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Questions raised by sinking seaweed: A Life Cycle Assessment of Macroalgae Cultivation and Sinking for Carbon Dioxide Removal

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Abstract

Purpose:

Among the portfolio of emerging marine carbon dioxide removal approaches, macroalgae cultivation and sinking (MCS) has attracted growing scientific, commercial, and policy interest; yet its environmental implications remain poorly understood. This study presents the first comprehensive cradle-to-grave life cycle assessment of the 'grow nearshore, sink offshore' MCS strategy with *Saccharina latissima* in Northern Europe. Beyond climate mitigation potential, it identifies environmental trade-offs and hotspots across three areas of protection, and evaluates key parameters influencing environmental performance.

Methods:

An attributional cradle-to-grave LCA was conducted, covering the complete MCS product system from onshore hatchery operations and nearshore cultivation to offshore transportation and deep-sea deposition. A functional unit of one tonne of atmospheric carbon dioxide (CO_2) stored for > 100 years via the intentional deep-sea deposition of cultivated macroalgae below the deep-ocean carbon sequestration horizon (> 1 000 m) was adopted. Using ReCiPe 2016, environmental impacts were assessed across climate change, ecosystem quality, human health, and natural resource scarcity, accounting for carbon (C) and nutrient uptake and leakage. Contribution analyses were performed to identify environmental hotspots, while the influence of seven key parameters (biomass yield, transportation distance, C/nutrient leakage, line seeding method, longline material, future background conditions, and LCIA method family) were examined via sensitivity analyses.

Results and discussion:

Under the modelled conditions, MCS achieves a net climate benefit of 227 kg CO_2-eq/t of CO_2 stored. This is, however, accompanied by net adverse 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). Offshore transportation, C/nutrient leakage, cultivation infrastructure, and hatchery electricity consumption emerge as the main environmental hotspots. Climate change impacts are the most susceptible to sensitivity, with the largest effects caused by biomass yield and sequestration durability variability, with a 50% reduction in yield or increase in C/nutrient leakage, shifting MCS from net carbon removal technology to net-emitter. Alternative longline materials, future background conditions, and LCIA method families also each substantially affect the environmental outcomes.

Conclusions:

Although MCS could potentially achieve net carbon removal under the assumed conditions, sequestration efficiency is limited (23%), and its broader environmental trade-offs and remaining uncertainties raise concerns regarding large-scale deployment. Improving biomass yields, reducing transportation, optimising cultivation and deposition infrastructure, and adopting energy-efficient, renewably powered hatchery operations could markedly enhance environmental performance. Nevertheless, further research is essential to quantify local post-deposition C/nutrient pathways and develop marine-specific impact assessment methods before large-scale implementation can be justified.

1. Introduction

Over the last decades, anthropogenic greenhouse gas emissions have been the main driver of climate change (Yoro & Daramola, 2020; IPCC, 2023). While rapid and massive emission reductions remain essential, it is increasingly presumed that carbon dioxide removal (CDR) will be a necessary complement to speed climate mitigation, compensate residual emissions from hard-to-abate sectors, and/or reverse historical emissions (IPCC, 2022; Gidden et al., 2024).Within the broader portfolio of CDR approaches, oceans are increasingly recognised for their potential to contribute to long-term carbon sequestration through marine carbon dioxide removal (mCDR) (IPCC, 2023; Jacobs et al., 2023; De Pryck & Boettcher, 2024). Several characteristics could make mCDR an attractive complement to terrestrial CDR approaches, including: (i) the scalability potential of effective solutions, (ii) the ocean's natural sequestration capacity, and (iii) research suggesting that some mCDR pathways could offer durability for carbon removal for more than millennia (Hendriks et al., 2020; Ocean Visions, 2022; Mertens et al., 2024).

One mCDR method that has received considerable attention in recent years is macroalgae cultivation and sinking (MCS). MCS captures carbon dissolved in seawater into biomass, causing the ocean to uptake atmospheric CO_2 to restore equilibrium. The macroalgae is then harvested and intentionally sunk to the deep-ocean seafloor, thereby, theoretically, preventing that carbon from re-entering the upper-ocean and ultimately the atmosphere for prolonged periods of time (NASEM, 2022; Sten et al., 2026). Estimates suggest that more than half of the carbon transferred to the deep ocean remains stored for at least 400 years across most oceanic basins, although this sequestration potential is spatially variable (Siegel et al., 2021; Baker et al., 2022). To facilitate MCS deployment, Alevizos and Barillé (2023) advocate a 'grow nearshore, sink offshore' (GNSO) strategy as an alternative to macroalgae open-ocean mariculture and sinking (MOS) (Wu et al., 2023; Sæther et al., 2024). Major macroalgae-producing countries encompass extensive open-ocean areas suitable exclusively for biomass sinking and not cultivation. Consequently, MOS may exclude significant deployment opportunities, while the proposed strategy enables cultivation under favourable nearshore conditions.

Despite growing interest in MCS, considerable uncertainties remain that could affect its mitigation effectiveness and environmental implications. Particularly, whereas carbon fixation of macroalgae has received notable research attention, 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 (Bauer et al., 2026). Uncertainties also concern the effect of operational and design choices, including transportation distances, cultivation infrastructure, and site-dependent factors such as yield (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 (Balaji, 2025; CDR.fyi, 2026), calls for additional assessments of MCS's effectiveness and robust evaluations of the environmental impacts are increasing (Boyd et al., 2022; Hurd et al., 2022; Ricart et al., 2022), with some even urging for an immediate moratorium on macroalgae sinking (Chopin et al., 2024).

A growing body of life cycle assessment (LCA) literature has examined macroalgae-based supply chains, notably for 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; Ayala et al., 2023; Li et al., 2023). In contrast, only two cradle-to-grave LCA studies specifically addressing MCS have been conducted to date (N'Yeurt et al., 2012; Coleman et al., 2022). While both studies suggest that MCS could lead to net carbon removal, they solely investigate the contribution of their product system to climate change, overlooking broader environmental implications and potential trade-offs. Moreover, neither study conduct sensitivity nor uncertainty analysis, despite the considerable uncertainties surrounding this approach (Delval et al., 2025).

This study therefore assesses the environmental performance and mitigation potential of MCS through a cradle-to-grave LCA of a GNSO system in Northern Europe, a region considered particularly suitable for MCS deployment (Alevizos & Barillé, 2023). The LCA spans the complete MCS supply chain, from the onshore *Saccharina latissima* (sugar kelp) hatchery through offshore transportation and deep-sea deposition. *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 (Dhakal et al., 2024). Going beyond previous MCS studies, this research evaluates impacts of three endpoint indicators: ecosystem quality, human health, and natural resource scarcity, alongside climate change at midpoint-level using ReCiPe 2016 and identifies environmental hotspots and trade-offs throughout the product system. The model explicitly accounts for biochemical flows by incorporating carbon (C), nitrogen (N), and phosphorus (P) uptake associated with biomass growth, thereby capturing their contributions to environmental impacts, including climate change and marine eutrophication (Howarth & Marino, 2006; Thomas et al., 2021; UNEP, 2026). Furthermore, the sensitivity of environmental performance to key parameters is assessed to examine how sensitive the results are to uncertain parameters and modelling choices. Ultimately, these findings contribute to ongoing debates regarding the environmental impact, risk, and feasibility of MCS, offering evidence to guide more informed decision-making about its role within the emerging portfolio of mCDR strategies.

2. Methods

The LCA is structured around the four ISO phases (goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Guinée et al., 2002; ISO, 2006)) and includes contribution and sensitivity analyses to assess environmental hotspots and the influence of key parameters on the product system's environmental outcomes. We also followed the recommendations in Delval et al. (2025) on conducting LCAs for mCDR approaches.

2.1 Goal and Scope definition

This attributional LCA seeks to evaluate the net CDR potential of the GNSO MCS strategy, as well as its broader environmental performance and key sources of uncertainty. The study includes both long-term C sequestration and local nutrient bioremediation. We assessed the system's impacts on climate change and three areas of protection (AoPs): ecosystem quality, human health, and natural resource scarcity. The study further identifies the main environmental impact drivers and, given the substantial uncertainty surrounding this technology, we also performed sensitivity analyses to investigate the influence of key parameters on MCS's performance.

