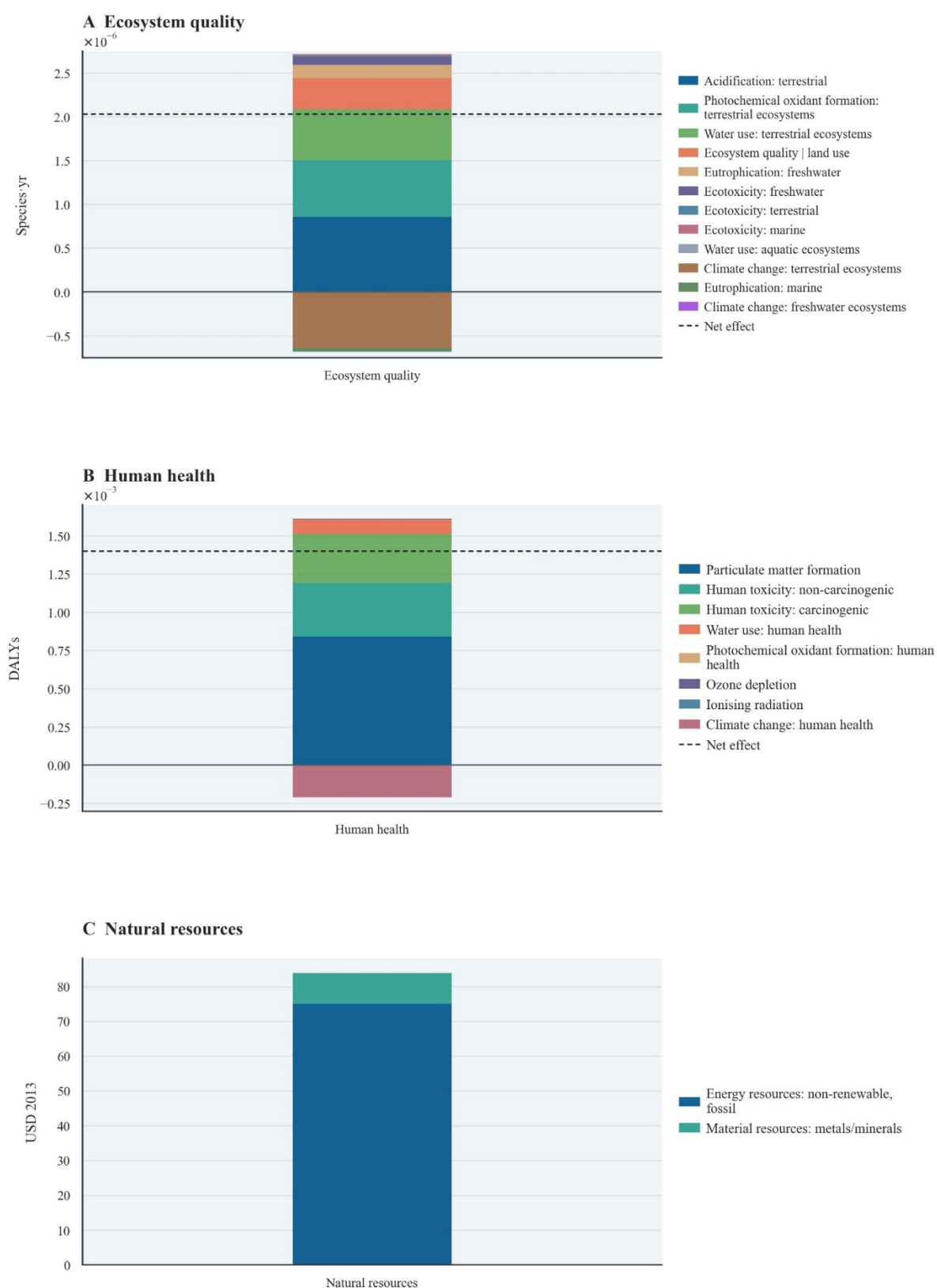


Figure 6: Absolute contributions of midpoint impact categories to ecosystem quality (species.yr) (A), human health (DALYs) (B), and resource scarcity (USD 2013) (C) endpoint impacts of MCS, assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method. N.b. negative values indicate mitigating effects, while positive values indicate environmental burdens.

The offshore transportation and deposition stage (vi) is the dominant contributor across all three AoPs, accounting for between 49% of total impacts for resource scarcity, 56% for ecosystem quality, and 73% for human health (Figure 7). Furthermore, it is worth noting that while the cultivation stage (iv) has a net-mitigating effect for ecosystem quality and human health, offsetting some of the damages related to the product system, it has a pronounced negative impact on resource depletion. Additionally, while stages i & ii and v, similarly as for climate change, contribute only marginally to the overall observed impacts (between 2% for natural resources and 4% for human health), line seeding does represent a notable environmental impact, particularly on human health, i.e., 17%.

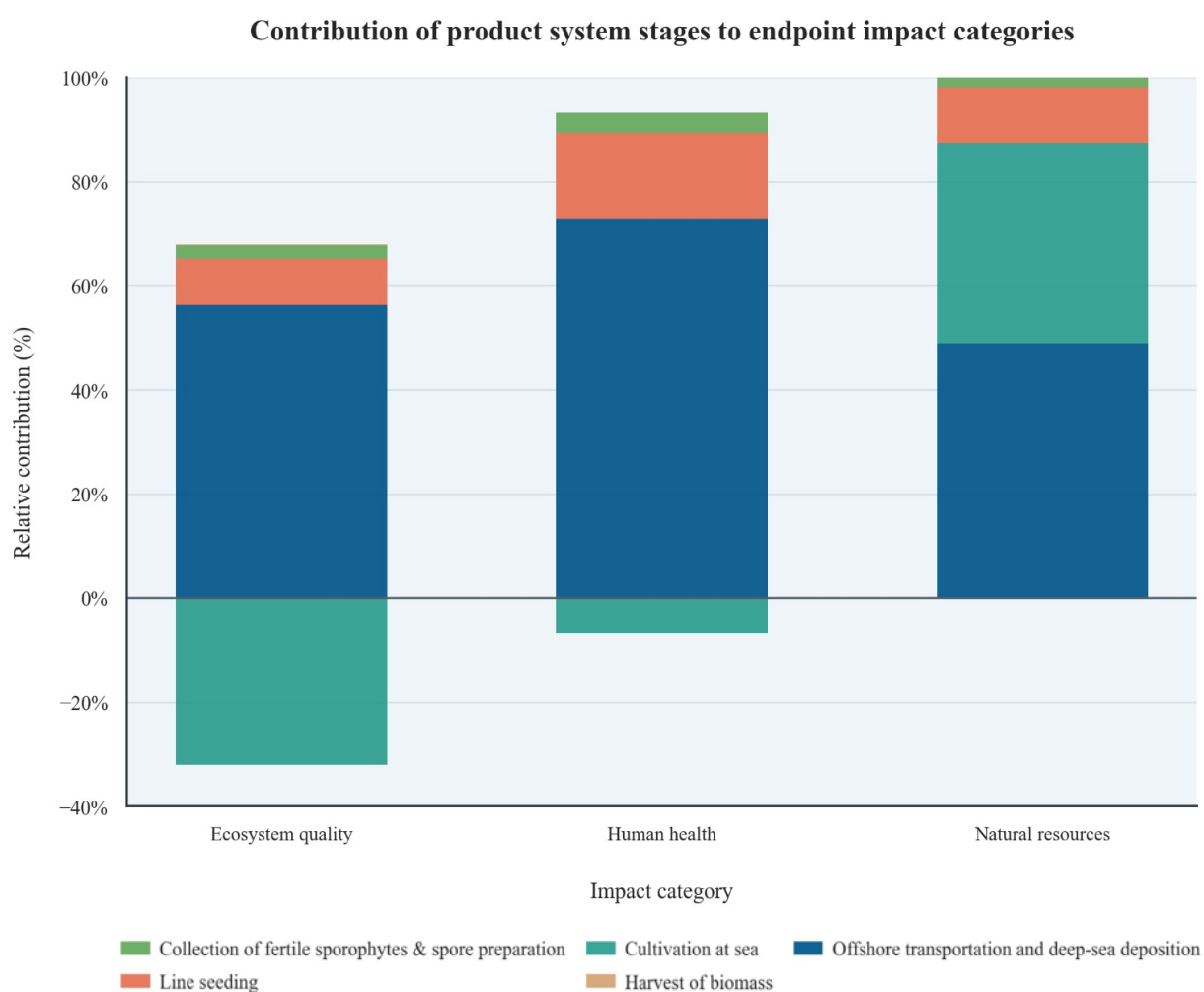


Figure 7: Relative net contributions of individual product system stages to endpoint indicators, assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method.

Investigating the processes affecting each endpoint more closely provides further insight into the product system stage contributions discussed above (Appendix C, Figure 4). Specifically, for ecosystem quality, 29% of impacts can be traced back to biomass transport and nutrient leakage before the end of the sequestration horizon, supporting the pronounced impact of stage vi observed above. Additionally, while cultivation has a net-mitigating effect, the process contribution analysis also reveals that the cultivation infrastructure, included in this stage, constitutes 21% of the total ecosystem quality impacts. Moreover, of these infrastructure-related impacts, 15% can be allocated to the flax fibre longline useage.

While similar trends are observed for human health, the smaller net-mitigating effect associated with the cultivation at sea shown in Figure 7, can be explained by the more pronounced human health impacts related to the nearshore cultivation infrastructure (i.e., 25% of which only 10% can be allocated to the flax fibre longline usage) and treatment of municipal solid waste (i.e., 6%). Together these burdens offset a large share of the benefits from the carbon and nutrient uptake during the macroalgae growth. Additionally, the process analysis also shows that relatively large impacts from line seeding on human health can be traced back to electricity consumption of the various systems at the nursery facility.

In contrast, resource scarcity is driven by a markedly different set of processes. Neither macroalgae growth nor nutrient leakage contributes to this endpoint category, explaining the absence of a mitigating effect observed as observed for ecosystem quality and human health. Instead, 45% of resource depletion impacts are explained by transportation to the deposition site, and 38% by the cultivation infrastructure (most of which due to the polyethylene lines (c2, d1,2,3), anchor bouys (a), and steel chackles (f)); explaining the large contributions of stages iv and vi for natural resource depletion above.

3.3 Assessing the sensitivity of MCS performance

To obtain a more comprehensive understanding of the robustness of the findings presented before and how the MCS system performs under different scenarios, the following section assesses how the product system behaves under a range of outcomes for three key parameters (Chapter 3.3.1). These parameters were identified to be subject to data variability and uncertainty and are expected, or came forward during the contribution analyses, to have a large impact on the total climate change and endpoint impact categories. Details regarding the adaptation of model variables for each scenario are provided in Appendix D, while Appendix E presents the rationale for the selection of the analysed parameters. Subsequently, Chapter 3.3.2 evaluates how the product system performs due to changes to four discrete parameters compared to the base-case.

