International Journal of Operations & Production Management

Received 16 June 2024
Revised 19 July 2024
Accepted 22 July 2024

Beyond the new normal for sustainability: transformative operations and supply chain management for negative emissions

Stelvia V. Matos
Centre for Social Innovation Management, Surrey Business School, University of Surrey, Guildford, UK
Martin C. Schleper
Information Systems, Supply Chain Management and Decision Support Department, NEOMA Business School, Reims, France
Jeremy K. Hall
SPRU, University of Sussex Business School, University of Sussex, Brighton, UK
Chad M. Baum and Sean Low
Department of Business Development and Technology, School of Business and Social Sciences, Aarhus University, Aarhus, Denmark, and
Benjamin K. Sovacool
Department of Business Development and Technology, School of Business and Social Sciences, Aarhus University, Aarhus, Denmark and SPRU, University of Sussex Business School, University of Sussex, Brighton, UK

Abstract

Purpose – This paper aims to explore three operations and supply chain management (OSCM) approaches for meeting the 2 °C targets to counteract climate change: adaptation (adjusting to climatic impacts); mitigation (innovating towards low-carbon practices); and carbon-removing negative emissions technologies (NETs). We suggest that adaptation nor mitigation may be enough to meet the current climate targets, thus calling for NETs, resulting in the following question: How can operations and supply chains be reconceptualized for NETs?

Design/methodology/approach – We draw on the sustainable supply chain and transitions discourses along with interview data involving 125 experts gathered from a broad research project focused on geoengineering and NETs. We analyze three case studies of emerging NETs (biochar, direct air carbon capture and storage and ocean alkalinity enhancement), leading to propositions on the link between OSCM and NETs.

Findings – Although some NETs are promising, there remains considerable variance and uncertainty over supply chain configurations, efficacy, social acceptability and potential risks of unintended detrimental consequences. We introduce the concept of transformative OSCM, which encompasses policy interventions to foster the emergence of new technologies in industry sectors driven by social mandates but lack clear commercial incentives.

Originality/value – To the best of the authors' knowledge, this paper is among the first that studies NETs from an OSCM perspective. It suggests a pathway toward new industry structures and policy support to effectively tackle climate change through carbon removal.

Keywords Carbon removal, Climate change, Negative emissions technologies (NETs), Sustainable innovation, Transformative operations and supply chain management

Paper type Research paper

Funding: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 951542).

International Journal of Operations & Production Management
Vol. 44 No. 13, 2024
pp. 263-295
Emerald Publishing Limited
0144-3577
DOI 10.1108/IJOPM-06-2024-0487

Introduction

The relationship between climate change and operations and supply chain management (OSCM) can be described as paradoxical: businesses are major causes of climate change, but will also be affected by, and necessary for, rectifying it. The 2,500 largest global corporations' supply chains contribute more than 20% of global emissions (Gopalakrishnan *et al.*, 2021) and eight of the world's supply chains according to sectors (food, construction, fashion, fast-moving consumer goods, electronics, automotive, professional services and freight) account for more than half of all global greenhouse gas emissions (WEF, 2021). At the same time, modern supply chains are globally complex with significant upstream processes in regions vulnerable to climate change (Burke *et al.*, 2015; Carleton and Hsiang, 2016). Hence, OSCM will be significantly affected by the upcoming costly cascading effects of climate change and emerging international regulations and policies (Ghadge *et al.*, 2020; Holgado *et al.*, 2024; Howard-Grenville *et al.*, 2014). Conversely, reducing the world's CO_2 emissions also offers industry huge opportunities (Bloomberg, 2020) – as much as \$100tn (Carlin, 2021) over the next three decades, with annual investments exceeding \$5tn. Therefore, any realistic effort to meet carbon neutrality and reduce climate change will require the expertise, resources and innovative capabilities of firms, and particularly OSCM (Helper *et al.*, 2021), either via changes in operations and supply-chain network designs or diffusing technological solutions (Atasu *et al.*, 2020).

Challenges however remain enormous. Although we now have consensus over the severity of the problem and a target of maintaining temperatures below 2 °C above the pre-industrial average, progress remains insufficient, thus making it "likely that warming will exceed 1.5 °C during the 21st century and make it harder to limit warming below 2 °C" (IPCC, 2023, p. 10). Consequently, the majority of the scientific community and the most recent International Panel on Climate Change (IPCC) report views carbon dioxide removal (CDR) as a necessary addition to a portfolio of climate strategies, which should be deployed in tandem with other mitigation methods (IPCC, 2023; Smith *et al.*, 2024). CDR involves "all anthropogenic activities removing CO2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products" (IPCC Intergovernmental Panel on Climate Change, 2019, p. 807) and is often envisioned through negative emissions technologies (NETs), which capture and safely store CO_2. A variety of such technologies exist, ranging from nature-based (e.g. afforestation) to engineering-based approaches (e.g. direct air capture and storage – DACCS) (Baum *et al.*, 2023) [1].

According to Cobo *et al.* (2022), NETs are needed to meet the 1.5 °C target, given that up to 1,000 gigatons of CO_2 need to be removed by 2100. Compared with traditional climate strategies of mitigation that seek to halt climate change and adaptation that adjusts to future climate realities, NETs can potentially be deployed to slow and reverse climate change. In addition to governments, NETs are already being supported by a surprisingly large coalition of actors such as, for example, industry, scientists, civil society, farmers, fishers, financiers and insurers (Sovacool *et al.*, 2024). Therefore, NETs present a vital fallback option if adaptation and mitigation prove inadequate.

Whereas techniques for adaptation and mitigation have been suggested in the OSCM literature (e.g. Bag *et al.*, 2023; Ghadge *et al.*, 2020; Nakano, 2021; Pankratz and Schiller, 2022), there remains a dearth of studies on how emerging NETs will be developed and diffused on larger scales through existing, or more likely new, OSCM mechanisms. Hence, this study seeks to answer the following research question: How can operations and supply chains be reconceptualized for NETs?

In what follows, we describe adaptation and mitigation through the lens of contemporary OSCM strategies and illustrate why they are necessary but not sufficient for rectifying climate change. We then describe our methodology, study approach and data analysis. Three NET case studies are presented through retrospective analysis of interview data and draw on two desperate discourses: from the OSCM literature, we utilize sustainable supply chain management (SSCM), and from innovation studies the sustainable transitions literature, to propose a third and complementary approach to adaptation and mitigation, which we call *transformative* OSCM.