The cradle-to-grave system boundary includes all relevant upstream and operational processes required for biomass production and transport, as well as the final deep-sea deposition for C sequestration and relevant end-of-life (EoL) processes.

The *temporal coverage* reflects contemporary conditions, i.e., both the adopted foreground and background LCI data represents the period from 2020–2025. The *geographical coverage* is Northern Europe, a region identified as highly suitable for MCS deployment based on factors including bathymetry, distance to port infrastructure, nutrient availability, and spatial conflicts (Alevizos & Barillé, 2023). We chose a functional unit of one tonne of atmospheric CO_2 stored for at least 100 years via the intentional deep-sea deposition of cultivated macroalgae below the deep-ocean carbon sequestration horizon (> 1,000 m). This storage duration is consistent with currently applied thresholds for durable C sequestration (Smith et al., 2024), while the C sequestration horizon depth is based on Coleman et al. (2022).

2.2 Description of the MCS product system and LCI analysis

The MCS product system assessed in this study represents one annual growth cycle, consisting of six 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). These stages are distributed across three locations: an onshore hatchery facility, a nearshore cultivation site, and a deep-sea deposition site beyond the continental shelf (Fig. 2). The LCI data are, to the extent possible, derived from the assessments of macroalgae cultivation under Northern European conditions of Thomas et al. (2021) and Nilsson et al. (2023), and extended with biomass transport and deep-sea deposition based on Coleman et al. (2022) and own calculations. Background data were sourced from the ecoinvent v3.12

cutoff database (Wernet et al., 2016). Unless stated otherwise, EoL treatment of material inputs was modelled using ecoinvent process ‘market group for municipal solid waste | municipal solid waste | Cutoff, U - RER’. A summarised LCI is presented in Table 1, while the supplementary information (SI, Section 1) provides a complete inventory, underlying calculations, and modelling assumptions. All LCI data were compiled and analysed using *Activity Browser* using the *Brightway2* framework (v2.4.6).

Table 1

Summary of foreground inventory inflows (↑) and outflows (↓) for each product system stage, specifying aggregated amounts required to durably sequester one tonne of CO_2. The complete LCI, including linked ecoinvent v3.12 background processes, biosphere 3 flows, and more detailed inventory flows is provided in the supplementary information (SI, Section 1), 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	Spool (seeded lines) (↑)	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	tkm	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	tkm
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

Inventory flows and unit processes	Amount	Unit	Inventory flows and unit processes	Amount	Unit
Collection of fertile sporophytes (i)			**Cultivation at sea (iv)**		
Electricity, medium voltage (↑)	1.87E + 01	kWh	Diesel barge transport (↑)	1.27E + 00	tkm
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	tkm
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
Spool (seeded lines) (↓)	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

Collection of fertile sporophytes

Local fertile *S. latissima* are collected at the cultivation site (Nilsson et al., 2022). Mature individuals bearing reproductive tissues are manually selected during routine harvesting activities and transported to the land-based hatchery facility by barge and lorry (Nilsson et al., 2022).

Spore preparation

Spore preparation encompasses the processes required to obtain a concentrated solution of healthy *S. Latissima* spores from parent specimens. Spore development is induced by removing the basal portion of the blade (meristem), after which the remaining tissue is cleaned and maintained for 6 to 10 weeks in a controlled flow-through system, with regulated temperature and lighting, suing filtered, aerated, and stirred seawater (Thomas et al., 2021), before being collected.

Line seeding

Spools are placed in a concentrated spore solution to obtain seeded lines (Boderskov et al., 2021; Thomas et al., 2021). The collectors are subsequently transferred to controlled aquaria, where the organisms develop into juvenile kelp over 3 to 5 weeks under regulated temperature and lighting conditions and the addition of a modified ES (Enriched Seawater) medium nutrient mix (Ayala et al., 2023).

Cultivation at sea

The seeded lines are unwound from the spools and attached to the longlines of the cultivation infrastructure. We also account here for the installation, maintenance, and decommissioning of this cultivation infrastructure, routine monitoring activities, and associated transportation via barge (Thomas et al., 2021; Nilsson et al., 2023; Slegers et al., 2021). During cultivation, nutrient uptake from the water though bioremediation and C fixation through photosynthesis occur. Different from the rest of the cultivation infrastructure, the longlines, which are made from flax fiber, are also a part of the sinking mechanism and are sunk together with the attached biomass after one year during the final product system stage (Coleman et al., 2022).

Harvesting of biomass

Following cultivation from early winter to early summer, the longlines bearing mature *S. latissima* biomass are retrieved using a vessel (Thomas et al., 2021). Fertile individuals are simultaneously collected for a new cultivation cycle. As both mature biomass and fertile sporophytes remain within the system boundary, no allocation is required (Guinée et al., 2002).

Offshore transportation and deep-sea deposition

For deep-sea deposition, recycled concrete weights are attached to the longlines (Coleman et al., 2022). The lines are subsequently towed 582 km to the deposition site, beyond the continental shelf (see SI, section 2 for calculations of the transportation distance). After removal of the flotation buoys, the C-rich biomass and longlines are assumed to sink below the C sequestration horizon (> 1 000 m) and are deposited on the deep seafloor (Coleman et al., 2022). Similar to Wu et al. (2023), who used an Earth system model to assess the carbon removal potential of MCS, we assume harvested biomass could be engineered to sink in a rapid and efficient manner with no remineralisation along the way. For the North Atlantic basin, which is the best available a proxy for modelling MCS in Northern Europe, it was estimated that 33% of C 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 are assumed for N and P.

2.3 Life Cycle Impact Assessment

ReCiPe 2016 v1.03 (H) was selected for its comprehensive coverage of environmental impact pathways, particularly marine-related impacts and N flows. An endpoint-oriented approach is employed, which translates midpoint indicators into endpoint damages, aggregated into AoPs (Hauschild and Huijbregts,

2015). Climate change is analysed separately to assess the system's C removal performance and climate impacts.

2.4 Sensitivity analysis

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, identified through a contribution analysis or previous research. Seven parameters were included: transportation distance to the sink site, biomass yield, C and nutrient leakage before the sequestration time horizon, future background conditions, line seeding technique, main cultivation line material, and LCIA characterisation method. Selection rationales and model adaptations are provided in SI Sections 3 and 4.

Two complementary one-at-a-time sensitivity analyses were adopted. Continuous parameters (i.e., transport distance, biomass yield, and carbon/nutrient leakage) were individually varied between 50% and 150% of their base-case values in 25% increments. 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+ (v2.1) LCIA method family instead of ReCiPe 2016.

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 adapts ecoinvent background processes using integrated assessment model (IAM) projections. Three shared socioeconomic pathways (SSPs) for the year 2050 were considered, spanning a best-case/worst-case 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) (Riahi et al., 2017). The IAM IMAGE was selected for its detailed representation of energy, land-use, and environmental systems interactions and sectoral coverage (Stehfest et al., 2014).

3. Results

3.1 Evaluating the climate change mitigation potential of MCS

The MCS system achieves a net carbon removal of 227 kg CO_2-eq per tonne of atmospheric CO_2 stored for at least 100 years. This results from a net uptake of 1 188 kg CO_2-eq during the cultivation stage and combined net emissions of 961 kg CO_2-eq from the remaining product system stages (Fig. 3). At the product system level, the total gross uptake of 1 496 kg CO_2-eq is mostly offset by gross GHG emissions of 1 269 kg CO_2-eq (see SI, Section 5 for gross climate change impacts and process-level contributions).

Offshore transportation and deep-sea deposition constitutes the largest source of GHG emissions, with 813 kg CO_2-eq emitted (i.e., 64% of the gross GHG emissions). Process-level contribution analysis indicates that this is primarily driven by C leakage occurring before the end of the 100-year time horizon and transportation of the biomass to the deposition site, respectively emitting 492 kg CO_2-Eq. (39%) and 305 kg CO_2-Eq. (24%). Line seeding represents the second-largest net emitting stage, contributing 113 kg CO2-Eq. (9%), primarily due to electricity consumption during hatchery operations (68 kg CO_2-eq emissions; 5%). On the other hand, the combined emissions from fertile sporophyte collection, spore preparation, and biomass harvesting are relatively minor, amounting to 35 kg CO_2-Eq. (3%). Although the net climate benefit can be traced back to cultivation, process-level analysis also reveals substantial GHG emissions associated with the cultivation infrastructure (269 kg CO_2-eq; 21% of gross emissions).