3.3.1 Influence of transportant distance, biomass yield, and carbon/nutrient leakage

Figure 8 illustrates the sensitivity of the climate change and endpoint impact categories due to variations in transportation distance, biomass yield, and carbon/nutrient leakage, ranging from 50% to 150% of their respective base-case values. The results on the y-axis are expressed as the percentage change in environmental impacts relative to the base-case scenario. Overall, this analysis reveals that the climate change impact category is the most susceptible to uncertainty, with a decrease of 50% in biomass yield, corresponding to a 198% increase in CO₂-eq emissions (panel A). On the other hand, an increase in biomass yield of 50% reduces the climate change impact by 66%, leading to the mitigation of -378 kg CO₂-eq per tonne of CO₂ durably sequestered. These findings highlight an asymmetric effect, i.e., the overall climate change impact is disproportionately influenced by poorer cultivation performance. Changes in transportation distance and carbon/nutrient leakage have a comparatively smaller influence on the climate change impact. However, the latter remains a critical determinant of the system's performance. Specifically, a 50% increase in carbon/nutrient leakage results in a 110% rise in climate change impacts, effectively shifting MCS from a net carbon removal technology to a net-emitter, with emissions reaching 24 kg CO₂-eq per tonne of CO₂ that is durably sequestered. Moreover, it is worth noting that in the scenario where sink-suitable locations are 50% closer to the cultivation site, hence halving transportation distance, the corresponding GHG-emissions are approximately 67% smaller. This is comparable to the improved climate change impacts resulting from a 50% reduction in carbon/nutrient leakage; highlighting the importance of organising cultivation operations within close proximity of a sink-suitable site wherever possible.

Sensitivity analysis of continuous parameters

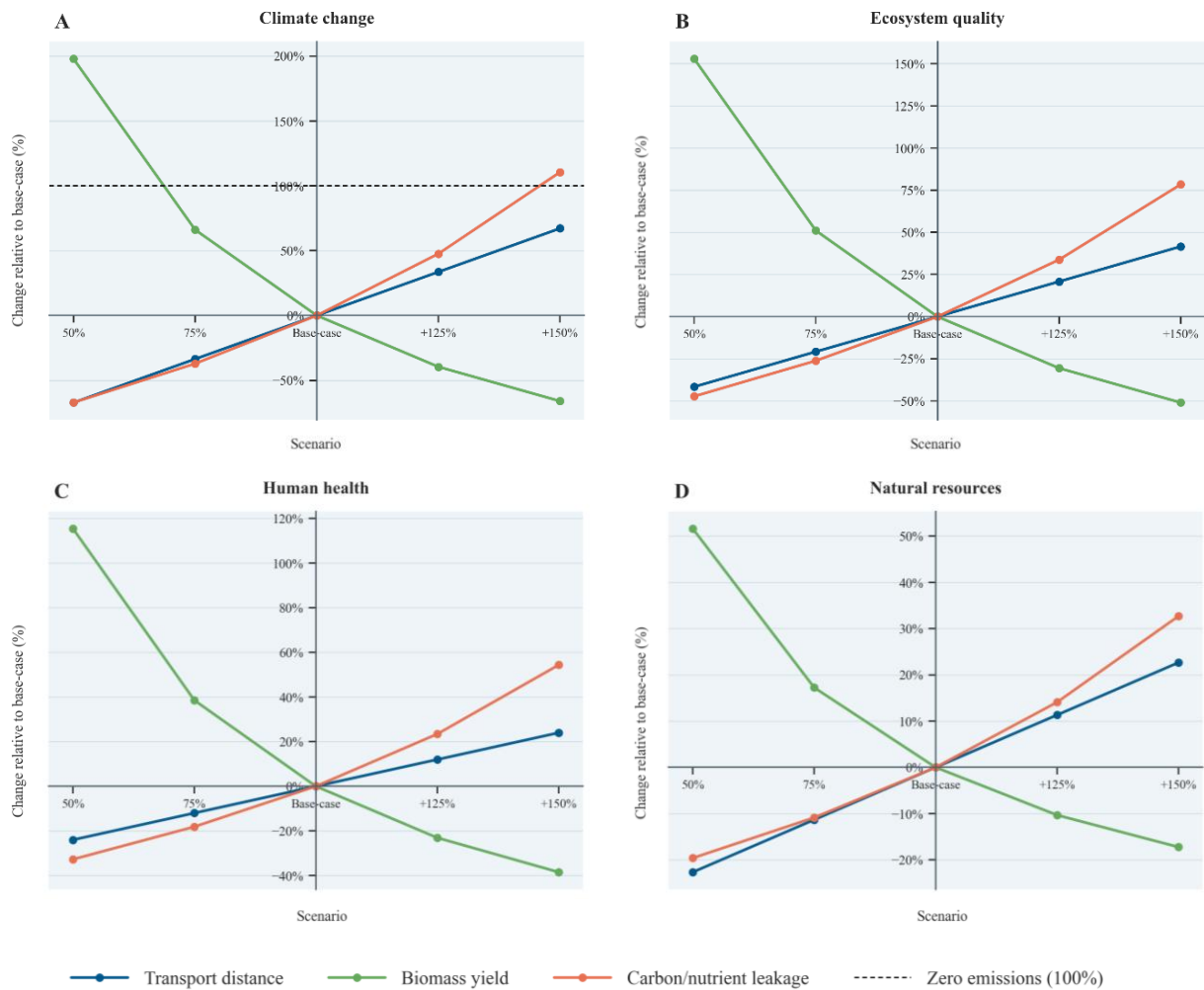


Figure 8: Sensitivity of the climate change (A), Ecosystem quality (B), Human health (C), and Natural resource scarcity (D) impact categories outcomes to variations in (i) transportation distance, (ii) biomass yield, and (iii) carbon/nutrient leakage, ranging from 50% to 150%, in 25% increments, of their respective base-case values. Results are expressed as the percentage change in environmental impacts relative to the base-case scenario and were assessed using the ReCiPe v.1.03 (H) characterisation methods. N.b. the dashed line in panel A shows the point at which MCS becomes a net-emitting technology.

Similar trends are observed for ecosystem quality, human health, and natural resource scarcity (panels B-D), with environmental impacts increasing under lower biomass yields, greater transportation distances, and higher carbon/nutrient leakage rates. Moreover, across all impact categories, reductions in biomass yield have the most pronounced negative effect, whereas the improvements associated with the respective best-case scenarios are more closely comparable across the three parameters. Nevertheless, the magnitude of these responses, and hence the sensitivity, is considerably smaller than that observed for climate change; particularly within the human health and natural resource categories. For example, the largest change in natural resource scarcity is associated with a 50% reduction in biomass yield, which increases impacts by 52%, compared to a 198% increase for climate change under the same scenario. Similarly, halving transportation distance reduces natural resource scarcity impacts by only 23%, whereas climate change impacts decrease by approximately 67%. Lastly, the reduction in sensitivity observed for biomass yield and carbon/nutrient leakage between the climate change and resource scarcity categories is substantially larger than that observed for transportation distance. Specifically, the worst-case impact associated with a 50% reduction in biomass yield decreases from a

+198% for climate change to +52% for natural resource scarcity, whereas the corresponding effect of transportation distance declines from +67% to only +23% between the two impact categories.

3.3.2 Influence of temporal scope, seeding method, cultivation line material, and characterisation family

To grasp to effect of implementing the MCS mCDR system under future background conditions, adopting an emerging seeding technique, i.e., spray-seeding, rather than conventional submersion seeding, changing the main cultivation line material (c1 in Figure 3) to widely-used polyethylene, and employing a different characterisation family to derive the LCIA results, Figure 9 shows the relative results of the MSC system against the base-case outcomes.

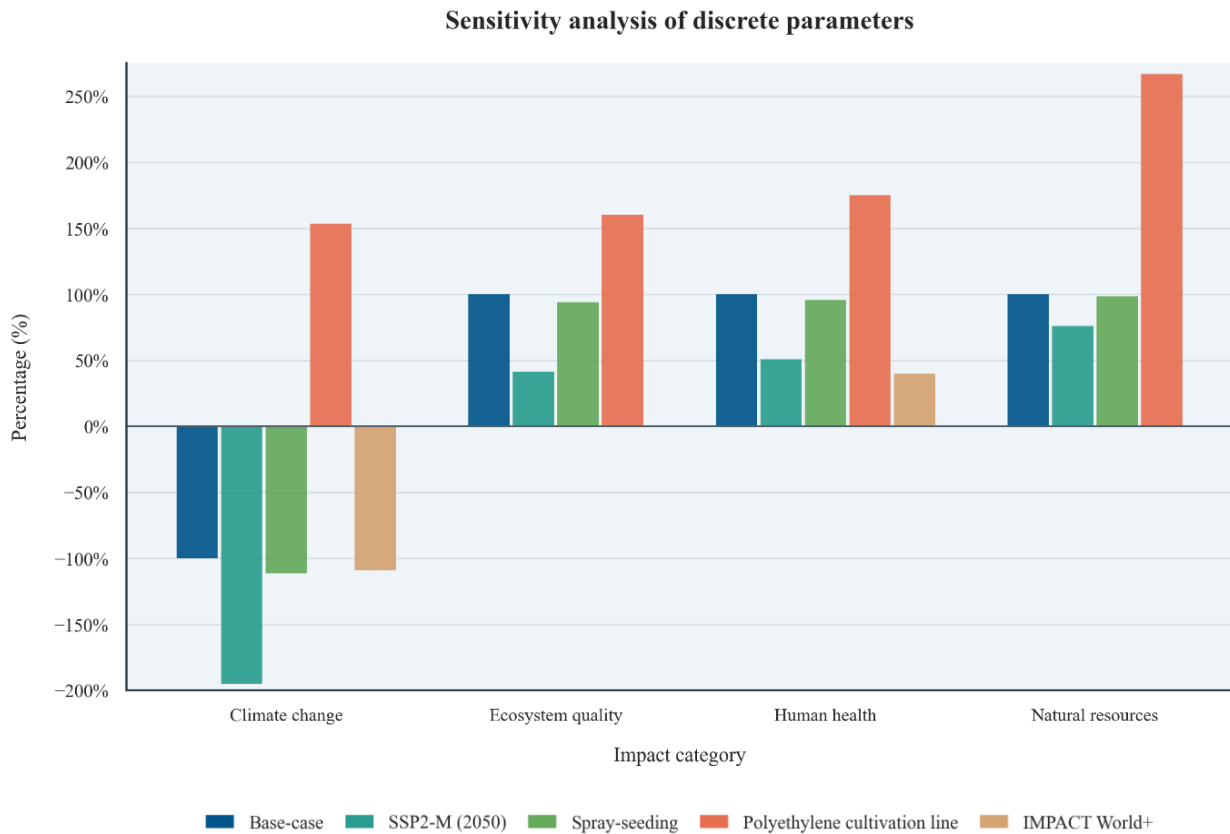


Figure 9: Relative impact of variations in discrete parameters on the climate change and endpoint impact categories. Results are normalised to the base-case (100%) and assessed using the ReCiPe v.1.03 (H) characterisation methods (apart from the scenario in which the IMPACT World+ method is adopted). Scenarios include: (i) background systems representing the SSP2-M pathway for 2050 (for more detailed results of all future scenario's, i.e., SSP1-M, SSP2-M, and SSP3-H, see Appendix F); (ii) adoption of spray-seeding as the line seeding technique, (iii) using polyethylene longlines; and (iv) employing the IMPACT World+ characterisation family.