While some emerging NETs show promise, there remains considerable uncertainty over supply chain configurations, governance, costs, efficacy, social acceptability and potential risks of unintended detrimental consequences (Augustine *et al.*, 2019; Bloomberg, 2023; Harvey, 2023; Smith *et al.*, 2024). The proposed concept of *transformative* OSCM complements contemporary sustainable OSCM thinking, which currently lacks adequate mechanisms to develop new technologies for emerging industry sectors driven by a social mandate but with elusive commercial incentives. It further emphasizes the need for policy intervention, a period of incubation for learning and a prioritization of ecological requirements over social and economic challenges. We concluded by exploring how OSCM can be reconceptualized to help rectify climate change through innovative NETs, thereby "moving towards a more desirable trajectory" (Davoudi *et al.*, 2013, p. 311).

OSCM approaches to climate change

Two fundamental approaches that businesses usually employ to address climate change are adaptation and mitigation. According to the IPCC Intergovernmental Panel on Climate Change (2019, p. 804), adaptation refers to "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities." Mitigation is defined as "a human intervention to reduce emissions or enhance the sinks of greenhouse gases" (IPCC Intergovernmental Panel on Climate Change, 2019, p. 819). In the following, we will introduce these two approaches from an OSCM perspective and link them to previously influential concepts, such as pollution control and pollution prevention. Table 1 provides an overview of the main concepts.

Adaptation: addressing the "new normal" with "old normal" OSCM practices

According to Atasu *et al.* (2020, p. 151), "adaptation for companies involves adjusting how they manage their supply chains, site their facilities, adjust their mix of products and services, and measure and report on their impacts in light of physical risks and regulatory changes related to climate change." Negative repercussions from climate on operations and supply chains include abandoning production locations in regions exposed to floods, storms, draughts or heat waves (Easterling *et al.*, 2000). Adaptation due to regulatory changes could for example include switching suppliers due to newly introduced CO2 limits in supply chains. How strongly these effects will materialize depends on the supply chain structure and which industry is considered, with sectors such as food being heavily impacted (Conway *et al.*, 2015). Interestingly and unlike the general IPCC Intergovernmental Panel on Climate Change (2019) definition of adaptation, Atasu *et al.* (2020)'s definition considers only risks but neglects beneficial opportunities, such as shorter trade routes due to melted polar ice.

Originally CO_2 emissions were seen as a by-product but subsequently recognized as a climate change pollutant, forcing firms to adapt in response to risks and regulatory changes. Such an account of adaptation is far from new and has been discussed under the concept of "pollution control" since the 1990s (Florida, 1996). Pollution control involves technologies that treat or dispose of pollutants or harmful byproducts at the end of a manufacturing process to reduce the overall toxic content of environmental emissions and wastes (Florida, 1996; Gupta, 1995). Firms adjust existing practices in response to environmental impacts ex-post via technologies that typically come at the expense of other *ex ante* improvements (Florida, 1996).

We perceive adaptation as preparing operations and supply chains for uncertain and turbulent environments by adjusting to what has commonly been referred to as the "new normal," albeit by utilizing the same pollution control approaches that ultimately minimize economic risks – i.e. embracing the "new normal" with tried and tested "old normal" practices. It thus reduces vulnerabilities by enhancing operations and supply chain resilience

Table 1. Labels and concepts related to climate change rectification according to climate change and OSCM literatures

	IPCC literature	OSCM literature
Adaptation	"The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects" (IPCC Intergovernmental Panel on Climate Change, 2019, p. 804)	"Adaptation for companies involves adjusting how they manage their supply chains, site their facilities, adjust their mix of products and services and measure and report on their impacts in light of physical risks and regulatory changes related to climate change" (Atasu *et al.*, 2020, p. 151)
Mitigation	"A human intervention to reduce emissions or enhance the sinks of greenhouse gases" (IPCC Intergovernmental Panel on Climate Change, 2019, p. 819)	"Mitigation engages the innovation pathway and involves developing new products, technologies and services that support the transition to a low-carbon economy" (Atasu *et al.*, 2020, p. 151)
Pollution control		Typically technologies that treat or dispose of pollutants or harmful by-products at the end of a manufacturing process to reduce the overall toxic content of environmental emissions and wastes. Control technology typically comes at the expense of other manufacturing improvements (e.g. pollution prevention) (Florida, 1996)
Pollution prevention		Changes in operations and supply chains that lead to less polluting or non-polluting products and processes (Florida, 1996)
NETs	"An activity or mechanism that results in negative emissions through removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e. in addition to the removal that would occur via natural carbon cycle processes" (IPCC, p. 819)	
Carbon supply chain management		"Designing and managing [. . .] unique supply chain networks for carbon capture, storage, transportation and usage" (Ghadge *et al.*, 2020, p. 59)
Transformative supply chain management		"The ability to transform structures and processes more radically in response to changing conditions or disruptions" (p. 3). New supply chains are created based on new set of suppliers' configuration and information exchange; and some supply chains might be displaced or disrupted (Wieland *et al.*, 2023)

Source(s): Authors' own creation

(Wieland *et al.*, 2023) and resembles traditional supply chain risk management, i.e. making "decisions that optimally align organizational processes and decisions to exploit opportunities while simultaneously minimizing risk," preventing supply chain disruptions and establishing resilience (Narasimhan and Talluri, 2009, p. 114).

Supply chain risk management can be either proactive or reactive, i.e. before or after a risk has materialized (Grötsch *et al.*, 2013), with the former potentially being more cost-effective (Ng *et al.*, 2018) but uncertain, whereas costs incurred by reactive approaches are typically passed on to consumers. For climate change, OSCM practitioners applying adaptation will navigate the actual and expected climate change repercussions and preempt regulatory changes by relocating supplier locations, establishing new processes or introducing modified or new products and services. For example, Ng *et al.*'s (2018) study on the Canadian port sector found that adaptation can reduce climate change impacts such as sea-level rise on shipping. However, insufficient collaboration among various stakeholders and the lack of incentive structures suitable for long-time horizons pose a major challenge to implementation (Madonna *et al.*, 2024). Pankratz and Schiller (2022) find that buying firms are 6–11% more likely to cease supplier relationships and choose less risk-exposed ones when climate-related negative events exceed historical expectations.