Overall, the results indicate durable net carbon removal under the modelled assumptions, while identifying carbon leakage and offshore transportation as major determinants of the system's climate change performance and sequestration potential.

3.2 Environmental impacts of MCS beyond climate change

Beyond climate change, the MCS system shows per t of CO_2 stored net impacts of 2.03 x 10^{-6} species.yr on ecosystem quality, net human health impacts of 1.40 x 10^{-3} DALYs, and additional cost due to resource depletion of 84 USD 2013 (Fig. 4). Ecosystem quality is most severely affected by terrestrial acidification (32% of gross ecosystem damage), photochemical oxidant formation (24%), and water use (21%) (Fig. 4a). Terrestrial acidification is primarily caused by flax fibre production for the cultivation infrastructure (33%) and biomass transportation to the deposition site (31%) (SI, Section 6, Fig. 1). Similar trends emerge for the other two impact categories, with photochemical oxidant formation caused by offshore transport (68%) and water use by flax fibre production and retting (88%). Conversely, terrestrial ecosystems benefit from the product system's effects against climate change, whereas marine ecosystems benefit from effects against marine eutrophication, reducing gross ecosystem damage by -6.84x10^{-7} species.yr (25%).

Human health impacts are primarily driven by particulate matter formation (52% of gross human health damage), followed by non-carcinogenic and carcinogenic human toxicity (22% and 20%) (Fig. 4b). Whereas the former stems primarily from offshore transportation (33%) and electricity generation from lignite and hard coal (20%), the latter two impact categories are largely affected by various waste treatment processes (SI, Section 6, Fig. 2). Similar to ecosystem quality, climate change impacts mitigate overall human health damage by -2.11x10^{-4} DALYs (13%). Lastly, for resource scarcity (Fig. 4c), non-renewable energy resource use is the primary driver and is primarily linked to petroleum and gas production (90%). Material resource depletion has a smaller impact, which is for 87% related to rare earth element extraction and treatment (SI, Section 6, Fig. 3).

When analysing at the stage level, offshore transportation and deposition is the primary driver across all three AoPs, constituting 56% of ecosystem quality impact, 73% of human health, and 49% of resource

scarcity (Fig. 5). While cultivation has a net-mitigating effect on ecosystem quality and human health, it continues to contribute to resource depletion. Line seeding represents another notable contribution, particularly to human health (17%), whereas the remaining stages contribute only marginally (between 2% for resource scarcity and 4% for human health). Endpoint level process contribution analyses yield similar results as discussed above (SI, section 6, Fig. 4).

3.3 Assessing the sensitivity of MCS performance

To assess the robustness of the findings and the performance of the MCS system under different scenarios, the following section examines variations in three continuous variables. Subsequently, Section 3.3.2 evaluates the effects of varying four discrete parameters relative to the base-case.

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

Figure 6 illustrates the sensitivity of climate change and endpoint impacts to variations in transportation distance, biomass yield, and C/nutrient leakage. Overall, climate change is the most sensitive impact category, with a 50% reduction in biomass yield increasing climate change impacts by 198% (Fig. 6a). Conversely, a 50% increase in biomass yield reduces climate change impact by 66%, resulting in net emissions of -378 kg CO_2-eq/t of CO_2 stored. This highlights an asymmetric effect, i.e., the overall climate change impact is disproportionately influenced by poorer cultivation performance. Changes in transportation distance and C/nutrient leakage have smaller effects. However, a 50% increase in leakage raises climate change impacts by 110%, shifting MCS from a negative emission technology to a net-emitter (24 kg CO_2-eq/ t of CO_2 stored). Reducing the transportation distance by 50% reduces GHG emissions by 67%, which is comparable to halving C/nutrient leakage. This highlights the importance of organising cultivation operations within close proximity to suitable deposition sites.

Similar trends are observed for ecosystem quality, human health, and natural resource scarcity (Fig. 6b-d), with impacts increasing under lower biomass yields, greater transportation distances, and higher C/nutrient leakage rates. Across all impact categories, reducing biomass yield leads to the most pronounced negative effect, whereas the improvements associated with the respective best-case scenarios are more comparable across the three parameters. Nevertheless, the magnitude of these responses is considerably smaller than the ones observed for climate change. For example, the largest change in the results for natural resource scarcity is associated with a 50% reduction in biomass yield, increasing impacts by 52% (compared to 198% for climate change). Similarly, halving transportation distance, which has the largest positive effect, reduces natural resource scarcity by 23%, whereas climate change impacts decrease by 67% under this scenario.

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

Figure 7 shows the effects on results of projecting the background processes to future conditions, adopting the emerging spray-seeding technique instead of submersion seeding, changing the main cultivation line material to more widely used polyethylene, and applying an alternative LCIA method family. Changes to the temporal scope and main cultivation line material exhibit the largest influence on both the climate change and endpoint impacts (except for human health where this is caused by the LCIA method family). Under the SSP2-M background system for 2050, the net climate change mitigation potential nearly doubles, reaching − 444 kg CO_2-eq/ t of CO_2 stored. Conversely, adopting polyethylene cultivation lines turns MCS into a substantial net-emitting technology (349 kg CO_2-eq/ t of CO_2 stored). For the endpoint impacts, similar patterns can be observed, with a reduction of 59%, 49%, and 24% for ecosystem quality, human health, and natural resource scarcity respectively under the SSP2-M 2050 scenario, and an increase of 60%, 75%, and 167% when using polyethylene cultivation lines. Only minor differences are observed between SSP1-M, SSP2-M, and SSP3-H (< 20%; SI, Section **7**).

Contrastingly, adopting the spray-seeding technique results in relatively minor improvements, reducing climate change, ecosystem quality, human health, and natural resource scarcity by 11%, 6%, 4%, and 2% respectively. Using IMPACT World+ instead of ReCiPe 2016 produces comparable outcomes for climate change but reduces human health impacts by 60%. This difference is largely attributable to variations in characterisation factors for elementary flows between LCIA method families.

As ecosystem quality and natural resource scarcity are expressed in different units under ReCiPe 2016 and IMPACT World+, their absolute outcomes cannot be directly compared. Instead, clear differences between the two methods can be observed through the relative net contributions of individual product system stages (Fig. 8). Most notably, using ReCiPe leads to substantial benefits for ecosystem quality and human health due to C and N uptake during macroalgae cultivation, resulting in a net benefit from this stage. In contrast, adopting IMPACT World+ results in considerably smaller benefits for ecosystem quality and no benefits for human health, resulting in a net impact from this stage. For non-renewable energy resource scarcity the impacts associated with line seeding represent a higher share of the overall impact when using IMPACT World+ than ReCiPe, while offshore transportation and deep-sea deposition represents a smaller share of the overall impact. This arises from differences in the elementary flows characterised in each LCIA method family and different characterisation factor values for a same substance, which particularly affect the energy-intensive line-seeding stage.

4. Discussion

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

The presented LCA suggests that MCS can be considered a CDR approach under the evaluated system configuration by achieving a net removal of 227 kg CO_2-eq/t of CO_2 stored. This aligns with previously conducted LCA studies on MCS (N'Yeurt et al., 2012; Coleman et al., 2022). Hence, large-scale

implementation of MCS could, theoretically, contribute to narrowing the projected CDR gap, estimated by Lamb et al (2026) to be of 5.2 $GtCO_2yr^{-1}$ by 2050. Nevertheless, the estimated sequestration efficiency remains limited (less than 23%), which indicates that only a small fraction of the C fixed by *S. latissima* contributes to durable net CDR. This highlights the need for efforts to improve the system's climate change performance before considering its large-scale deployment. To that end, we find that the main hotspots contributing to climate change impacts are offshore transportation, C/nutrient leakage, the cultivation infrastructure, and hatchery electricity consumption. Therefore, lower-emission transportation, a less C-intensive cultivation infrastructure, and improved hatchery energy efficiency and supply, represent important opportunities to enhance the climate mitigation potential of MCS.