Changes to the temporal scope and main cultivation line material exhibit the largest influence on both the climate change and endpoint impacts of MCS. These results highlight that the net-mitigation potential is expected nearly double due to changes in the underlying background system by 2050 (i.e., -444 kg CO₂-eq per tonne of CO₂ durably sequestered under SSP2-M). On the other hand, adopting polyethylene cultivation lines would result in net-emissions of 349 kg CO₂-eq. Furthermore, for the endpoint impact categories similar patterns can be observed. The SSP2-M future background system approximately halves the total impact compared to the base-case, with more pronounced effects for ecosystem quality (-59%) and human health (-51%), and less impact on natural resource scarcity (-24%). Adopting polyethylene cultivation lines, on the other hand, increases ecosystem quality and human

health impacts by 60% and 75%, while natural resource scarcity is most severely affected (+167%). Only minor differences were observed between the different socio-economic pathways, indicating that while the environmental performance of MCS is highly sensitive to the transition from present-day to future background systems, this is less the case for inter-pathway differences (Appendix F).

Additionally, while the analysis shows that adopting the spray-seeding method results in slight environmental improvements, i.e., net-mitigation, ecosystem quality, human health, and natural resource scarcity all improve by 11%, 6%, 4%, and 2% respectively compared to the base-case, the overall effect of this parameter remains limited. Lastly, plotting the results for impact categories with identical units, i.e., climate change (kg CO₂-eq) and human health (DALYs), next to each other for the two characterisation families, shows that while the choice between characterisation method does not influence the conclusions that can be drawn for climate change, it does result in different outcomes for human health. Specifically, adopting IMPACT World+ to derive the human health impact of MCS, results in outcomes that are 60% smaller compared to the base-case. This can be explained by the differences in characterisation factors for key environmental flows contributing to human health impacts between the two methods. Particularly, in the base-case, nitrogen oxides (NO_x), chromium VI, and sulfur dioxide (SO₂), are related to 23%, 22%, and 13% of the net human health impacts, however, IMPACT world+ reports 240% smaller impacts related to NO_x, 23 times smaller impacts for chromium VI and 94% smaller impacts for SO₂.

Futhermore, because the ecosystem quality and natural resource scarcity endpoint indicators are measured differently in ReCiPe 2016 and IMPACT World+, their absolute outcomes cannot be directly compared. Instead, Figure 10 presents the relative net contributions of the individual product system stages, highlighting key differences between the two characerisation methods. Since, both LCIA methods assess climate change impacts very similarly this impact category has been omitted from this analysis. Comparing the cultivation at sea (iv) stage between the two approaches for the ecosystem quality and human health impact categories shows that while ReCiPe 2016 accounts for the benefits of CO₂ and nutrient removal, this is not considered within the IMPACT World+ approach. Ultimately, this leads to very different outcomes with a greater emphasis on the cultivation stage (iv), and less on the offshore transport and deep-sea deposition (vi) and line seeding (iii) stages when adopting IMPACT World+. Furthermore, while the results for natural resource scarcity are more closely comparable between characterisation methods, IMPACT World+ shows an increased importance of the line seeding stage (iii), while displaying less emphasis on the offshore transportation and deep-sea deposition stage (vi).

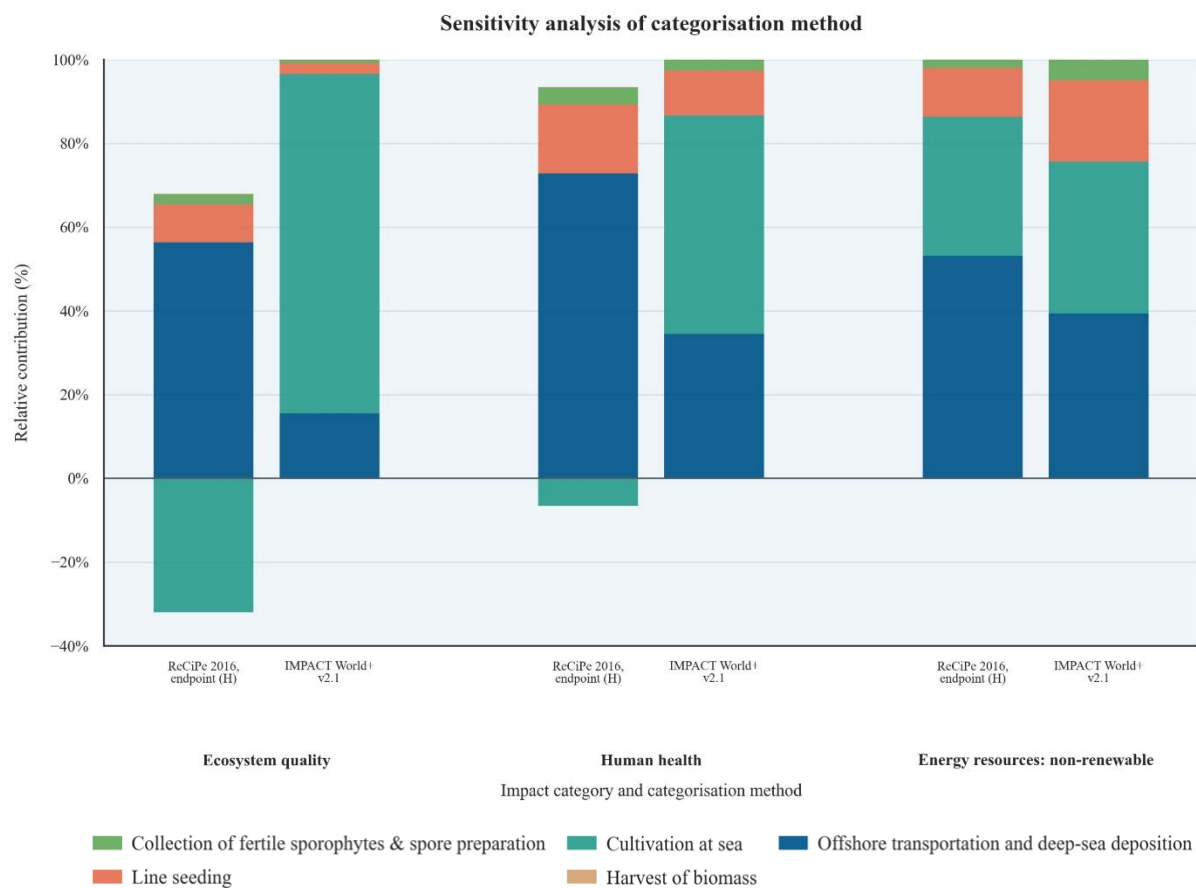


Figure 10: Relative net contributions of individual product system stages on endpoint indicators, assessed using the ReCiPe 2016 v1.03 (H) and IMPACT World+ v2.1 characterisation methods.

4. Discussion

4.1 Towards a more holistic understanding of the environmental impacts of MCS as a mCDR approach

The presented LCA suggests that MCS can function as a NET under the system design evaluated in this study, resulting in a net reduction of 227 kg CO₂-eq per tonne of CO₂ durably sequestered. Consequently, large-scale implementation of MCS could, theoretically, contribute to narrowing the projected ‘CDR gap’ and achieving international climate targets (Lamb et al., 2026; Smith et al., 2026). This finding is consistent with previous modelling research that identified MCS as a potentially effective mitigation strategy despite considerable differences in system configuration and geographical scope compared to this research (N’Yeurt et al., 2012; Coleman et al., 2022; Chapter 1). Nevertheless, the estimated sequestration efficiency of less than 23% indicates that only a relatively small fraction of the carbon fixed by cultivated *S. latissima* ultimately contributes to durable net CDR, emphasising that real-world deployment of this technology, as a means to mitigate climate change, should proceed with caution and further technological improvements remain essential. To that end, our findings demonstrate that the overall climate change performance of MCS is governed by a limited number of elements, most notably offshore transportation of macroalgae biomass, carbon/nutrient leakage, electricity consumption in the onshore hatchery, and cultivation infrastructure. This finding reinforces broader observations in mCDR literature that these elements are likely to determine the viability of large-scale macroalgae-based carbon removal (NASEM, 2022). Therefore, shifting to less emitting modes of transport, reducing the carbon intensity of the nearshore cultivation infrastructure, and decarbonising hatchery energy supply while increasing its energy efficiency may offer valuable opportunities to enhance to overall climate change performance and real-world viability of MCS.

When considering climate change in isolation, the presented results suggest that MCS could function as an environmentally beneficial technology. However, extending the assessment beyond climate change reveals a more nuanced picture. Although offshore transportation and cultivation infrastructure remain the dominant environmental hotspots across all AoPs, unlike climate change, the environmental benefits associated with carbon sequestration and nutrient bioremediation are insufficient to fully offset the burdens generated by this mCDR technology. Hence, while net benefits are observed for climate change, the MCS system continues to generate net adverse impacts on ecosystem quality, human health, and natural resource scarcity. These findings highlight that the environmental sustainability of MCS cannot be inferred from climate change impacts alone, supporting recent calls within the mCDR literature to move beyond climate-centric assessments and evaluate MCS across a broader range of environmental impact categories (Boyd et al., 2022; Hurd et al., 2022; Rickart et al., 2022; Chopin et al., 2024; Delval et al., 2025). In doing so, this research extends previous LCAs of MCS, which focused exclusively on climate change (N’Yeurt et al., 2012; Coleman et al., 2022), by demonstrating that net carbon removal of 227 kg CO₂-eq is accompanied by measurable trade-offs in potential loss of biodiversity (2.03×10^{-6} species.yr) and healthy life years (1.40×10^{-3} DALYs), and potential additional future extraction costs (84 USD 2013). Consequently, future research, certification schemes, and policy frameworks should adopt holistic assessment approaches to ensure that climate mitigation is not achieved at the expense of other environmental objectives.

Detailed assessments further revealed that the environmental performance of MCS is shaped by fundamentally different environmental mechanisms across the AoPs (Figure 6). Ecosystem quality is primarily affected by terrestrial acidification, water consumption, and photochemical oxidant formation, largely attributable to flax fibre cultivation and offshore transportation. Natural resource scarcity, in contrast, is primarily influenced by non-renewable energy use driven by the extraction of petroleum and

natural gas required for offshore transportation and plastic-based cultivation infrastructure components. Likewise, human health impacts are mainly driven by particulate matter formation and (non) carcinogenic toxicity resulting from electricity generation, offshore transportation, and waste treatment. Consequently, while broad improvements in the environmental performance of MCS could be achieved by addressing overlapping hotspots such as offshore transportation, these results also provide the basis for developing potentially more effective targeted environmental improvement strategies. For example, strategies aimed at reducing fossil-based material use may be most effective for lowering natural resource scarcity, whereas limiting the use of flax fibres emerges as a surprisingly effectively strategy for improving ecosystem quality, because it is heavily linked to terrestrial acidification (33%) and water consumption (89%) impacts (Appendix C, Figure 1). To the author's knowledge, this represents the first work to identify the driving mechanisms and underlying hotspots across multiple AoPs, providing the evidence required to develop targeted interventions tailored to specific environmental objectives rather generic system-wide improvements.