From an uncertainty and risk perspective, a plethora of supply and demand side adaptation risks can be observed (Ghadge *et al.*, 2020). Key issues with climate change include its influence on supply and raw materials and production processes (Alves *et al.*, 2017; Kara *et al.*, 2021), changes in demand and consumer behavior and regulatory uncertainty (Chen and Wang, 2016; Drake, 2018; Sunar and Plambeck, 2016). Ghadge *et al.* (2020) and Jira and Toffel (2013) suggest that most of these climate change risks on supply chains lack rigorous investigation.

In summary, adaptation is an inherently reactive approach to dealing with climate change by focusing on the economic viability and survivability of the firm by, for example, modifying supply chains in an attempt to return to normality (Wieland *et al.*, 2023). However, while these responses to climate change are widely utilized in OSCM, they do little to rectify its root causes, resulting in "[…] a reductionist and static view on the supply chain and its management, promoting a global hunt for cheap labor and resources" (Wieland, 2021, p. 58).

OSCM mitigation: addressing the "new normal" with contemporary OSCM practices

Whereas adaptation focuses on reacting to actual and expected impacts of climate change, mitigation focuses on proactively lowering or eradicating emissions. For OSCM, mitigation is defined by Atasu *et al.* (2020, p. 151) as "developing new products, technologies, and services that support the transition to a low-carbon economy." Hence, mitigation aligns with the established OSCM concept of pollution prevention (Geffen and Rothenberg, 2000; Klassen and Vachon, 2003) and "end of pipe" pollution control, where both approaches lower pollution, although through different means. The former has long been recognized as an advancement over pollution control by firms attempting to become more sustainable [2]. Both however still focus on "adjusting the existing system in response to an actual or expected change or disruption" (Wieland *et al.*, 2023, p. 3), but otherwise continues the core business. Supply chain mitigation strategies thus mirror the shortcomings discussed in the SSCM literature (e.g. Montabon *et al.*, 2016 Pagell and Shevchenko, 2014; Pagell and Wu, 2009; Sarkis, 2021). Indeed, progress toward sustainable supply chains has been described as modest (Gold and Schleper, 2017) or "slow, sporadic, myopic" and sometimes resulting in unsustainable practices (Sarkis, 2021, p. 65).

Drivers for supply chain mitigation include regulatory pressures to address climate change (Naumov *et al.*, 2023), demand for green products (Ghadge *et al.*, 2020), cost savings through emission reductions (i.e. eco-efficiency) or CO_2 tax anticipation (Dooley *et al.*, 2019). Studies focusing on greenhouse gas emissions reduction often emphasize, if not prioritize, economic aspects (e.g. Plambeck, 2012; Saunders *et al.*, 2020). Sartal *et al.* (2020) find a trade-off between decarbonization projects and firms' labor productivity, which could jeopardize the former. An exception is Kagawa *et al.* (2015), who studied, from a macro-perspective, global CO_2 emission hotspots within more than 300 million supply networks. Given this non-firm-centric view, they provide an opportunity to detect and prioritize the largest emitters, allowing for more targeted mitigation efforts.

In addition to drivers, OSCM mitigation studies explore the role of emissions assessment (Alvarez *et al.*, 2018; Rizet *et al.*, 2012), the use of established practices such as supplier collaboration and information exchange (Dahlmann and Roehrich, 2019; De Stefano and Montes-Sancho, 2024; Jira and Toffel, 2013) and local sourcing and production (Nieuwenhuis *et al.*, 2012), all of which have been found to reduce emissions. However, prior studies mostly focus on making unsustainable supply chains more sustainable, thus offering “limited insight into how to create an economically viable supply chain that at a minimum creates no harm and may even have positive or regenerative impacts on social and environmental systems” (Pagell and Shevchenko, 2014, p. 46).

Such deficiencies result from retrofitting established supply chains to become more sustainable by focusing on “synergistic and familiar” aspects, but neglecting trade-offs and radical innovation (Montabon *et al.*, 2016; Pagell and Shevchenko, 2014). Synergistic in this context refers to the instrumental logic prioritizing economic supply chain performance over environmental and social parameters (Montabon *et al.*, 2016). As Sarkis (2021, p. 65) states, firms tend to take the “road of least resistance focusing on win–win opportunities in meeting sustainability challenges,” where measures that fail to result in short-term economic benefits are discarded. “Familiar” relates to the tendency to enrich traditional OSCM research with sustainability perspectives, resulting in incremental progress (Pagell and Wu, 2009), as it retains the hegemony of economic profitability while addressing environmental and/or social issues. This familiarity is best expressed in the question “does it pay to be sustainable?”

In addition to most SSCM research being essentially incremental and focused on retrofitting, Bals and Tate (2018) also suggest that the design phase has been mostly neglected. A truly proactive approach would thus involve incorporating OSCM issues upstream in for example R&D and technology development phases (Wheelwright and Clark, 1992). This would involve difference forms of knowledge, such as competency enhancing (incremental) or destroying (radical), modular versus architectural innovation (Henderson and Clark, 1990), appropriability issues (Teece, 1987) and societal issues, which Hall and Martin (2005) and Matos and Hall (2007) have argued adds complexity and ambiguity to decision-making. Thus, like adaptation, mitigation will unlikely be enough to meet the Paris Accord targets (Financial Times, 2023), nor would they be sufficient to diffuse NETs.

Toward transformative OSCM

While adaptation and mitigation are necessary, many climate scientists argue that more drastic means are needed to meet the Paris Accord targets (Financial Times, 2023). For example, Minx *et al.* (2018) call for intentional efforts to remove greenhouse gases from the atmosphere through NETs. Given the potentially catastrophic and irreversible nature of the problem, they suggest that – counter to much of the OSCM discourse – it should be prioritized over social and economic parameters. Thus, if climate targets are to be met, entirely new industrial structures may be needed, or at least incumbent systems must be substantially retrofitted, areas which have until recently been underexplored. One such approach is “Transformative” OSCM strategies, defined by Wieland *et al.* (2023, p. 3) as an “ability to transform the system’s structures and processes more radically in response to changing conditions or disruptions”. Hence, we follow Ghadge *et al.*’s (2020, p. 59) call for “carbon supply chain management” (i.e. “designing and managing such unique supply chain networks for carbon capture, storage, transportation and usage”) and investigate NETs as a third and transformative approach to tackle climate change.