Assessing the MCS system across a broader range of impact categories, however, reveals a more nuanced picture. In contrast to climate change, the environmental benefits associated with C sequestration and bioremediation are insufficient to offset the burdens generated by MCS across the three AoPs. Consequently, the system result in a net adverse impact in all three categories: 2.03×10^{-6} species.yr for ecosystem quality, 1.40×10^{-3} DALYs for human health, and 84 USD 2013 for natural resource scarcity. These findings highlight the importance of broader environmental assessments beyond the climate change impact category for the studied mCDR approach to avoid burden-shifting, as already previously argued in the scientific literature (Boyd et al., 2022; Hurd et al., 2022; Rickart et al., 2022; Chopin et al., 2024; Delval et al., 2025).

Across the three AoPs, the environmental performance of MCS is shaped by distinct environmental mechanisms. Ecosystem quality is primarily affected by terrestrial acidification, water consumption, and photochemical oxidant formation, which are largely attributable to flax fibre production and offshore transportation. Human health impacts are mainly driven by particulate matter formation and (non-) carcinogenic toxicity linked to electricity generation, offshore transportation, and waste treatment. Natural resource scarcity is primarily influenced by non-renewable energy use driven by the extraction of petroleum and natural gas required for offshore transportation and plastic-based infrastructure components. Consequently, while broad improvements could be achieved by addressing overlapping hotspots such as offshore transportation, improving the overall performance of MCS would also require the development of a range of diversified and targeted strategies, such as reducing fossil-based material use for lowering natural resource scarcity as well as limiting the use of flax to improve ecosystem quality (as it is heavily linked to terrestrial acidification (33%) and water consumption (88%) impacts). To the author's knowledge, this represents the first work to identify the driving environmental mechanisms and underlying hotspots across multiple AoPs for MCS, providing support to develop targeted interventions tailored to specific environmental objectives.

4.2 Implications of key uncertainties on MCS implementation

The sensitivity analyses reveal that, among the environmental impacts assessed, climate change is the most sensitive to parameter variability, ranging from + 198% to -67% relative to the base-case. Therefore,

caution is warranted when drawing conclusions regarding the climate mitigation potential of MCS, particularly given its limited estimated sequestration efficiency. Our findings further demonstrate that the viability of MCS is highly dependent on achieving consistently high biomass yields. A 50% yield reduction turns MCS into a substantial net emitter (+ 222 kg CO_2-eq). Similar concerns have been raised by the National Academies of Sciences, Engineering, and Medicine (NASEM) (2022), who identified biomass losses during cultivation, harvesting, transport, and deep-sea conveyance as one of the principal constraints on the scalability of MCS, owing to increased spatial requirements and operational costs. The present study extends these findings by highlighting that this parameter is not only a determinant of technical and economic feasibility, but also of environmental viability. Since yields depend strongly on local conditions, site selection is essential (Khan et al., 2024). This supports the GNSO strategy, which is expected to provide more reliable yields through greater nutrient availability and reduced storm exposure (Alvizos & Barillé, 2023).

Most critically, sequestration durability represents the highest uncertainty of the MCS system. Although increases in C and nutrient leakage have a smaller influence on climate change and endpoint impacts than biomass yield losses, a 50% increase nevertheless turns MCS into a net-emitter. This finding is particularly relevant given the limited understanding of long-term particulate and dissolved organic carbon sequestration pathways, and recent year-long *in-situ* measurements 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 et al. (2026) note that some C likely enters 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. Together with the substantial spatial variability in sequestration potential reported by Siegel et al. (2021), our results emphasise the need for improved understanding of local post-deposition C cycling.

Unlike biomass yield and sequestration durability, which depends on biological and oceanographic processes, transportation requirements represent a key parameter that can be more directly controlled through operational design. Therefore, limiting the distance between cultivation and deposition sites may offer one of the most readily implementable improvement strategies. Our results show that halving transport distance would increase MCS' climate mitigation potential by 67%. Consequently, proximity to suitable deep-sea deposition sites should be a key site-selection criterion. Although Alevizos and Barillé (2023) consider port proximity in their spatial feasibility assessment, their maximum accepted one-way distance of 1 000 km may be insufficiently restrictive. Our results suggest that increasing the transportation distance by 50% (i.e., resulting in a total distance of 874 km) reduces the sequestration efficiency to only 7%. Future spatial suitability assessments should therefore consider this parameter more critically.

The discrete parameters sensitivity analysis further identifies future background conditions, longline material, and LCIA method family as important determinants of environmental performance. Projecting background processes to possible 2050 conditions substantially improve climate change and endpoint results, with minor differences between the different socioeconomic pathways evaluated. Replacing flax

cultivation lines with polyethylene, a material used in previous aquaculture studies (Koesling et al., 2021; Thomas et al., 2021), could more than double impacts on natural resources scarcity and substantially increase GHG emissions (+ 349 kg CO_2-eq). This results from the deposition method used in the MCS system, in which cultivation lines are used for a single cycle before being sunk alongside the biomass (Coleman et al., 2022) thereby requiring large quantities of material. Although reducing flax use may sharply reduce ecosystem quality impacts, polyethylene is therefore not a viable alternative under the current system configuration. Alternative deposition techniques that avoid sinking cultivation infrastructure altogether, such as the 'baling' approach proposed by Sten et al. (2026), may offer a better solution.

Finally, substantial differences in endpoint outcomes between LCIA method families highlight variation in their assessment of marine environmental impacts, including those of mCDR approaches (Delval et al., 2025). Hence, these results should be interpreted as guidance for identifying priority areas for technological development and deployment strategies, rather than as definitive measures of MCS environmental sustainability, consistent with the role of life cycle interpretation as a decision-support process (Laurent et al., 2020). Future assessments should continue to conduct sensitivity analysis on the choice on the LCIA method families (Delval et al., 2025).

Ultimately, these findings show that the climate mitigation potential and broader sustainability indicators must be interpreted with precaution. MCS environmental performance is highly dependent on biomass yield, sequestration durability, transportation distances, cultivation infrastructure materials, and future background conditions, while differences between LCIA method families indicate that methodological choices can also influence the LCA outcomes. These uncertainties suggest that, despite the issuance of MCS carbon credits, net carbon removal cannot be assumed without further validation and robust monitoring and verification frameworks, reinforcing calls for greater scrutiny of MCS (Boyd et al., 2022; Hurd et al., 2022; Ricart et al., 2022; Chopin et al., 2024).

4.3 Limitations and research priorities

Although this study provides one of the most comprehensive environmental assessments of MCS to date, several methodological and data-related limitations remain, highlighting priorities for future research and reducing uncertainties surrounding MCS' environmental performance. First, current LCIA method families have important shortcomings in assessing marine impacts (Delval et al., 2026). Specifically, (i) numerous environmental flows relevant to mCDR approaches remain uncharacterised, e.g., marine eutrophication models do not account for P, (ii) models are often grounded on freshwater rather than marine-specific data, and (iii) ocean acidification is entirely absent from ReCiPe 2016 (Huijbregts et al., 2016; Delval et al., 2026). Consequently, both potential burdens and environmental benefits associated with MCS may be underestimated. Moreover, conventional LCIA method families omit potential impacts of large-scale MCS deployment, 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). Developing marine-specific impact assessment models is therefore essential for comprehensive and accurate evaluations of mCDR technologies (Delval et al., 2026).

Secondly, MCS performance 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 for the present study, given that C/nutrient leakage and transportation distance were identified as hotspots and are both inherently location-dependent. Moreover, sequestration durability varies with local environmental conditions (Siegel et al., 2021), while biomass yield may be affected by local nutrient availability, oceanic temperatures, salinity, and ambient conditions (Khan et al., 2024). Furthermore, this LCA focuses exclusively on *S. latissima*, despite variations in species productivity and biochemical composition, and excludes seasonal variability in C, N, and P contents. Future research should therefore aim to identify the most suitable MCS deployment conditions by assessing different geographic contexts and macroalgae species and incorporate seasonal variability.