4.2 Implications of key uncertainties on MCS implementation

Among the environmental impacts covered by this research, climate change is the most susceptible to uncertainty, i.e., impacts range between +198% and -67% across the different scenarios compared to the base-case. Therefore, caution is warranted when drawing conclusions regarding the climate mitigation potential of the MCS system, particularly given the limited sequestration efficiency estimated in this study. The sensitivity analysis further demonstrates that the viability of MCS is highly dependent on achieving consistently high biomass yields, especially since a reduction in yield of 50% was estimated to change the technology into a substantial net emitter (+222 kg CO₂-eq per FU). Similar concerns have been raised by the National Academies of Sciences, Engineering, and Medicine (2022), who identified biomass losses during cultivation, harvesting, transport, and deep-sea conveyance as one of the principal constraints on the scalability of seaweed-based CDR, as lower productivity necessitates larger cultivation areas and increases operational costs. The present study extends these findings by uncovering that this parameter is not only a determinant of technical and economic feasibility, but also of environmental viability. Given that biomass yields are strongly influenced by local environmental conditions, site selection should be a critical operational design decision (Khan et al., 2024). Moreover, these findings also support the “cultivate nearshore, sink offshore” strategy, as nearshore cultivation is expected to generate more reliable yields through greater nutrient availability and reduced exposure to storm-induced biomass losses compared to offshore cultivation (Alvizos & Barillé, 2023).

However, sequestration durability arguably represents the most critical uncertainty facing MCS deployment. Although increases in carbon and nutrient leakage come paired with smaller influences on climate change and endpoint impacts than yield losses, a 50% increase is nevertheless estimated to be sufficient to shift the system from net carbon removal technology to net-emitter. This finding is particularly relevant given the limited understanding of long-term sequestration pathways of POC and DOC, and recent year-long in-situ measurements at a northeast pacific sink site (at 1255 m) showing 90% decomposition of artificially sunk macroalgae biomass within 100 days, due to microbial and fungal activity (Pessarrodona et al., 2023; Bauer et al., 2026). Even though Bauer and colleagues (2026) note that some carbon likely entered dissolved pools with longer residence times, these findings raise doubts regarding the viability of deep-sea biomass deposition as a long-term carbon sequestration pathway under such conditions. Combined with the substantial spatial variability in sequestration potential reported by Siegel et al. (2021), our results highlight that improved understanding of local post-deposition carbon cycling and robust monitoring and verification frameworks are essential before MCS can credibly underpin carbon credit certification or climate policy (NASEM, 2022).

Unlike biomass productivity and sequestration durability, transportation requirements represent a key parameter that can be directly controlled through operational design decisions rather than being largely determined by biological and oceanographic processes. Therefore, limiting the distance between cultivation and deposition sites may offer one of the most readily implementable strategies for improving the environmental performance of MCS. To illustrate, halving the transport distance is estimated to increase the climate mitigation potential of MCS by 67%, comparable to the improvements achieved by increasing biomass yields or reducing carbon/nutrient leakage by 50% (Figure 8). Consequently, proximity between cultivation and suitable deep-sea deposition sites should become a key criterion in MCS site-selection and deployment strategies. Although Alevizos and Barillé (2023) do incorporate distance to the nearest port in their operational feasibility assessment of suitable MCS locations, their maximum accepted one-way distance of 1000 km may be insufficiently restrictive. Our sensitivity analysis suggest that increasing the transportation distance to 874 km reduces the sequestration efficiency to only 7%. Hence, future spatial suitability assessments should consider this parameter more critically, since it is crucial to the sequestration viability of the technology and has large implications for its broader environmental performance.

Lastly, the analysis of key discrete parameters revealed that future background conditions, material selection, and LCIA method can each substantially alter the estimated environmental outcomes and mitigation potential of MCS. While the transition from present-day to 2050 energy systems and industrial processes approximately halve both climate change and endpoint impacts, minor differences are observed between socio-economic pathways, suggesting that regardless of large scale trends the technology will become more sustainable in the near future. Additionally, replacing flax fibre cultivation lines with polyethylene, used in previous macroalgae aquaculture studies (Koesling et al., 2021; Thomas et al., 2021), could more than double natural resources scarcity impacts and cause substantial net-emission (+ 349 kg CO₂-eq). This pronounced impact reflects the deposition concept adopted in this study, in which cultivation lines are only used for a single cultivation cycle before being sunk alongside the biomass (Coleman et al., 2022). Therefore, although reducing flax use may sharply improve ecosystem quality impacts, polyethylene does not present a viable alternative under this system configuration. Instead, adopting alternative deposition techniques that avoid sinking cultivation infrastructure altogether, such as the ‘baling’ approach proposed by Sten et al. (2026), might be a better solution. Finally, the choice of characterisation family substantially affects the endpoint outcomes, showing that existing LCIA methods were not developed specifically to accurately and consistently reflect mCDR technologies (Delval et al., 2026). Hence, consistent with the role of life cycle interpretation as a decision-support process (Laurent et al., 2020), the results presented here should be interpreted as guidance for identifying priority areas for technological development and deployment strategies, rather than as absolute measures of the environmental sustainability of MCS. Furthermore, future assessments should continue to apply multiple LCIA methods until available methods more comprehensively represent long-term carbon sequestration and marine-specific environmental processes and impacts (Delval et al., 2026).

4.3 Limitations and suggestions for future research

Although this study provides one of the most comprehensive environmental assessments of MCS to date, several methodological and data-related limitations remain. Addressing these limitations expose relevant avenues for future research and will be essential for reducing uncertainty surrounding the environmental performance of MCS. First of all, as noted by Delval et al. (2026), current LCIA methods are faced with several critical shortcomings, limiting their ability to adequately assess marine impacts. Specifically, (i) numerous emissions and resource flows relevant to mCDR remain uncharacterised, (ii) models are grounded on freshwater rather than marine-specific data, drawing

incorrect correlations, (iii) marine eutrophication models do not account for P, causing the benefits of P bioremediation to be overlooked in the presented research, and (iv) ocean acidification is entirely absent from the ReCiPe 2016 characterisation framework (Huijbregts et al., 2016; Delval et al., 2026). Consequently, both potential burdens and environmental benefits associated with MCS may be underrepresented. Moreover, several environmental impacts potentially associated with large-scale MCS adoption fall entirely outside the scope of current LCIA methods, including microplastic pollution from degradation or loss of cultivation infrastructure, as well as ecological disturbances to benthic communities caused by biomass deposition (Haward, 2018; Koesling et al., 2021; Thomas et al., 2021; Xayachak et al., 2024). Recent findings suggest that macroalgae deposition can alter deep-sea community structures (Bauer et al., 2026), while broader ecological consequences, including oxygen depletion and biodiversity impacts, remain poorly understood (Ricart et al., 2022). Further development of marine-specific impact assessment models is therefore essential to enable more comprehensive and accurate evaluation of mCDR technologies.

A second limitation relates to the geographical and technological scope of this research, as the environmental performance of MCS is expected to vary across regions due to differences in oceanographic conditions, cultivation practices, and sequestration pathways (Siegel et al., 2021; Alvizos & Barillé, 2023; Passarona et al., 2023). This is particularly relevant given that carbon and nutrient leakage and transportation distance emerged as some of the most influential parameters in the presented study, both of which are inherently location-dependent. For example, sequestration durability was found to vary spatially due to differences in environmental conditions and ecosystem processes (Siegel et al., 2021), while biomass yield may be affected by local nutrient availability, oceanic temperatures, salinity and ambient conditions, such as exposure to sunlight and (tropical) storms (Khan et al., 2024). Furthermore, this LCA focuses exclusively on *S. latissima*, despite variations in species productivity and biochemical composition, and seasonal variability in C, N, and P contents was not taken into account. Further research could therefore benefit from investigating different geographic regions and macroalgae species, while incorporating seasonal changes in biomass composition and productivity enabling comparison with the present study and critical evaluation of the most suitable locations and conditions for potential MCS deployment strategies.

Lastly, several critical modelling assumptions should be acknowledged. First, the presented MCS model assumes that the uptake of N leads to eutrophication benefits, however, this is only the case if the marine environment is N-limited (Howarth & Marino, 2006). This assumption aligns with Thomas et al. (2021), who used data from the Swedish Environmental Protection Agency (2008), and the European Joint Research Centre (2012), who found that marine waters are generally N-limited (Delval et al., 2026). Moreover, the leakage-rates of N and P are assumed to be similar to C, due to a lack of flow-specific data, and since P is not characterised as discussed above eutrophication impacts could be over or underestimated. Second, the *ecoinvent* database lacks an adequate sea-going transportation vessel. Hence, this research used an inland barge and removed all canal-related sub-processes as a proxy (Melara et al., 2020; Thomas et al., 2021). Given its prominent contribution to overall MCS impacts, offshore transportation merits more detailed investigation in future studies. Third, while this research builds on the findings of Baker et al. (2022), sequestration pathways of POC, DOC, and nutrients like N and P related to the artificial sinking of macroalgae remain insufficiently understood. Given the large uncertainty of this parameter and pronounced implications for the viability and impacts of MCS presented in this study, improving our understanding of post-deposition carbon and nutrient cycling, as well as investigating alternative deposition techniques, should be considered a research priority. These findings align with recommendations of Bauer et al. (2026) that, ultimately, site-specific process-based monitoring is essential to inform the carbon mitigation potential and ecological impacts of MCS and ensure responsible deployment of this mCDR technology.

5. Conclusion

To limit global warming to 1.5°C, large-scale deployment of CRD technologies will be required alongside rapid decarbonisation efforts (IPCC, 2022; Smith et al., 2026). Although at present, approximately 2.2 GtCO₂ yr⁻¹ of CDR is achieved globally, a substantial “CRD gap” remains (Lamb et al., 2026). One approach that has received considerable attention in recent years is MCS. However, despite the surge in commercial and political interest, calls for a moratorium on the sinking of macroalgae into deep-ocean ecosystems are increasing, pending evidence of its effectiveness and robust assessments of its environmental sustainability (Boyd et al., 2022; Hurd et al., 2022; Rickart et al., 2022; Chopin et al., 2024; Delval et al., 2025). To answer these calls and move beyond the narrow assessment of climate change impacts (N’Yeurt et al., 2012; Coleman et al., 2022), this exploratory research presented the first cradle-to-grave LCA of MCS, identifying hotspots and trade-offs pertaining to climate change, ecosystem quality, human health, and natural resource scarcity. Moreover, given the considerable uncertainties surrounding this technology, the sensitivity of its environmental performance to seven key parameters was evaluated, which so far has not received any attention in the LCA literature.