NETs capture and safely store CO2, thereby slowing down and potentially reversing climate change and regenerating social–ecological systems (Gualandris *et al.*, 2024) in the likely event that adaptation and mitigation prove inadequate. However, research on these technologies is still in its infancy and its ultimate viability requires knowledge on the “socio-technical” perspectives in their deployment (Sovacool *et al.*, 2023). Furthermore, NETs might be “facilitated or impeded through a variety of societal, political, economic, and resource-related factors" (Baum *et al.*, 2023, p. 2). To fulfil their purpose, the supply chains and infrastructure also need to be demonstrably sustainable, where resource inputs, including carbon-neutral energy throughout the supply chain, do not negate the technologies' carbon reduction efforts.

Given their novelty, NETs face poorly defined markets, infrastructure and partnerships, thus requiring radically new supply chain reconfigurations. A paradigmatic shift is thus needed, given its urgency and overshadowing implications. It thus corresponds to an "ecologically dominant logic" where social and economic parameters are nested within the environmental one as a prerequisite (Montabon *et al.*, 2016). Consequently, we need to satisfy ecological requirements before we can turn to social and economic challenges (Griggs *et al.*, 2013), which departs from the dominant contemporary sustainable OSCM thinking.

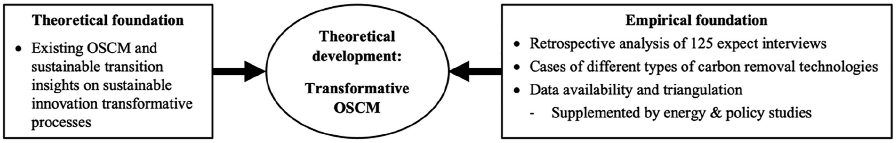
Building on these arguments, we thus postulate that research is needed that goes beyond SSCM to facilitate the development and distribution of NETs. As we will argue below, to do so we integrate SSCM insights with the sustainable transitions discourse, which explicitly addresses new policies for sustainable innovation, but so far offers only anecdotally limited empirical studies on how this can be operationalized through supply chains. Our argument is based on the premise that adaptation and mitigation can only reduce or eliminate CO_2 emissions, but that they are not intended to *reduce* global emissions. In contrast, NETs have no other (or limited) purpose other than to reduce global emissions and act as insurance in the likely event that mitigation will not be enough. As a result, the fundamental business model is very different, thus requiring new OSCM thinking.

Methodology

Research approach

Our approach to theoretical development follows similar OSCM studies dealing with novel contexts by combining the theoretical with the empirical to extend theory as abductive research (Ketokivi and Choi, 2014; Voss *et al.*, 2015). As depicted in Figure 1, our theory elaboration process stemmed from a recursive dialogue between the theoretical (meaning) and empirical foundations (action), that led to the conceptual model of transformative OSCM at its center. The theoretical foundation provided by OSCM and SSCM studies helped us explain the need for considering the complex factors required for a low-carbon transition, and the transitions literature illuminated key aspects of transformative OSCM legitimacy. The empirical grounding of the research, on the other hand, focused on case studies to help unravelling the underlining mechanisms that shape the proposed transformative OSCM. In this process, theoretical reasoning was supported by empirical foundation, which in turn gained meaning through its integration with theory (Corley and Gioia, 2011).

Research on emerging NETs in the context of OSCM is complex because most are at early stages of development and/or implementation. This hinders access to data and restricts choices of methodological approaches, especially quantitative methods. To address this challenge, we follow other OSCM studies dealing with research constraints by looking retrospectively at data sources that would provide insights into the phenomena under investigation (DuHadway *et al.*, 2022). More specifically, we used interview data involving 125 experts gathered from a broad research project on environmental, technical, social, legal, ethical and policy aspects of



Source(s): Authors' own creation

Figure 1. Overview of theory elaboration process

geoengineering and NETs (blinded to protect anonymity). We used this data to identify insights related to operations and supply chain issues, including related terms such as "value chain," "suppliers" and "buyers" [3]. All interview data were triangulated with energy and policy studies to develop an initial understanding of the phenomena.

The original interview data collection involved open-ended questions used "to 'open' the talk and obtain 'authentic' accounts" (Rapley, 2001, p. 304). NET experts were identified from high-quality, peer-reviewed research publications or published patents, between 2011 and 2020 (Table 2). Interviews usually started by asking "*What are the critical issues related to . . .* ,“ "*Who are the most important . . .* " and "*What are the . . . .*" Then non-inquisitorial questions would follow such as – "*Why do you think that . . ., How do you work something . . ., This is interesting, why*?" to invite interviewees to raise relevant issues within technological, commercial, organizational and societal dimensions of NETs (see Appendix for our interview guidelines). All interviews were conducted remotely in English, recorded and transcribed resulting in 130 h of data.

Interview data analysis and coding

Drawing on the "Gioia method" (Gioia *et al.*, 2013), the initial stages of analysis (first order) involved a "rough" categorization of the data regarding technology development and OSCM issues. For example, the first order code "*Can be facilitated via current OSCM practices*" was created based on interviewee statements such as "*What we propose is to replace some of these industrial fertilisers by slow-release fertilisers. Specifically, where the combination of the methods makes sense, like in the humid tropics, like in South America or in Africa. There, often, the farmers do not have the money for the expensive industrial fertilisers so there is the question: 'what are alternatives?'. Slow-release fertilisers made out of minerals is what is coming into play*" (R015). Another first order code "*Needs to be built or repurposed from other industries (e.g. oil and gas)*" resulted from quotes as:

> Of course, there's an enormous role for the oil and gas industry because they have all the skills and experience. I think there are four different direct air capture technologies. And all of them can be coupled with basically every kind of energy supply source (R094).
>
> [. . .] What do you do with the CO2? So, you need to have it as close to sequestration sites as possible (R086).
>
> Of course, if you are thinking about modularity, if you are going to have smaller plants, then you cannot really justify dedicated pipelines, can you? (R082).