Lastly, several modelling assumptions should be acknowledged. Firstly, our model assumes that N uptake provides eutrophication benefits. However, this depends on the marine environment being N-limited (Howarth & Marino, 2006). This assumption aligns with previous LCA work (Thomas et al., 2021; EC-JRC, 2012), who generally consider marine waters to be N-limited. Moreover, the calculated eutrophication impacts could be over- or underestimated, as N and P leakage-rates are assumed to equal those of C due to a lack of flow-specific data and P is not characterised. Secondly we relied on *ecoinvent* data, which lacks a suitable 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 performance, offshore transportation should be more accurately represented in future LCA works. Moreover, *ecoinvent* assumes no CO_2 uptake during flax production, thus potential CO_2 uptake from flax is not included in our model. Therefore, we also did not consider leakage from sunken flax longlines. Thirdly, the carbon sequestration pathway and nutrient fate related to the artificial sinking of macroalgae remain insufficiently understood. Given the sensitivity of MCS performance to sequestration durability, improving our understanding of these mechanisms, as well as investigating alternative deposition techniques, should be a research priority. As stated by Bauer et al. (2026), 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

This research presents the first comprehensive cradle-to-grave LCA of MCS and identifies hotspots and trade-offs across climate change, ecosystem quality, human health, and natural resource scarcity. Additionally, we conducted sensitivity analyses to evaluate the influence of seven key parameters, an aspect previously unexplored in MCS LCA literature.

Our findings suggest that MCS could achieve a net C removal of 227 kg CO_2-eq/ t of CO_2 stored, which represents only a 23% CDR efficiency. This is accompanied by net adverse impacts on ecosystem quality ($2.03x10^{-6}$ species.yr), human health ($1.40x10^{-3}$ DALYs), and natural resource scarcity (83.9 USD 2013). Across impact categories, the offshore biomass transport and C/nutrient leakage emerged as the dominant hotspots, with cultivation infrastructure and energy use during line seeding also contributing notably. Also taking into account findings from the sensitivity analyses reveal several opportunities to improve performance: (i) prioritising proximity to the sink site when selecting the cultivation site, (ii) aiming for high biomass yields and limited losses, (iii) improving the design of cultivation and sinking infrastructure, and (iv) adopting renewable energy while reducing energy demand at the hatchery.

Nevertheless, the sensitivity analyses demonstrate that relatively small changes in biomass yield or C/nutrient leakage could potentially shift the system from net carbon removal to net emitter. Combined with the limited estimated sequestration efficiency, this raises concerns regarding the viability of large-scale deployment. Moreover, sequestration durability remains contested and existing LCIA method families inadequately represent marine-specific environmental impacts. Research priorities include investigating C and nutrient fate following deep-sea deposition, improving site-specific monitoring and verification, and developing more comprehensive marine-specific impact assessments methods.

Ultimately, although MCS may deliver net CDR under the modelled conditions, its broader environmental trade-offs and substantial uncertainties make large-scale deployment difficult to justify until these environmental impacts and uncertainties are further reduced and more robust sequestration efficiency is demonstrated.

Declarations

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Author contributions

Conceptualisation: I.J.P.R.v.G, N.T., S.E.T., M.H.D.; Methodology: I.J.P.R.v.G.; Investigation: I.J.P.R.v.G.; Formal analysis: I.J.P.R.v.G.; Validation: N.T., S.E.T., M.H.D.; Visualisation; I.J.P.R.v.G., M.H.D.: Writing – original draft; I.J.P.R.v.G.: Writing – review & editing: N.T., S.E.T., M.H.D..

Declaration of competing interests

The authors declare no competing interests.

Data availability statement

Data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

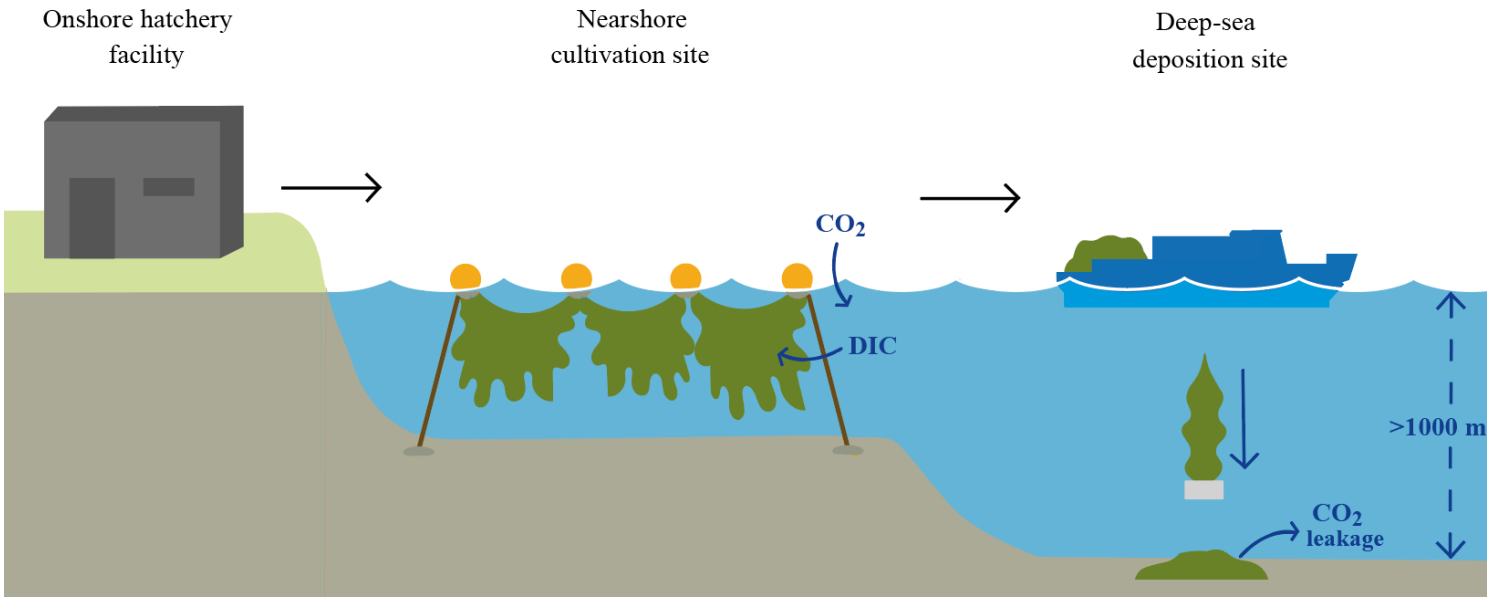


Figure 1

Schematic overview of MCS as an 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 (see section 2.2 for more details).