Our findings suggest that MCS could function as a net carbon removal technology, yielding a mitigation potential of 227 kg CO₂-eq per tonne of CO₂ durably sequestered. At the same time, this environmental benefit is accompanied by net adverse environmental impacts on ecosystem quality (2.03 × 10⁻⁶ species.yr), human health (1.40 × 10⁻³ DALYs), and natural resource scarcity (83.9 USD 2013), exposing critical environmental trade-offs. Across impact categories, the biomass transportation requirements and carbon/nutrient leakage emerged as the dominant hotspots, while cultivation infrastructure and energy use during line seeding also contributed notably to the environmental performance of MCS. Taking into consideration the findings from the sensitivity analyses, several opportunities to improve the environmental performance of MCS can be identified. Sink site proximity should be a critical determinant in cultivation site-selection and transportation requirements must be reduced wherever possible. Additionally, biomass yields could be enhanced through optimisation of juvenile density on seeded lines and cultivation site selection, while, most importantly, losses should be minimised through the adoption of storm-resilient infrastructure (Thomas et al., 2021; Alvizos & Barillé, 2023; Khan et al., 2024). Furthermore, cultivation and sinking infrastructure designs could be improved by seeking better alternatives for the main longline material or adopting alternative deposition techniques that avoid sinking cultivation infrastructure altogether. Lastly, the adoption of renewable energy combined with reducing energy demand at the onshore hatchery should be a strategic priority.

Ultimately, even though the deployment of the MCS system under the assumption and conditions assessed in this research could potentially help to bridge the “CRD gap”, the positive impacts related to climate mitigation and eutrophication are insufficient to offset the damage to ecosystems, human health, and natural resource scarcity caused by this technology. Moreover, given the particularly large uncertainty of climate change impacts combined with the relatively limited estimated sequestration efficiency (i.e., 23%), adoption of this technology, as a means to mitigate climate change, should proceed with great caution, and further technological improvements remain essential. Furthermore, the viability of MCS remains highly dependent on sequestration durability, which emerged as one of the most critical sources of uncertainty and remains contested in the current literature, and current LCIA methods are limited in their ability to adequately assess marine impacts. Future research should especially prioritise the quantification of post-deposition pathways of C, N and P and the development of marine-specific impact assessment methods that are capable of accurately and consistently reflecting the environmental impacts of mCDR technologies (Haward et al., 2018; Ricart et al., 2022; Passarona et al., 2023; Bauer et al., 2026; Delval et al., 2026). Until these uncertainties are reduced and a more robust sequestration efficiency is achieved, large-scale MCS deployment remains difficult to justify.

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Appendix

Appendix A: Detailed LCI data for MSC product system

Table A1: Complete LCI of the collection of fertile sporophytes (1), spore preparation (2), line seeding (3), cultivation at sea (4), harvest of biomass (5) and offshore transportation and deposition (6) stages of the MCS product system, specifying the amounts of each input/output required to durably sequester one tonne of CO₂ and the names of the ecoinvent v.3.12 and biosphere 3 processes selected for the present study (See [LCI data MCS model.xlsx](#) for more details and calculations).

Inventory inputs and unit processes	Input/output type	Amount	Unit	Providing process, ecoinvent v.3.12 – cutoff background process, or biosphere 3 flows
Collection of fertile sporophytes				
Inflows				
Fertile kelp	N/a	1.00E+00	kg	Harvest of biomass
Harvesting bags	Polypropylene, granulate	1.00E-02	kg	Market for polypropylene, granulate (RER)
Fabric cloths	Woven cotton	1.00E-02	kg	Market for textile, woven cotton (GLO)
Kelp transport to hatchery	Transport, freight, lorry 16-32 metric ton, diesel, EURO 5	1.00E-02	t*km	Market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER)
Outflows				
Parent specimens	N/a	1.00E+00	kg	N/a
Solid waste	Municipal solid waste	2.00E-02	kg	Market group for municipal solid waste (RER)
Spore preparation				
Inflows				
Parent specimens	N/a	1.00E+00	kg	Collection of fertile sporophytes
Aeration and stirring system	Electricity, medium voltage	9.81E-01	kWh	Market group for electricity medium voltage (RER)
Bucket	Extrusion, plastic pipes	5.67E-03	kg	Market for extrusion, plastic pipes (GLO); adjusted by replacing plastic inputs with “Polyethylene, high density, granulate”
Seawater filter	Fleece, polyethylene	1.51E-02	kg	Market for fleece, polypropylene (GLO)
Seawater filter	Steel, chromium steel 18/8	1.68E-03	kg	Market for steel, chromium steel 18/8 (GLO)
Seawater source and filter system	Electricity, medium voltage	1.48E-02	kWh	Market group for electricity medium voltage (RER)
Temperature control system	Electricity, medium voltage	3.44E+00	kWh	Market group for electricity medium voltage (RER)
Lighting system	Electricity, medium voltage	2.10E+00	kWh	Market group for electricity medium voltage (RER)
Outflows				
Concentrated solution of healthy spores	N/a	1.00E+00	l	N/a
Solid waste	Municipal solid waste	2.25E-02	kg	Market group for municipal solid waste (RER)
Line seeding				

Inflows				
Concentrated solution of healthy spores	N/a	1.00E+00	l	Spore preparation
Aeration and stirring system	Electricity, medium voltage	2.04E+00	kWh	Market group for electricity, medium voltage (RER)
Aquaria	Polymethyl methacrylate	2.91E-01	kg	Market for polymethyl methacrylate (RER)
Production of aquaria	Injection moulding	2.91E-01	t*km	Market for injection moulding (GLO)
Bucket	Extrusion, plastic pipes	1.13E-02	kg	Market for extrusion, plastic pipes (GLO); adjusted by replacing plastic inputs with "Polyethylene, high density, granulate"
Collectors	Extrusion, plastic pipes	2.75E-01	kg	Market for extrusion, plastic pipes (GLO); adjusted by replacing plastic inputs with "polyvinylidenechloride, granulate"
Lighting system	Electricity, medium voltage	9.19E+00	kWh	Market group for electricity, medium voltage (RER)
Seawater filter	Fleece, polyethylene	3.02E-02	kg	Market for fleece, polypropylene (GLO)
Seawater filter	Steel, chromium steel 18/8	3.36E-03	kg	Market for steel, chromium steel 18/8 (GLO)
Seawater source and filter system	Electricity, medium voltage	2.62E-02	kWh	Market group for electricity, medium voltage (RER)
Seeding line	Nylon 6	1.58E-01	kg	Market for Nylon 6
Temperature control system	Electricity, medium voltage	7.08E+00	kWh	Market group for electricity, medium voltage (RER)
Water heating system	Electricity, medium voltage	3.33E-01	kWh	Market group for electricity, medium voltage (RER)
	Sodium nitrate	9.74E-01	g	Market for sodium nitrate (GLO)
	EDTA, ethylenediamine-tetraacetic acid	1.29E-02	g	Market for EDTA, ethylenediaminetetraacetic acid (GLO)
	Ammonium sulfate	1.77E-01	g	Market for ammonium sulfate (RER)
	Boric acid, anhydrous, powder	1.13E-02	g	Market for boric acid, anhydrous, powder (GLO)
	Manganese sulfate	1.21E-03	g	Market for manganese sulfate (GLO)
	Zinc monosulfate	2.23E-04	g	Market for zinc monosulfate (RER)
	Tap water	2.53E-01	l	Market for tap water (Europe without Switzerland)
Outflows				
Collector (seeded line)	N/a	1.00E+00	item	N/a
Solid waste	Municipal solid waste	6.11E-01	kg	Market group for municipal solid waste (RER)
Wastewater	Market for wastewater, average	2.53E-04	m ³	Market for wastewater, average (Europe without Switzerland)
Cultivation at sea				
Inflows				
Collectors	N/a	1.00E+00	item	Submersion seeding/spray seeding
Anchor (g)	Concrete block	2.87E-02	kg	Market for concrete block (RoW)
Production of anchor buoy (a)	Stretch blow moulding	6.66E-01	kg	Market for stretch blow moulding (GLO)
Anchor buoy (a)	Polyethylene high density, granulate	6.66E-01	kg	Market for polyethylene high density, granulate (RoW)

Production of buoys (b)	Stretch blow moulding	5.77E-01	kg	Market for stretch blow moulding (GLO)
Buoys (b)	Polyvinyl chloride, unspecified polymerisation, weighted average	5.77E-01	kg	Market for polyvinyl chloride, unspecified polymerisation, weighted average (RoW)
Chain (e)	Steel, low-alloyed, hot rolled	2.59E+00	kg	Market for steel, low-alloyed, hot rolled (GLO)
Longline (c1)	Fibre, flax	7.64E+00	kg	Market for fibre, flax (GLO)
Longline (c2)	Fleece, polyethylene	1.65E-01	kg	Market for fleece, polyethylene (GLO)
Longline (d1/d2)	Fleece, polyethylene	8.08E-01	kg	Market for fleece, polyethylene (GLO)
Longline (d3)	Fleece, polyethylene	5.77E-02	kg	Market for fleece, polyethylene (GLO)
Shackle (f)	Steel, low-alloyed, hot rolled	1.49E-01	kg	Market for steel, low-alloyed, hot rolled (GLO)
Installation, monitoring, repair, and cultivation vessel operations	Transport, freight, inland waterways, barge, diesel	3.92E+00	t*km	Market for transport, freight, inland waterways, barge, diesel (RER); adjusted by removing canal related sub-processes
Nitrogen	N/a	4.08E+00	kg	Nitrogen (water, ocean)
Carbon Dioxide	N/a	1.45E+02	kg	Carbon dioxide, fossil (air)
Phosphorus	N/a	3.62E-01	kg	Phosphorus (water, ocean)
Outflows				
Mature macroalgae	N/a	1.00E+03	kg	N/a
Solid waste	Municipal solid waste	5.04E+00	kg	Market group for municipal solid waste (RER)
Harvest of biomass				
Inflows				
Mature macroalgae	N/a	1.00E+03	kg	Cultivation at sea
Vessel operations during harvesting	Transport, freight, inland waterways, barge, diesel	1.27E+00	t*km	Market for transport, freight, inland waterways, barge, diesel (RER); adjusted by removing canal related sub-processes
Outflows				
Harvested macroalgae	N/a	1.00E+03	kg	N/a
Fertile kelp	N/a	1.00E+00	kg	N/a
Offshore transportation and deposition				
Inflows				
Harvested macroalgae	N/a	1.03E+04	kg	Harvest of biomass
Transport of macroalgae to deposition site vessel operations	Transport, freight, inland waterways, barge, diesel	7.10E+03	t*km	Market for transport, freight, inland waterways, barge, diesel (RER); adjusted by removing canal related sub-processes
Outflows				
Durably sequestered carbon dioxide	N/a	1.00E+00	t	N/a
Reclaimed concrete ballasting weights	Waste concrete	7.61E-01	m ³	Market for treatment of waste concrete, not reinforced (Europe without Switzerland); adapted by removing sorting and recycling related sub-processes)
Nitrogen	N/a	1.38E+01	kg	Nitrogen (water, ocean)
Carbon dioxide	N/a	4.92E+02	kg	Carbon dioxide, fossil (air)
Phosphorus	N/a	1.23E+00	kg	Phosphorus (water, ocean)