A second-order analysis then looked for differences and similarities within and across the three selected technologies. For example, the first-order codes mentioned above "*Can be facilitated via current OSCM practices*" and "*Needs to be built or repurposed from other industries (e.g. oil and gas)*" were then refined into the second-order code "*Infrastructure*." This process led to

Table 2. Overview information of semi-structured expert interviews

Total number of experts	125
No. of organizations represented	104
No. of countries represented	21
Civil society and nongovernmental organizations	12
Government and intergovernmental organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

Source(s): Authors' own creation

the identification of key themes: infrastructure, technological readiness, establishing legitimacy through learning, regulatory regime, policy incentives, business models, uncertainty, carbon accounting and reputation risk. Table 3–5 (further below) illustrate the data structure and provide illustrative quotes used during the analyses, which were then used as the basis of propositions and model development. Building on the example above, a detailed analysis of the many aspects related to the theme "*Infrastructure*" led us to conclude, among other things, that facilitating the development of NETs, requires OSCM to surpass incrementalism and establish the necessary infrastructure. The overall analysis process involved constant back-and-forth between the data, categories, concepts and literature, analyzing whether our findings were similar, contrasting or adding previous insights (Corbin and Strauss, 2015). To address internal validity, the authors regularly met to discuss each author's coding, challenging one's interpretation and codification of data until a consensus was reached.

Case sampling

The original qualitative dataset used in this study involved in total of 10 types of NETs: Carbon capture and utilization and storage, afforestation and reforestation, bioenergy with carbon capture and storage (BECCS), biochar, soil carbon sequestration or enrichment, ocean iron fertilization, ocean alkalinity enhancement (OAE), direct air carbon capture and storage (DACCS), enhanced rock weathering and ecosystem restoration. Using theoretical case sampling (Eisenhardt and Graebner, 2007), we selected three NETs: one biological or nature-based (i.e. biochar), one engineered or chemical (i.e. DACCS) and one ocean-based (i.e. OAE), IPCC, 2023). These technologies were the most frequently mentioned by the interviewees with regard to OSCM issues and could thus provide both depth and breadth of analysis, allowing us to capture as many OSCM issues as possible that either hinder or facilitate the adoption and diffusion of NETs. As per Table 6, the cases present different types of technology, degree of maturity, efficacy, potential applications, advantages and production cost estimates, providing a breath of differences and commonalities in maturity, scaling effects and infrastructure requirements. Such differences raise a diverse range of OSCM issues providing the opportunity to identify and analyze uncertainties over supply chain configurations, acceptability and potential risks of unintended consequences, thus illuminating underlining OSCM mechanisms for NETs.

Biochar. Biochar employs pyrolysis (i.e. chemical decomposition at elevated temperatures in an inert atmosphere) to convert organic material into a form of charcoal (i.e. biochar). By heating without oxygen, it is possible to obtain a stable, CO_2-rich solid. This offers a carbon sequestration method with relatively high efficiency that can endure for thousands of years when mixed with soil (Joseph *et al.*, 2021; Lehmann *et al.*, 2021).

Prior research found that biochar can facilitate soil amendment, enhance agricultural yield and improve soil and water quality (Kamau *et al.*, 2019; Vijay *et al.*, 2021). As a result, some recent field trials are exploring the carbon-sequestration potential and impacts on agricultural productivity of combined soil amendments of biochar and enhanced weathering (Bijma *et al.*, 2021; Low *et al.*, 2022). This results in primarily four objectives of biochar systems: reducing climate change, generating renewable energy, managing waste and soil improvement (Anderson *et al.*, 2017).

Direct air carbon capture and storage (DACCS). DACCS is an approach where mechanisms capture CO_2 from the atmosphere, compress it and safely store it in geological sinks or used to make long-lasting products like cement. Although featured in climate strategy since an IPCC (2007) report, it remains under-scaled. Distinct features of DACCS include two key aspects; the mechanism to capture the CO_2, and the infrastructure to store it, which in turn will determine their supply chain configuration and more generally efficacy and feasibility.

To capture CO_2, DACCS must first put ambient air in contact with a chemical reagent that removes the CO_2. Two chemical reagent systems are envisioned, with varying energy needs

Table 3. Overview of selected cases and key features – Biochar

Biochar – first-order analysis, sample quotes (emphasis added) and second-order themes First order	 Second order
Can be facilitated via current OSCM practices ● What we propose is to replace some of these industrial fertilisers by slow-release fertilisers. Specifically, where the combination of the methods makes sense, like in the humid tropics, like in South America or in Africa. There, often, the farmers do not have the money for the expensive industrial fertilisers so there is the question: "what are alternatives?" Slow-release fertilisers made out of minerals is what is coming into play. (R015)	Infrastructure
Established and in use; based on established science ● One of the projects I'm working on is with coffee farmers in Latin America. We believe that they can turn some of their agricultural residues into biochar, *in a very low-tech manner*, and then use the biochar to filter the effluent from the milling of coffee. That turns the biochar into a kind of slow-release fertiliser, which can then be used to displace fertiliser. So, obviously, that improves their economics as well as greenhouse gas emissions are reduced. (R019)	Technological readiness and Radicalness
Opportunities to improve economics and cognitive legitimacy ● For that application, you would need some kind of matrix, large matrix, which is very simple. It says you have this climate, this soil, you want to grow this or that, then you must apply that rock powder, that biochar to optimise the carbon storage in the plant and in the soil. *That means we need to do a lot of different experiments* so that we have, I say it in a simple way, *some kind of look-up table: "Where are you? What do you want to do?" Then you will get a best-practice guide from the system*." (R015)	Establishing Legitimacy through learning
Evolving, but currently limited to specific sectors ● Now, *we're starting to see what these carbon credits that are selling to farmers*, which has, generally, got to be very high-quality biochar, it's going to go very low. (R019) ● If you speak about breakthroughs and biochar, I think, and maybe you can correct me, it was just this year that biochar will be allowed on the fields, for application. *In Germany it wasn't allowed, until now*, to do that. There couldn't be an economic model if it's not allowed. (R015)	Regulatory regime
Initially as catalyst to get started ● For the basalt powder, for example, the rock powder, it is costly. Only if you have a certain minimum *CO2 certificate price* it will make some sense to apply that. For €25 per tonne of CO2, that's not something. Probably *the breakthrough for some of these measures* comes if we go beyond €100 per tonne of CO2. (R015)	Policy incentives
Established and based on dual use ● *Biochar, there's a market for it in terms of veterinarian products, so it's often found in medicine for stabilising gut activity in horses and dogs and other types of pets*. Often, that's large farms. They have large buckets of biochar to give to their horses to prevent diarrhoea and stuff. That's one market that's already existing. Of course, *it has been around as a tool for improving agricultural yields and soil quality for a long time. There, is already a market.* (R067)	Business models
Relatively minor; relatively uncomplex and spatially controlled ● [. . .] If you use the land for food production, it's not clear what's happening with the nickel and the chromium in the soil. (R015) ● *I don't think there's anything wrong with doing small-scale, locally adapted biochar, for example, and that could have ecological benefits* or whatever. [. . .] So yes, I do think the problem is scale and the way it's being done. I think, from our perspective, doing the type of biochar at a	Uncertainty/unintended consequences