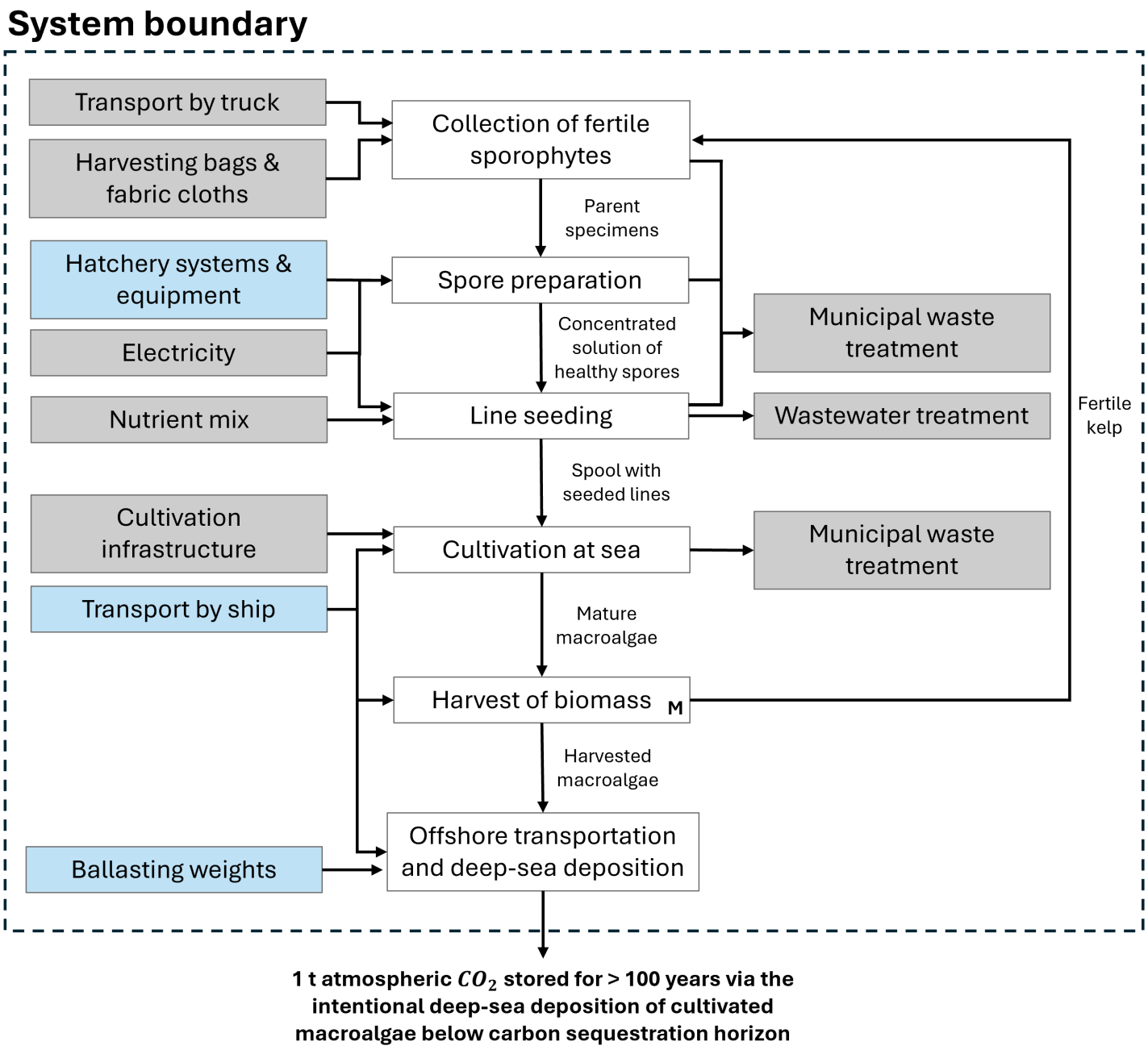


Figure 2

The MCS product system showing all stages and intermediate goods for the production and deposition of S. latissima biomass. Grey box = background process; blue box = adjusted background process; white box = foreground process; solid arrow = good; M = multifunctional process

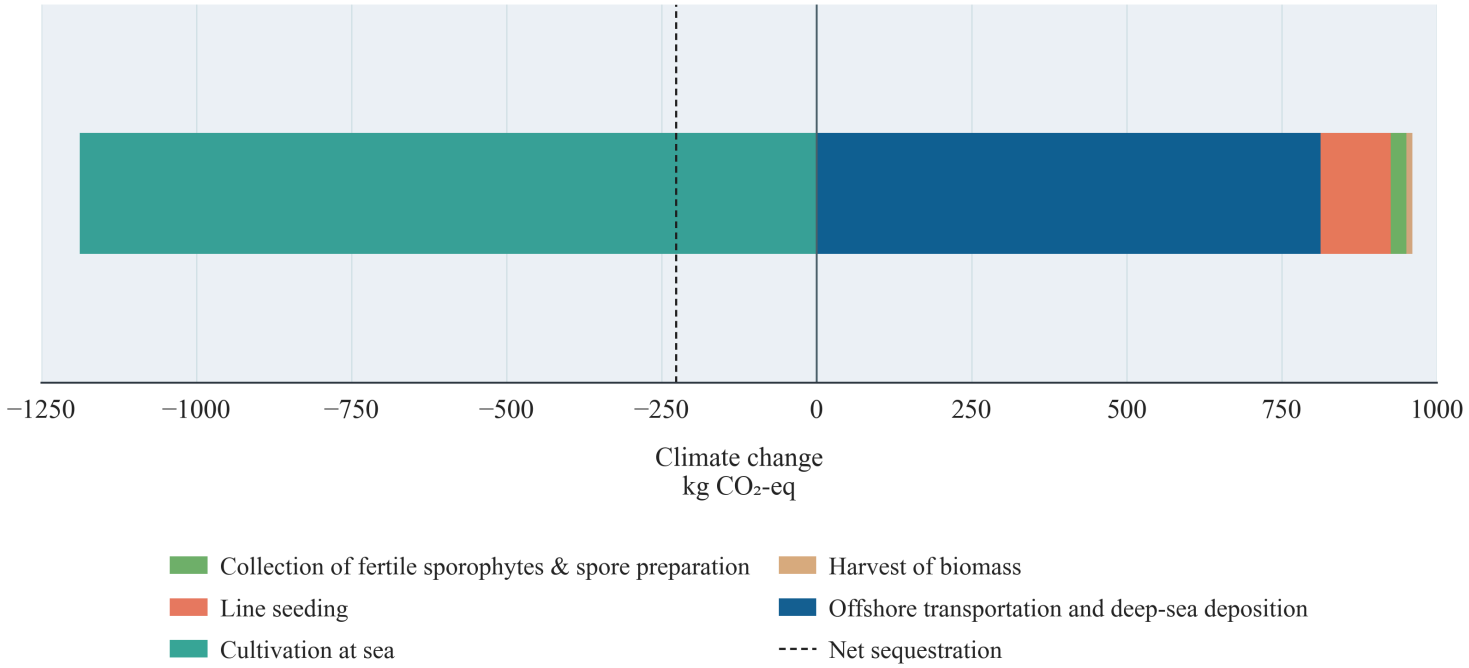


Figure 3

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.

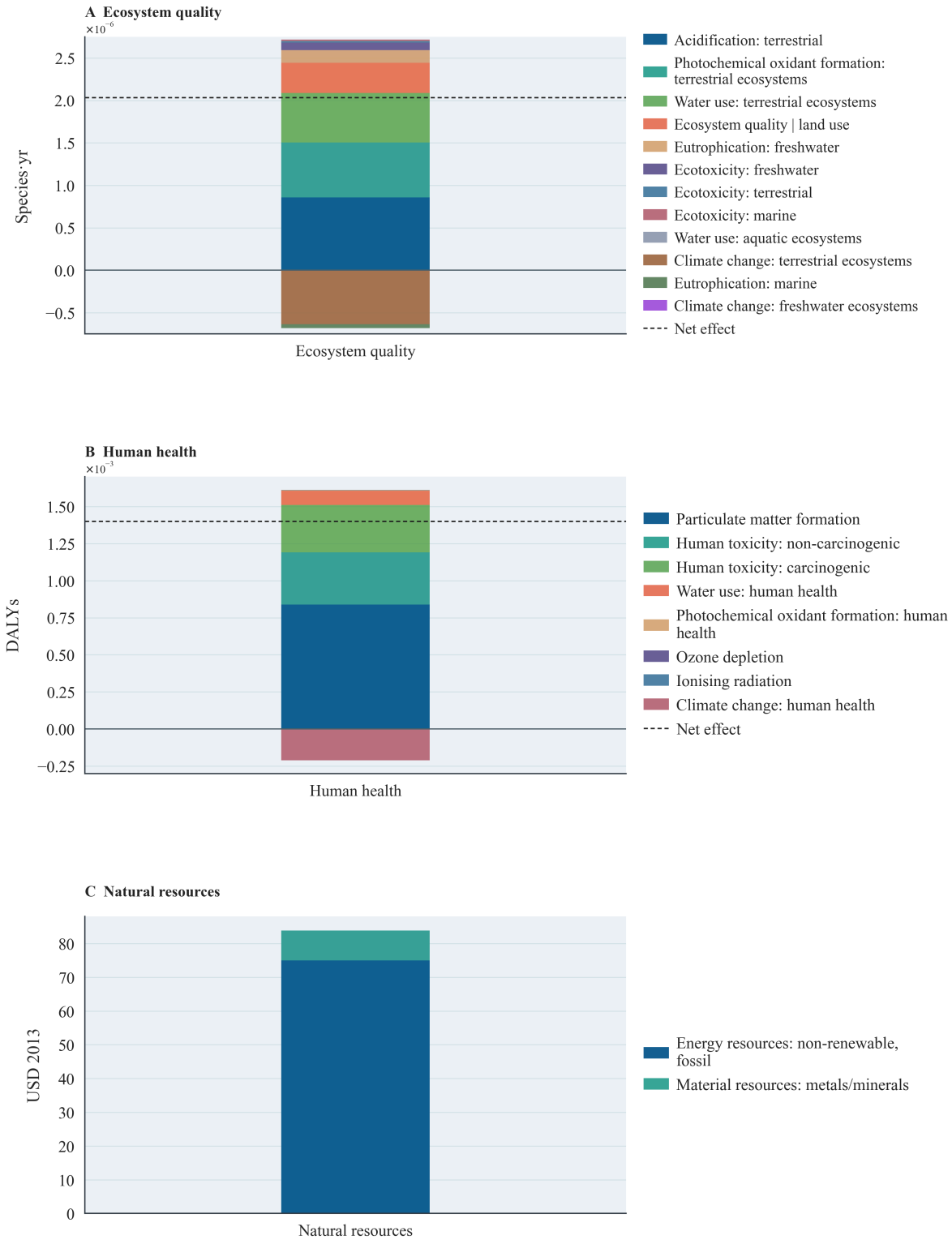


Figure 4

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.