Appendix B: Process contribution analysis MCS (base-case) climate change

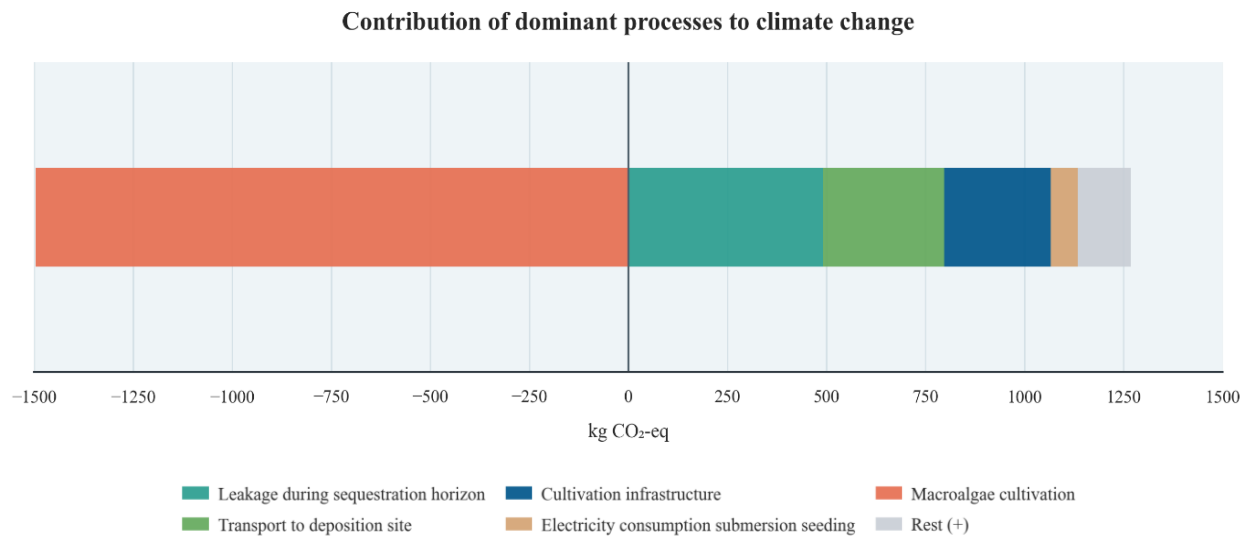


Figure B1: Absolute contributions of the main processes associated with the climate change impact of durably sequestering one tonne of CO₂ through MCS, assessed using the ReCiPe 2016 v1.03 midpoint (H) characterisation model. For more details see: [Base case LCIA results.xlsx](#)

Appendix C: Process contribution analysis MCS (base-case) endpoint indicators

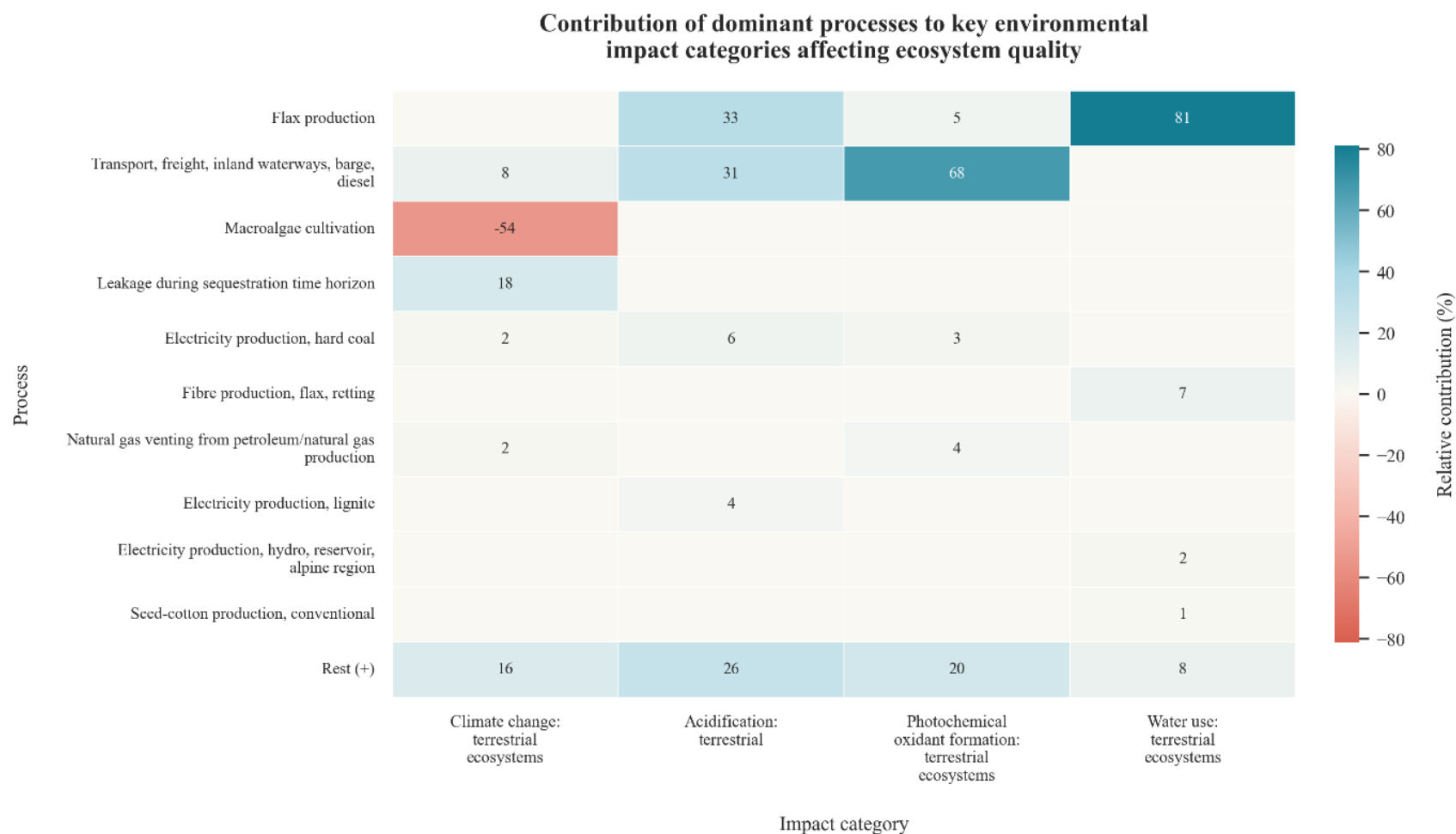


Figure C1: Relative contributions of dominant processes to the four largest contributing midpoint impact categories affecting total ecosystem quality (as can be derived from Figure 6), i.e. (i) climate change: terrestrial ecosystems, (ii) acidification: terrestrial, (iii) photochemical oxidant formation: terrestrial ecosystems, and (iv) water use: terrestrial ecosystems. Results are expressed as relative contributions within each impact category and were assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method. For more details see: [Base case LCIA results.xlsx](#)

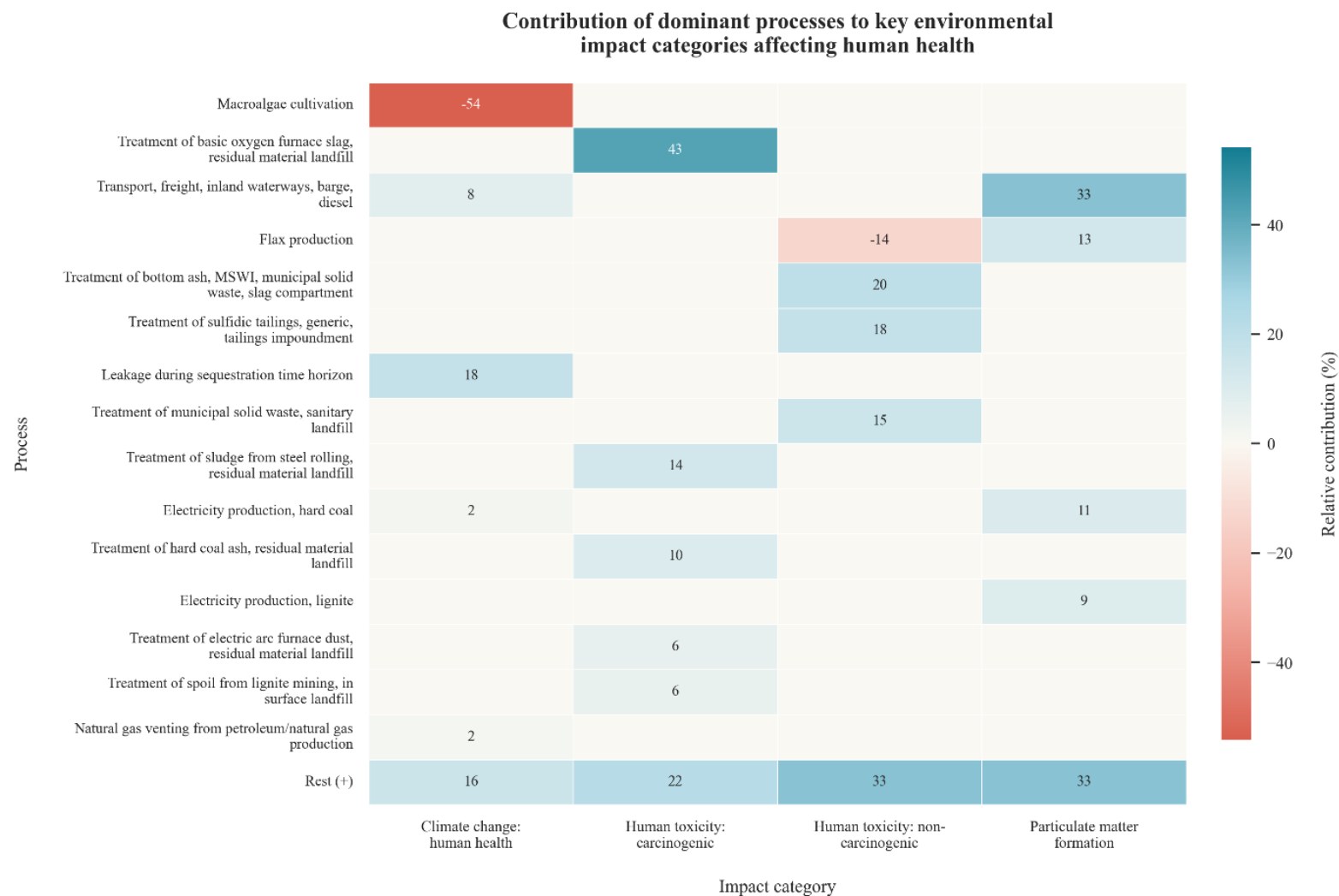


Figure C2: Relative contributions of dominant processes to the four largest contributing midpoint impact categories affecting total human health (as can be derived from Figure 6), i.e. (i) climate change: human health, (ii) human toxicity: carcinogenic, (iii) human toxicity, non-carcinogenic, and (iv) particulate matter formation. Results are expressed as relative contributions within each impact category and were assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method. For more details see: [Base case LCIA results.xlsx](#)