(*continued*)

Biochar – first-order analysis, sample quotes (emphasis added) and second-order themes

First order	Second order
small scale that I just described has nothing to do with geoengineering. (R114)	
Relatively simple • We are still working on the carbon accounting: how much carbon is really bound? *With biochar, this is simple*. You weigh your biochar, you know that in the first 10 years, you lose 3% of that and then it's stable, and you put it in the ground. Then you know how much it was. We can easily certify that. (R015) • *There can be a huge amount of spatial variation. And then, of course, there's temporal variation* based on weather conditions. And so, there's a signal-to-noise issue as well, if you've laid biochar in soil. (R065)	Carbon accounting

Source(s): Authors' own creation

(Ozkan *et al.*, 2022). The first includes various solid sorbents that require heating at 150C, which can hypothetically be powered by diverse energy sources, including renewables (solar, wind and geothermal) or waste heat from local grids (Madhu *et al.*, 2021). The sorbents' efficacies, however, vary depending on their locations; currently, humidity has a deleterious effect, so dryer climates are preferred. The second utilizes liquid solvents requiring process heating of 900C, which necessitates natural gas (Realff *et al.*, 2021). DACCS systems relying on low temperature, solid sorbents can therefore leverage emerging (but still-unscaled) renewable energy but require high capital costs and technological improvements, whereas liquid sorbent systems require lower capital costs and can leverage existing fossil fuel and industrial systems albeit with lower net CO_2 captured.

Ocean alkalinity enhancement (OAE). OAE or "enhanced weathering" employs alkaline materials (such as basalt or lime) which naturally interact with CO_2 to provide long-term sequestration of CO2 in the form of solid carbonate minerals. Limestone and basalt rocks wear from exposure to natural processes like rain, wind or waves, allowing them to absorb CO_2 from the air. However, this process is extremely slow, so enhanced weathering employs physical or chemical grinding of rocks before placing them onto land to expedite the process. Over time, the CO_2 can be stored in oceans indefinitely. Enhanced weathering is attracting growing attention for its potentially low-cost carbon-removal method on the magnitude of 2.9–8.5bn tons per year by 2100 (Beerling *et al.*, 2020; Lehmann and Possinger, 2020).

Theoretical development

As discussed above, most of the SSCM discourse has been primarily focused on improving sustainability parameters while maintaining economic viability and thus provides useful insights for adaptation and mitigation. However, most focus on retrofitting existing infrastructures, with scant attention paid to the development of entirely new industries that support NETs. In this section, we develop a theoretical framework for transformative OSCM suitable for NETs that draws on the SSCM and innovation studies literature.

The diffusion of sustainable innovation via the supply chain has been discussed in the literature, starting with environmental innovation (e.g. Hall, 2000) and later focused on interactions amongst economic, societal and environmental parameters (Corbett and Klassen, 2006; Matos and Hall, 2007; Pagell and Wu, 2009). More recently, Kumar *et al.* (2020) and Costantini *et al.* (2017) suggest that environmental management in supply chains drives sustainable innovations, while eco-innovations are crucial for firms' CO_2 emission reductions. However, implementation remains a challenge (Bals and Tate, 2018), especially "strong sustainability" (Sarkis, 2021) or "truly sustainable supply chains," which "[. . .] at worst do no net harm to natural or social systems while still producing a profit over an extended period of

Table 4. Overview of selected cases and key features – DACCS

DACCS – first-order analysis, sample quotes (emphasis added) and second-order themes	
First order	Second order
Needs to be built or repurposed from other industries (e.g. oil and gas) ● Of course, there’s an enormous role for the oil and gas industry because they have all the skills and experience. I think there are four different direct air capture technologies. And all of them can be coupled with basically every kind of energy supply source. (R094) ● [. . .] what do you do with the CO2? So, you need to have it as close to sequestration sites as possible. (R086) ● Of course, if you are thinking about modularity, if you are going to have smaller plants, then you cannot really justify dedicated pipelines, can you? (R082)	Infrastructure
Niche applications and some proven technologies; mix of established and new science ● I think there is *great potential for innovation in the solid sorbent* technology. It’s Climeworks, isn’t it? I think it’s Climeworks that is sort of a- start in that direction, *but I think there is a lot going on in university labs on solid sorbents. At the moment though, the solid sorbent costs really drive the cost of that technology.* It’s a huge component. If you can drive down those costs, increase performance, you can go a long way. (R014)	Technological readiness and radicalness
Need to establish socio-political legitimacy first (e.g. currently a waste, not a value-input) ● There *is no commercial benefit of any of these geological storage options, if you exclude EOR* [. . .] So, leaving EOR aside, I don’t see any direct economic benefit of any of the geological storage options. So, again, it’s a political market. (R106)	Est. legitimacy through learning
Needs to be established: dependent on future carbon pricing regulations ● I think the initial market would probably be enhanced oil recovery, would be my hunch. That’s sort of consistent with what you see [. . .] like oil and gas companies announcing partnerships with DAC companies [referring to carbon engineering]. *So, I think like that would probably be the initial business model, but I mean that’s assuming some level of carbon pricing and climate policy.* (R006)	Regulatory regime
Essential and likely needed long term, as there is otherwise no market ● *Of course, it’s hard unless it’s paired with some government subsidies or some political imperative to do it, because they’re significant more expensive.* I think it’s just that the chemical processes are not so efficient and to reach the scale that it would need would be a lot. (R052)	Policy incentives
Needs to be established, and dependent on policy (incentives and policy) ● I think EOR, it’s a promising, near-term business case, and that’s why I think [. . .] because whatever incentive that you get, you’re also getting the incentive of the barrel of oil that you’re producing. (R115)	Business models
Potentially relatively high unintentional consequences, both positive (e.g. transition away from for example oil and gas dependency) and negative (negative: leakages, hazardous siting, etc.) ● Anything that involves carbon capture and storage clearly has all the *storage risks* that have been discussed for many years in that domain. It’s a thing that worries people, isn’t it? *What happens if this stuff leaks from a major storage site in the North Sea?* (R026) ● For us, *that’s a very strange way of using potential carbon removal technologies, to expand oil and gas production.* (R096) ● [. . .] *But it also shows you who can benefit from them because, for example, Exxon Mobil, I think, was interested in Global Thermostat’s technology.* (R082)	Uncertainty/unintended consequences