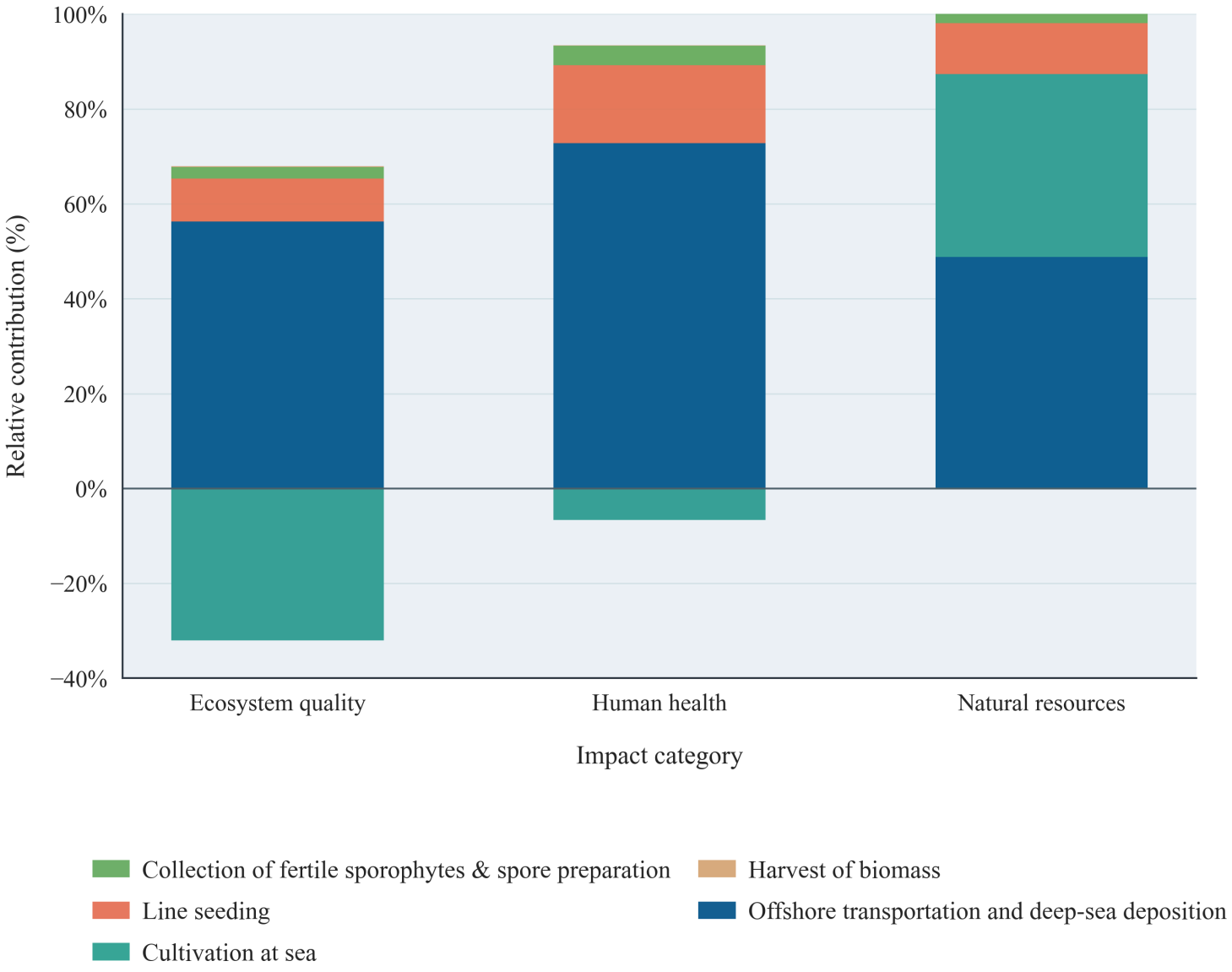


Figure 5

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

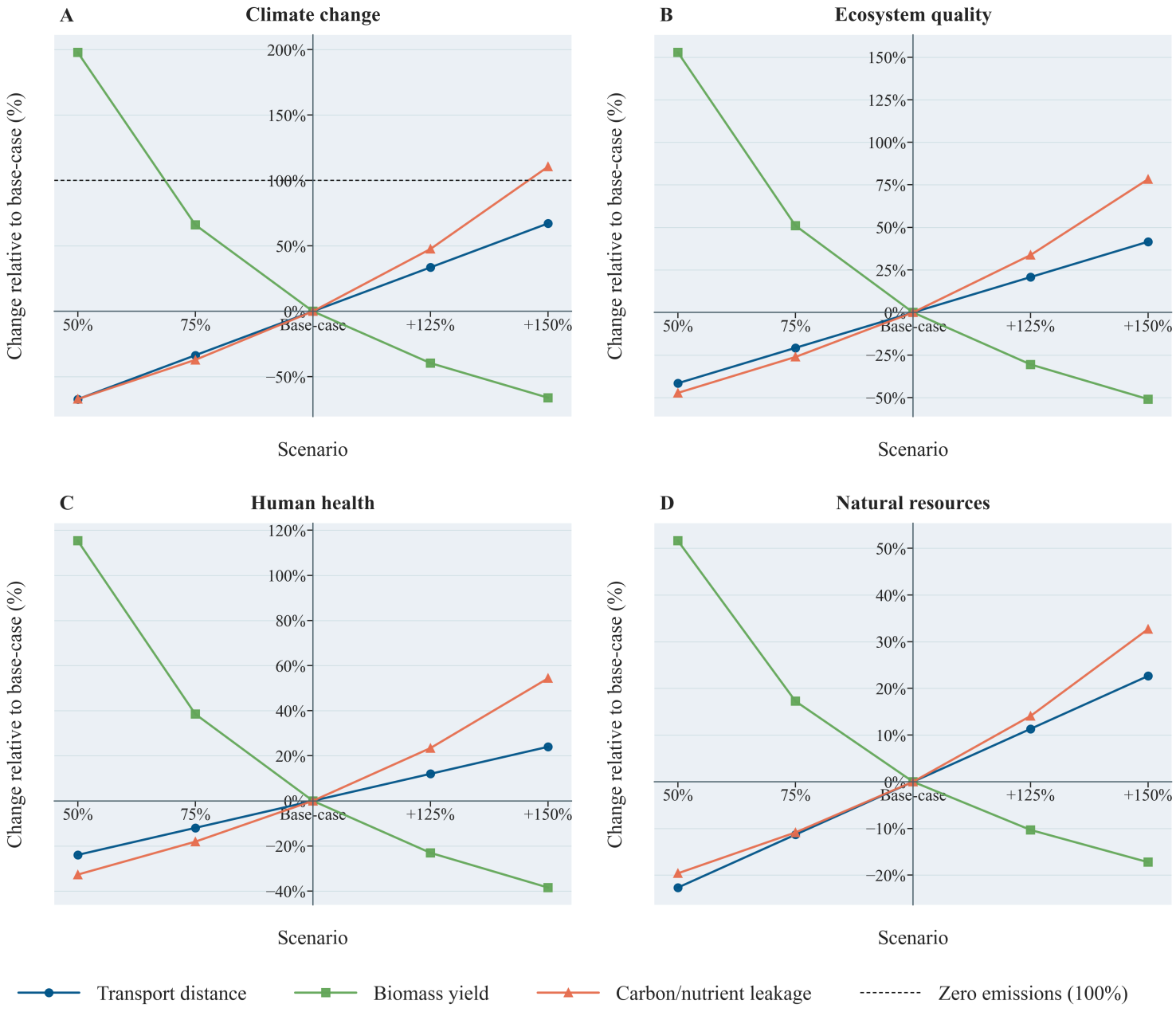


Figure 6

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) C/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.