Contribution of dominant processes to key environmental impact categories affecting natural resource scarcity

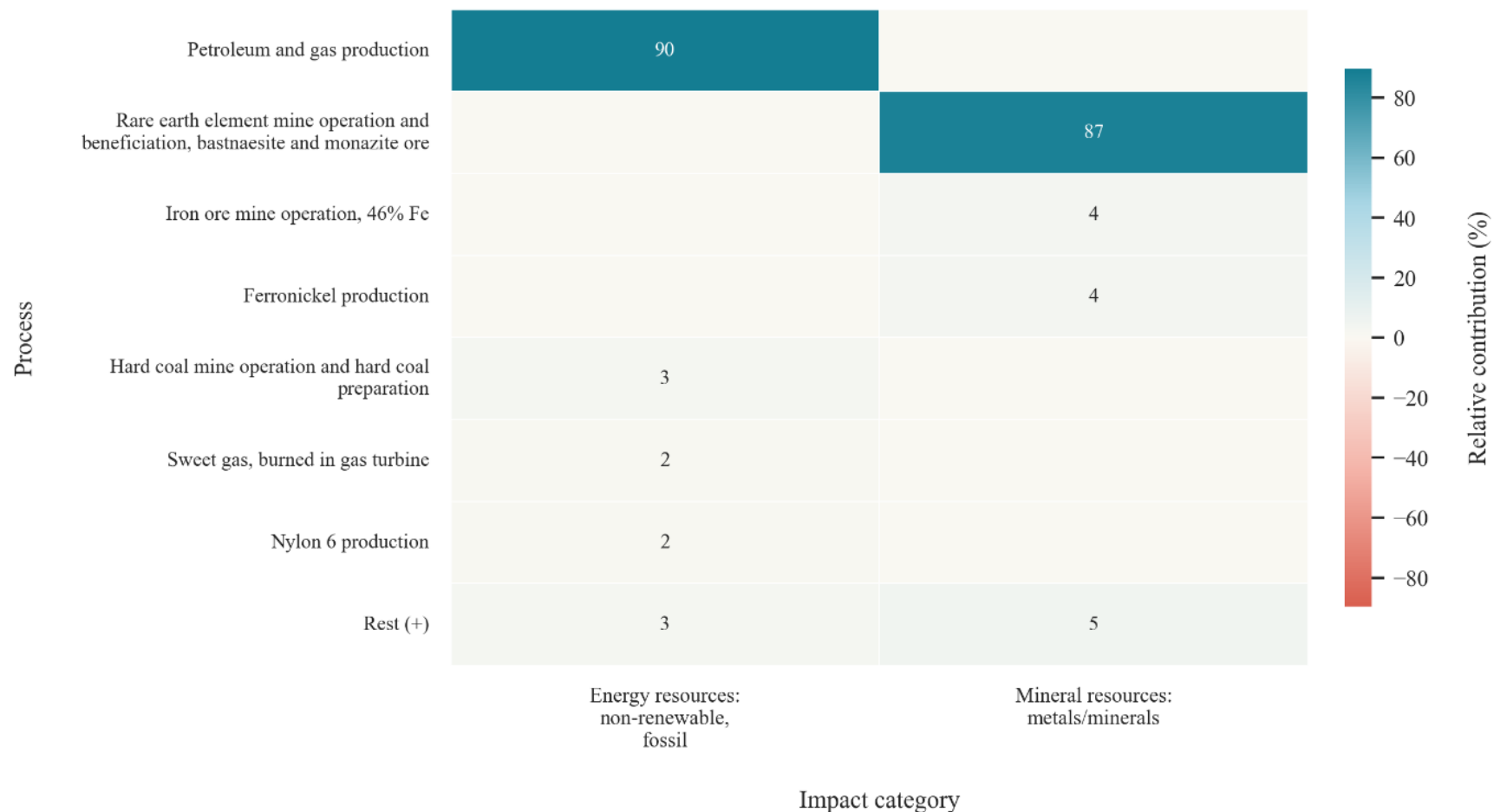


Figure C3: Relative contributions of dominant processes to both midpoint impact categories affecting total natural resource depletion, i.e., (i) energy resources: non-renewable, fossil, and (ii) mineral resources: metals/minerals. Results are expressed as relative contributions within each impact category and were assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method. For more details see: [Base case LCIA results.xlsx](#)

Contribution of dominant processes to endpoint impact categories



Figure C4: Relative contributions of dominant processes to endpoint indicators, i.e., ecosystem quality, human health, and natural resource depletion, assessed using the ReCiPe 2016 v1.03 endpoint (H) characterisation method. For more details see: [Base case LCIA results.xlsx](#)

Appendix D: Adaptations to variables for sensitivity analysis

Table D1: Overview of the LCI flows modified for the sensitivity analysis of continuous parameters, including: (i) distance to sink site, (ii) biomass yield, (iii) carbon/nutrient leakage. The values are presented for the 50%, 75%, base-case, 125%, and 150% scenarios and show the adaptations applied to the LCA model to reflect the changing conditions across the three parameters of interest. For calculations see: [Graphs scenario analyses.xlsx](#)

Parameter	Variable	Product system stage	50%	75%	Base-case	125%	150%
Distance to sink site	Market for transport, freight, inland waterways, barge, diesel (RER)	Offshore transportation and deep-sea deposition	3548.66 t*km	5322.99 t*km	7097.32 t*km	8871.65 t*km	10645.97 t*km
Biomass yield	Mature macroalgae	Cultivation at sea	500 kg	750 kg	1000 kg	1250 kg	1500 kg
	Carbon dioxide, fossil	Cultivation at sea	-72.60 kg	-108.89 kg	-145.19 kg	-181.49 kg	-217.79 kg
	Nitrogen	Cultivation at sea	-2.04 kg	-3.06 kg	-4.08 kg	-5.10 kg	-6.12 kg
	Phosphorus	Cultivation at sea	-0.18 kg	-0.27 kg	-0.36 kg	-0.45 kg	-0.54 kg
	Market for transport, freight, inland waterways, barge, diesel (RER)	Offshore transportation and deep-sea deposition	7150.15 t*km	7123.85 t*km	7097.55 t*km	7084.40 t*km	7071.25 t*km
Carbon/nutrient leakage	Harvested macroalgae	Offshore transportation and deep-sea deposition	8250 kg	9150 kg	10270 kg	11720 kg	13640 kg
	Carbon dioxide, fossil	Offshore transportation and deep-sea deposition	197.60 kg	328.90 kg	492.06 kg	702.12 kg	980.18 kg
	Nitrogen	Offshore transportation and deep-sea deposition	5.55 kg	9.24 kg	13.82 kg	19.72 kg	27.52 kg
	Phosphorus	Offshore transportation and deep-sea deposition	0.49 kg	0.82 kg	1.23 kg	1.75 kg	2.45 kg
	Waste concrete, not reinforced (Europe without Switzerland)	Offshore transportation and deep-sea deposition	1466.89 kg	1627.72 kg	1826.42 kg	2084.86 kg	2425.46 kg
	Market for transport, freight, inland waterways, barge, diesel (RER)	Offshore transportation and deep-sea deposition	5710.11 t*km	6330.74 t*km	7097.56 t*km	8094.94 t*km	9409.34 t*km

Table D2: Overview of LCA model and calculation set-up modifications applied in the discrete parameter sensitivity analysis. The table presents the differences between the base-case configuration and the corresponding alternatives, i.e., potential future scenarios (SSP1-M, SSP2-M, and SSP3-H; 2050), LCIA characterisation method (IMPACT World+), and main cultivation line material.

Parameter	Variable	Product system stage	Base-case	Sensitivity analysis
Time	Background LCI database	Complete LCA model	Ecoinvent v3.12 - cutoff	Ecoinvent v3.12 – cutoff – IMAGE SSP1-M 2050 (adapted using <i>premise</i>) Ecoinvent v3.12 – cutoff – IMAGE SSP2-M 2050 (adapted using <i>premise</i>) Ecoinvent v3.12 – cutoff – IMAGE SSP3-H 2050 (adapted using <i>premise</i>)
Characterisation family	Impact categories	N/a (concerns LCIA)	ReCiPe 2016 v1.03, midpoint (H) – Climate change ReCiPe 2016 v1.03, endpoint (H) – Ecosystem quality ReCiPe 2016 v1.03, endpoint (H) – Human health ReCiPe 2016 v1.03, endpoint (H) – Energy resources: non-renewable	IMPACT World+ v2.1 – Climate change IMPACT World+ v2.1 – Ecosystem quality IMPACT World+ v2.1 – Human health IMPACT World+ v2.1 – energy resources: non-renewable
Main cultivation line material	Market for fibre, flax (GLO) Market for fleece, polyethylene (GLO)	Cultivation at sea Cultivation at sea	7.64kg N/a	N/a 17.25kg

Table D3: Overview of the LCI of the line seeding stage (iii), specifying the differences in input/output required to produce sufficient collectors to provide one tonne of *S. latissima* biomass between the two line seeding alternatives, i.e., submersion and spray seeding, based on Thomas et al. (2021). For more details on how these values were derived see the detailed LCI data in Appendix A.

Inventory inputs and unit processes	Input/output type	Amount		Unit	Providing process, ecoinvent v.3.12 – cutoff background process, or biosphere 3 flows
		Submersion seeding	Spray seeding		
Line seeding					
Inflows					
Concentrated solution of healthy spores	N/a	1.00E+00	1.00E+00	l	Spore preparation
Aeration and stirring system	Electricity, medium voltage	2.04E+00	1.24E-00	kWh	Market group for electricity, medium voltage (RER)
Aquaria	Polymethyl methacrylate	2.91E-01	2.91E-01	kg	Market for polymethyl methacrylate (RER)
Production of aquaria	Injection moulding	2.91E-01	2.91E-01	t*km	Market for injection moulding (GLO)