(*continued*)

DACCS – first-order analysis, sample quotes (emphasis added) and second-order themes

First order	Second order
Relative complexity ● [. . .] Whereas in other contexts, *circular economy is taken to represent a form of CO2 removal, which it might not be. And so, there is a risk of obfuscating, from an atmospheric carbon perspective, what is actually happening.* And I have been always very cautious with the term carbon capture and use, CCU. Or worse even CCUS, where even the concept as such doesn't state what it is meant to do in terms of carbon flows. Yes, it has big potential for obfuscation. (R115)	Carbon accounting
Partnering with oil and gas could undermine initial socio-political legitimacy; Will be undermined without sustainable OSCM practices ● Something that emerged from our stakeholder engagements was the *risk of associating too closely with the fossil or the aviation industry, which seemed to be very publicly criticised.* They say that this close association may kill [DACCS] these companies. (R082) ● But they still need to be very thoughtful in the location of these systems, *number one, because if you must be via renewables, you need to make sure you have access to very large renewables.* (R115)	Reputation risk

Source(s): Authors' own creation

time" (Pagell and Shevchenko (2014, p. 45). NETs however face poorly defined markets, infrastructure and partnerships, thus requiring radically new supply chain reconfigurations.

Such challenges of sustainable innovation have been examined by socio-technical transition studies as a transformative process involving technology management, user practices, policy, industrial networks and infrastructure (e.g. Geels, 2002, 2004; Geels *et al.*, 2018; Weber and Rohracher, 2012). Transitions occur through processes of change in technological, material, organizational, institutional, political, economic and socio-cultural systems that lead to a complete (radical) or partial (incremental) replacement of the "old" with the "new" (Markard, 2011).

Energy supply is one type of socio-technical system, which involves interrelated networks of stakeholders (e.g. firms, government, consumers, NGOs), institutions (e.g. regulations, standards, incentives), materials (e.g. equipment, reagents, etc.) and knowledge (Geels, 2004; Markard *et al.*, 2012). For example, Jacobsson and Bergek (2011) find that key weaknesses in supply chain diffusion among vertically connected firms include an inadequate technology base and lack of institutional support (e.g. R&D policies). Such difficulties are strongly related to coordination challenges when dealing with complementary firms and technologies in long supply chains.

According to the sustainable transitions literature, radical innovation usually requires an incubation period, where favorable market conditions and resource access incentives are available, allowing for experimentation and learning until adoption and diffusion hurdles are overcome (Geels, 2002). Building on Aldrich and Fiol (1994) and Hall *et al.* (2014) refer to this process as legitimization, specifically cognitive legitimacy, the knowledge that is needed to succeed in an industry, versus socio-political legitimacy, the value placed on it by cultural norms and political influences. They suggest that innovations establish legitimacy as technical performance and social acceptance co-evolve, allowing them to expand and reduce uncertainty. More recently, Hall *et al.* (2019) suggest that sustainability-focused new technologies typically lack cognitive legitimacy, specifically an economically viable business model. By leveraging socio-political legitimacy through, for example, demonstrating more sustainable products or services, the technology developers can justify longer term investment and time to establish cognitive legitimacy.

Previous research emphasizes the importance of defined business models for sustainable OSCM (Erhun *et al.*, 2021; Van Wassenhove, 2018). Using the case of bioenergy from organic

Table 5. Overview of selected cases and key features – OAE

OAE – First-order analysis, sample quotes (emphasis added) and second-order themes	
First order	Second order
Needs to be built, but has almost unlimited CO2 storage potential ● From my understanding, to have an impact you would build up an industry like the global coal industry. So, you would move a lot of stones and I do not think that's so realistic. (R008) ● Certainly, alkalinisation is one of those because people have said that, if we were to try and raise the alkalinity of a global ocean, we'd need the entire world shipping fleet to ship the stuff around. We'd need a mining industry that's probably as big as the rest of the mining industry, almost, as exists today. (R060)	Infrastructure
Technology has yet to be proven, difficult to test in situ and draws on relatively new science ● There are some ideas of many different ways one can do ocean alkalisation, but *there isn't a lot of solid engineering behind how you would actually deploy an ocean alkalisation technology.* There's, "okay, we know, if we increase the alkalinity of seawater, we can get the ocean to take up more carbon," but how exactly you do that, there's still an innovation gap there that really needs to be filled. (R036)	Technological readiness and radicalness
Need to establish both socio-political and cognitive legitimacy since the technology is unproven ● What does the public want? People, I think, are *very sceptical* of dumping anything that seems like chemicals into the ocean, so I think that's going to constrain it. (R036) ● *We need a lot more experimentation* – laboratory, and perhaps even some very small-scale field trials – before we can really start to get a handle on that. (R060)	Est. legitimacy through learning
Needs to be established: dependent on future carbon pricing regulations; complexity due to ocean rights ● When you're plonking enhanced rock dust down on the ground, you know where you've put it, and it pretty much stays there. When you're doing that in the ocean, there's no telling where that's going to end up. So, *there are some international and transnational boundary issues, and governance issues associated with it.* (R037)	Regulatory regime
Essential and likely needed long term, as there is otherwise no market ● [. . .] so, *if there's not a carbon tax or some company isn't willing to pay to remove their legacy CO2*, there's probably not a good business case to do ocean alkalinity enhancement at the moment. (R036) ● For many of these approaches, they *rely on a carbon tax at the moment. Nobody is going to pay you to do ocean alkalisation right now*, so, if there's not a carbon tax or some company isn't willing to pay to remove their legacy CO2, there's probably not a good business case to do ocean alkalinity enhancement at the moment. (R036)	Policy incentives
Currently hypothetical; dependent on policy (incentives and policy); differs from DACCS in that it does not allow for captured carbon use ● That's the beauty of this – alkalinity is made of CO2. At the same time, this alkalinity helps to take up more CO2 from the atmosphere. *So, you could, in theory, make ships CO2 neutral.* (R015) ● So, [dredging] *companies that are very well-positioned to do that, those companies that are specialised in that will be very well-positioned to become a seller* as well as a developer of these carbon-negative projects. [. . .] Other dredging companies are starting to look into this. (R080) ● This might be different for ocean alkalinity management. From my understanding, to have an impact you would build up an industry like the global coal industry. *So, you would move a lot of stones and I do not think that's so realistic.* (R008)	Business models
Highly complex, with unknown ecosystem impacts; geopolitical issues; requires yet-to-be established international governance regime ● We've got to be realistic about the *biophysical constraints*, and we've got to be realistic about what that means for places where we live at scales we live at? (R004)	Uncertainty/ unintended consequences