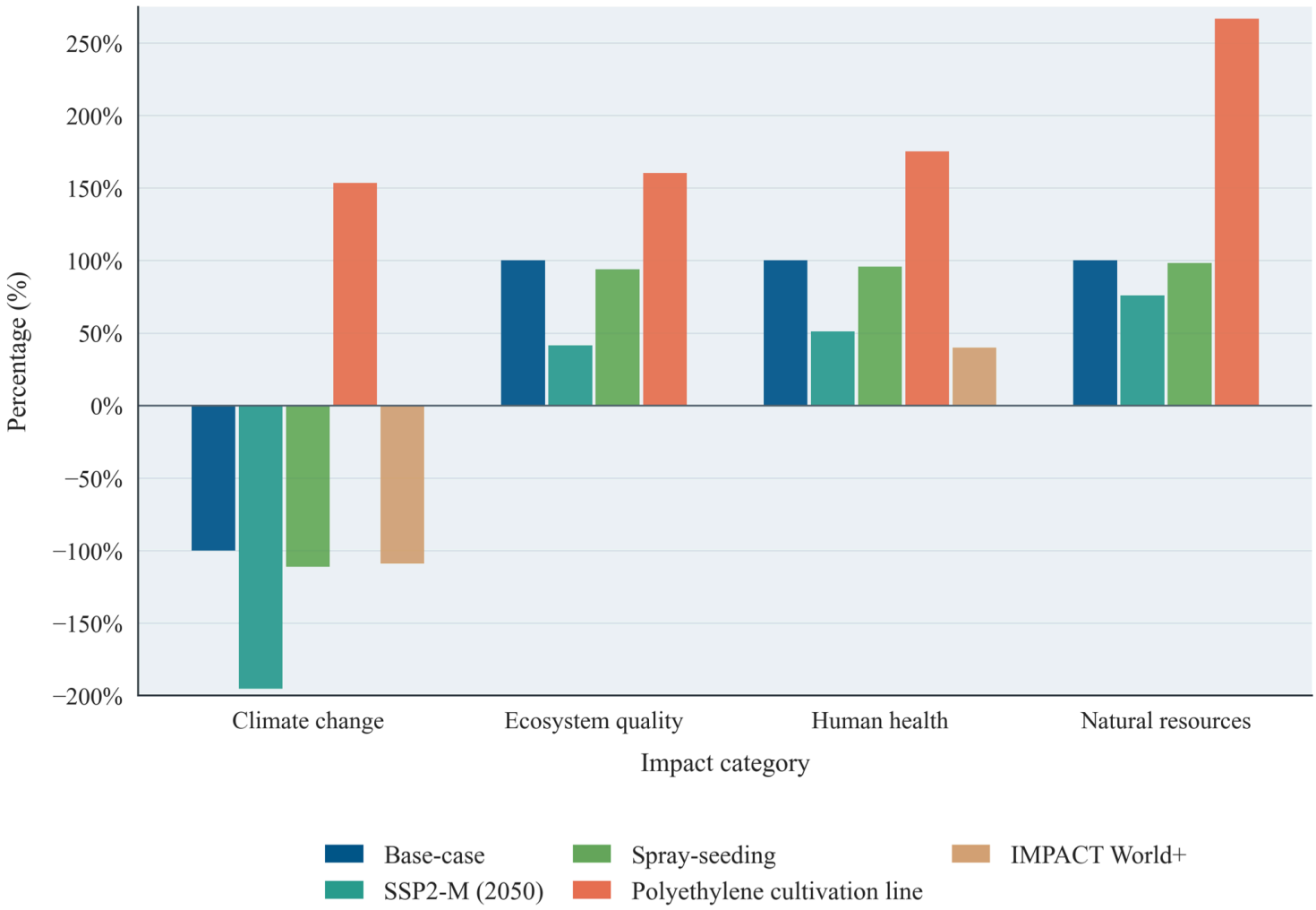


Figure 7

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 projecting the SSP2-M pathway for 2050; (ii) adoption of the spray-seeding technique, (iii) using polyethylene longlines; and (iv) employing the IMPACT World+ LCIA method family.

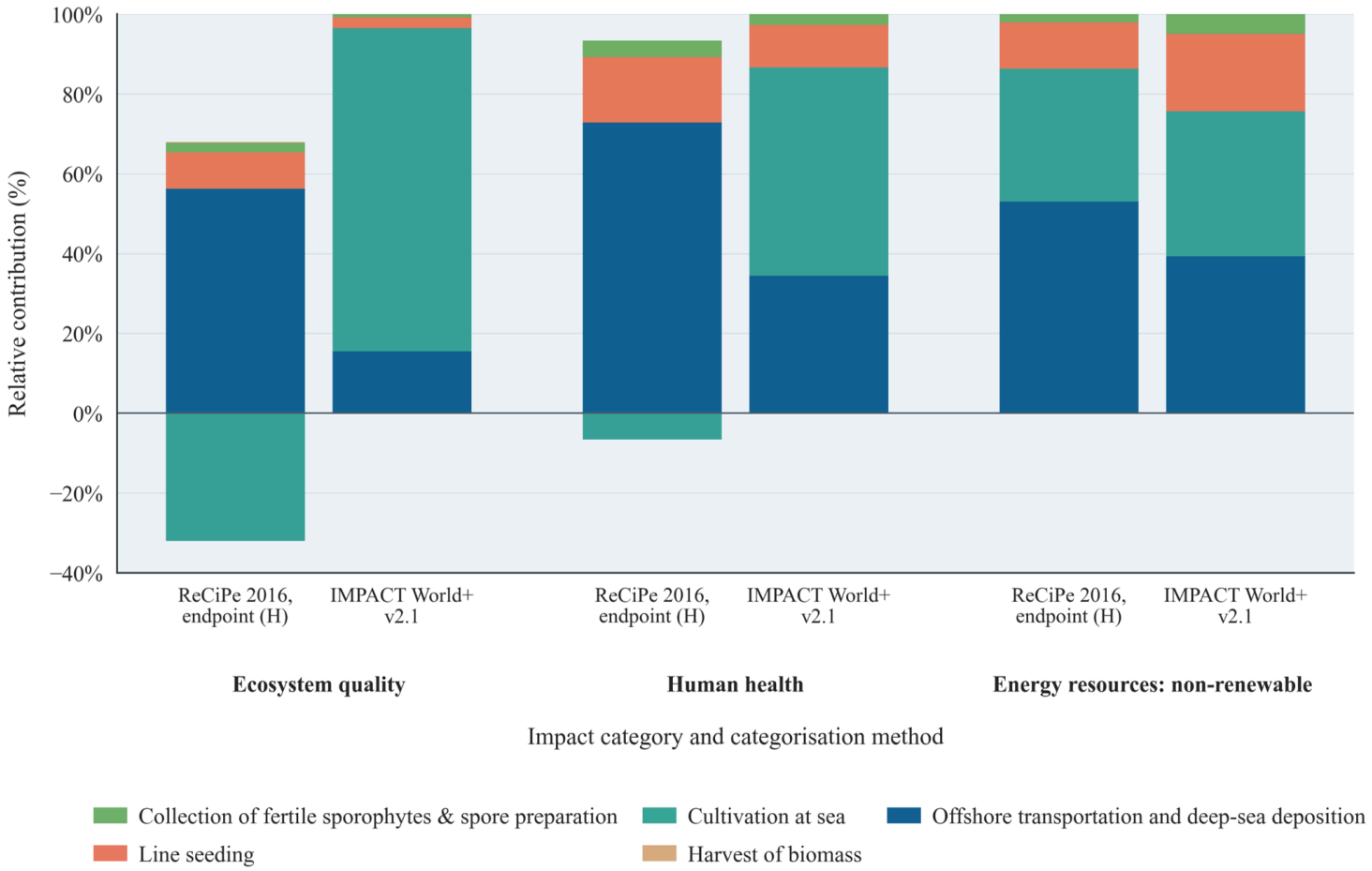


Figure 8

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

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterialI.xlsx
- SupplementaryMaterialII.pdf