Bucket	Extrusion, plastic pipes	1.13E-02	1.13E-02	kg	Market for extrusion, plastic pipes (GLO); adjusted by replacing plastic inputs with “Polyethylene, high density, granulate”
Collectors	Extrusion, plastic pipes	2.75E-01	2.75E-01	kg	Market for extrusion, plastic pipes (GLO); adjusted by replacing plastic inputs with “polyvinylidenchloride, granulate”
Autoclave	Electricity, medium voltage	N/a	4.67E-02	kWh	Market group for electricity, medium voltage (RER)
Lighting system	Electricity, medium voltage	9.19E+00	5.78E-00	kWh	Market group for electricity, medium voltage (RER)
Seawater filter	Fleece, polyethylene	3.02E-02	3.02E-02	kg	Market for fleece, polypropylene (GLO)
Seawater filter	Steel, chromium steel 18/8	3.36E-03	3.36E-03	kg	Market for steel, chromium steel 18/8 (GLO)
Seawater source and filter system	Electricity, medium voltage	2.62E-02	1.51E-02	kWh	Market group for electricity, medium voltage (RER)
Seeding line	Nylon 6	1.58E-01	1.58E-01	kg	Market for Nylon 6
Temperature control system	Electricity, medium voltage	7.08E+00	4.31E+00	kWh	Market group for electricity, medium voltage (RER)
Water heating system	Electricity, medium voltage	3.33E-01	3.33E-01	kWh	Market group for electricity, medium voltage (RER)
Nutrient mix (modified ES medium)	Sodium nitrate	9.74E-01	5.85E-01	g	Market for sodium nitrate (GLO)
	EDTA, ethylenediamine-tetraacetic acid	1.29E-02	7.75E-03	g	Market for EDTA, ethylene-diaminetetraacetic acid (GLO)
	Ammonium sulfate	1.77E-01	1.06E-01	g	Market for ammonium sulfate (RER)
	Boric acid, anhydrous, powder	1.13E-02	6.81E-03	g	Market for boric acid, anhydrous, powder (GLO)
	Manganese sulfate	1.21E-03	7.30E-04	g	Market for manganese sulfate (GLO)
	Zinc monosulfate	2.23E-04	1.34E-04	g	Market for zinc monosulfate (RER)
	Tap water	2.53E-01	1.52E-01	l	Market for tap water (Europe without Switzerland)
Outflows					
Collector (seeded line)	N/a	1.00E+00	1.00E+00	item	N/a
Solid waste	Municipal solid waste	6.11E-01	6.11E-01	kg	Market group for municipal solid waste (RER)
Wastewater	Market for wastewater, average	2.53E-04	1.52E-04	m ³	Market for wastewater, average (Europe without Switzerland)

Appendix E: Sensitivity analysis parameter selection

Table E1: Rationale for the selection of parameters included in the sensitivity analysis. The table summarises the relevance of each parameter to the environmental performance of MCS, associated sources of variability and uncertainty, and motivation for their inclusion in the assessment.

Parameter	Narrative/description
Parameters of interest (discrete)	
Time (present-day vs. SSP1-M 2050, SSP2-M 2050 & SSP3-H 2050)	Although the technological components required for MCS are relatively mature and the system could be deployed within a limited time span, various elements prevent this mCDR technology from large-scale implementation, e.g., legal barriers, high degrees of uncertainty regarding its environmental impacts, efficiency, and cost-effectiveness (NASEM, 2022). Nevertheless, given the projected CDR gap of 5.2 GtCO ₂ yr ⁻¹ by 2050 (Lamb et al., 2026), it is plausible that MCS may become part of the broader portfolio of mCDR technologies in the coming decades. As mCDR technologies are intended for deployment within future low-carbon societies, the environmental performance of MCS will strongly depend on the socio-economic and technological context in which it is implemented. In particular, future developments in electricity generation, transportation, and industrial production could substantially influence the environmental impacts associated with the system (Sacchi et al., 2022). Therefore, while the mature foreground processes are unlikely to differ substantially in future conditions, the background conditions under which it is implemented is likely to witness substantial changes. Hence, incorporating prospective LCI background data enables the assessment of how sensitive the environmental performance of MCS is to future conditions.
Characterisation family (ReCiPe vs. IMPACT world+)	As argued by Delval and colleagues (2025), the choice of characterisation model could influence the environmental outcomes of the LCA; different characterization models rely on varying assumptions, impact pathways, and characterization factors, potentially affecting both the magnitude and relative importance of impact categories. Therefore, sensitivity analysis with an alternative LCIA methodology should be performed to evaluate the sensitivity of the results to this modelling choice Delval et al. (2025).
Cultivation/sinking line material (polyethylene, fleece)	Due to the design of the ‘quick-sinking’ deposition concept adopted from Coleman et al. (2022), in which the macroalgae are sunk to the deep sea while still attached to the cultivation line, this specific component of the cultivation infrastructure has a relatively large material footprint, being only used for a single cultivation cycle. Moreover, while Coleman and colleagues (2022) advocate the use of natural longline materials, contemporary macroalgae cultivation systems commonly rely on polyethylene longlines (Thomas et al., 2021; Koesling et al., 2021; van Oirschot et al., 2017). Consequently, both the substantial environmental contribution and uncertainty surrounding the appropriate longline material warrant the assessment of the sensitivity of the system to alternative cultivation-line materials.
Line seeding method (spray-seeding vs. submersion seeding)	To obtain a seeded line ready for deployment at sea, the two most successful methods employed at existing macroalgae cultivation facilities, and the only ones for which reliable data could be acquired, are spray-seeding and submersion seeding, which differ in terms of their operational inputs and associated energy requirements (Thomas et al., 2021). Similarly, Slegers et al. (2021) argue that cultivation technologies and seedling breeding strategies could significantly influence the environmental performance of macroalgae systems. Moreover, while submersion seeding is traditionally applied, Boderskov et al. (2021) also highlight operational differences between both methods. Therefore, evaluating the sensitivity of the MCS system to alternative seeding technologies is considered worthwhile.
Primary parameters of interest (continuous) (50-150, with 25% increments)	
Carbon/nutrient leakage	Contribution analysis revealed that leakage of sequestered carbon and nutrients before the end of the sequestration time horizon constitutes one the largest environmental hotspots within the MCS system. Moreover, although leakage estimates from Baker et al. (2022) were adopted in the present study, long-term sequestration pathways remain uncertain and geographically dependent (Siegel et al., 2021; Passarona et al., 2023). Therefore, as argued by Delval et al. (2025), the sensitivity of mCDR systems

	to storage security and carbon leakage should be explicitly evaluated through sensitivity analysis, particularly for approaches where reversibility of stored carbon remains uncertain.
Biomass yield	In practice, macroalgae biomass yields are highly uncertain, mostly due to variations in conditions from year to year, due to possible risk factors such as disease or storms, and variability resulting from slight changes in technical protocols, for instance in the hatchery (Thomas et al., 2021; Khan et al., 2024). This is reflected by Zhang et al. (2022), who investigated nine <i>S. latissima</i> cultivation sites and reported a yield difference of +140% and -85% compared to the average between all macroalgae farms. Additionally, factors such as harvesting depth and harvesting month could further influence biomass productivity, and future yields are expected to increase due to changes in areas such as seeding techniques and cultivation infrastructure (Koesling et al., 2021; Slegers et al., 2021). As biomass yield is directly linked to the amount of material and energy inputs required to achieve the FU, it may substantially influence the overall environmental performance of the MCS system and is therefore relevant to assess through sensitivity analysis.
Distance to sink-site	The contribution analysis revealed that transportation of macroalgae biomass to the sink-site presents a significant environmental hotspot, which aligns with the findings of Slegers et al. (2021) and Coleman et al. (2022), prompting the former to also include transportation distance in their sensitivity analysis. At the same time, the distance to the nearest sink-site is highly geography dependent presenting an area of uncertainty, which causes impacts to differ between cultivation sites. Hence, assessing the impact of variations in this parameter could provide valuable insights regarding where to apply MCS.

Appendix F: Comparison of MCS performance under different future background conditions

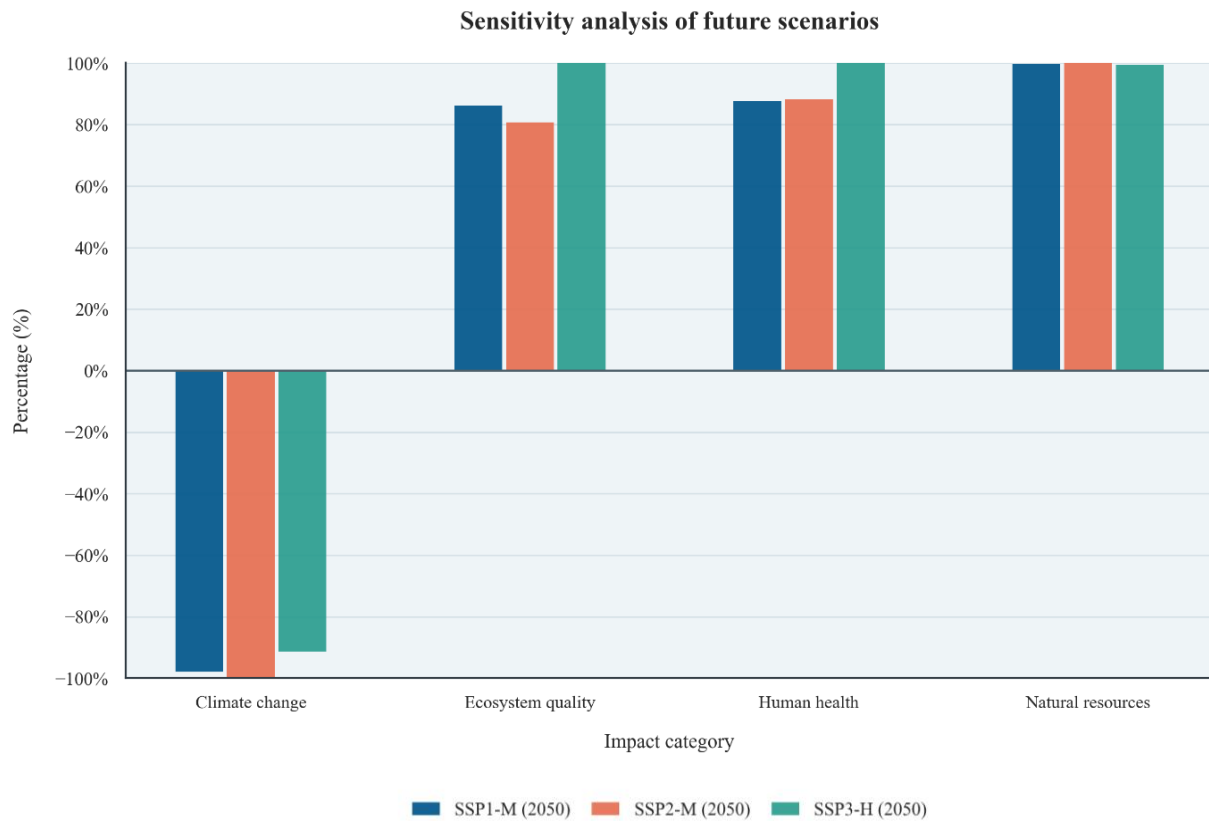


Figure F1: Relative performance of the MCS system under different future background conditions for the climate change and endpoint impact categories. Results are normalised to the largest impact within each impact category and assessed using the ReCiPe v.1.03 (H) characterisation methods.

As presented in the figure above, only minor differences can be observed between the environmental performance of MCS due to variations in socio-economic pathways by 2050. Moreover, while the results for ecosystem quality and human health show a larger extent of sensitivity, the overall outcomes change by <20%. Notably, SSP2-M results in slightly favorable climate change impacts compared to SSP1-M. Further analysis revealed that this can be traced back a reduction of 72.0% in electricity consumption impact during the line seeding stage, one of the main contributors (Chapter 3.1), between the two pathways; showing that the energy mix used in SSP2-M performs favorably compared to the one in SSP1-M by 2050.