(*continued*)

OAE – First-order analysis, sample quotes (emphasis added) and second-order themes

First order	Second order
• And you have high energy consumption, probably a bad carbon balance in that with the current energy sources, you have *unpredictable income from the marine sector*, and you have significant *biodiversity and land-use impacts* in the terrestrial ecosystems. So, I don't think that's an option. (R041) • When you're plonking enhanced rock dust down on the ground, you know where you've put it, and it pretty much stays there. When you're doing that in the ocean, there's no telling where that's going to end up. *So, there are some international and transnational boundary issues and governance issues associated with it.* Maybe it's got some- because of the co-benefits on reducing ocean acidification, maybe that's got more potential in the future. (R037)	
Highly complex • One of the *problems*, I mentioned before, for enhanced weathering, is the *carbon accounting*. We are *still working* on the carbon accounting: how much carbon is really bound? [. . .] With enhanced weathering, it's not so simple because the effects are so complex, with the soil and with the plant system. You can say that, likely, in thousands of years, this has sequestered so much CO2, but we do not know if it's in 5 years or 100 years, or in 1,000 years. (R015)	Carbon accounting
Major opposition likely (lacks legitimacy); will be undermined without sustainable OSCM practices; cannot exist without transitional sustainable OSCM • The chemistry and the physical potential is there, but we need to know: what are the biological impacts, because *I don't think you can just increase alkalinity as much as you want? You can only do so much before you start having a negative impact on ecosystems.* (R036) • [. . .] Even if it's not the case, it's just the perception of people. *If people have the perception what Microsoft doing there is not good, that would be for them the worst case.* Therefore, I think they would be *very resistant to do something like ocean alkalinity management, putting something into the ocean. I rather see that on the state level.* (R008)	Reputation risk

Source(s): Authors' own creation

Table 6. Overview of selected cases and key features

	Biochar	DACCS	OAE
Type of technology	Biological based	Chemical based	Ocean based
Technological maturity	Established and in use; based on established science	Niche applications and some proven technologies; mix of established and new science	Technology has yet to be proven, difficult to test *in situ* and draws on relatively new science
Efficacy	High	Variable	Potentially high
Estimate production costs	\$200 t $CO2^{-1}$ or less *	\$430–570 t $CO2^{-1}$ **	\$60 t $CO2^{-1}$ removed for dunite and \$200 t $CO2^{-1}$ removed for basalt **
Application and potential advantages	Reduce climate change, generating renewable energy, managing waste and improvement of soils		Drawdown and provide long-term sequestration of CO2

Note(s): *Elias *et al.* (2024), **Strefler *et al.* (2018)
Source(s): Authors' own creation

residues, Knight *et al.* (2015) identified pricing and availability of feedstock as key supply constraints in the technology adoption, which could be through collaborations among buyers and intermediaries. Drawing on a biochar supply chain analysis, Anderson *et al.* (2017)

identify information management, resources and materials across the supply chain as key factors in moving this technology from a nascent to an established industry.

Combined, the above studies raise the need for effective guidance in dealing with the complex confluence of factors required for a low-carbon transition. However, according to the sustainability transitions view, OSCM for NETs must start with a clear prioritization of environmental criteria (i.e. carbon negativity) as the basis of the business model, otherwise, NETs would lack legitimacy. Consistent with Montabon *et al.* (2016) and Griggs *et al.* (2013), only then can other criteria, such as economic performance be incrementally addressed and eventually establish cognitive legitimacy through learning (Hall *et al.*, 2014).

Regarding supply chains and network design, research focuses mainly on the economic optimization of physical flows, decisions about location, amount and capacity of facilities and supplier selection aspects using analytical modeling (see Meixell and Gargeya, 2005 for an overview). Accordingly, studies on sustainable and low-carbon supply chain design have also been approached through these methodologies (e.g. Eskandarpour *et al.*, 2015; Gopalakrishnan *et al.*, 2021). However, studies exploring how supply chains can be designed for sustainability transitions remain sparse. One exception includes Erhun *et al.* (2021) who reconceptualize Lee's (2004) triple-A supply chain to propose a "sustainable triple-A supply chain" by incorporating sustainability in the definitions of agile, adaptable and aligned supply chains and achieved through radical innovation that focuses on sustainability in products/services, processes or infrastructure, restructuring existing supply networks or vertical integration. Similarly, Dooley *et al.*'s (2019) supply chain links to emissions study find empirical evidence that more modular process networks and those with higher commonality have lower production emissions than less modular ones.

In response, we propose to expand the SSCM literature by including insights from the sustainable transitions discourse, resulting in "transformative OSCM." As we explore next, such an approach requires policy intervention, including new regulatory regimes and incentives that will provide the basis for business models. It also departs from mostly retrofitting changes, the focus of much of the OSCM discourse. Such transformative innovation usually requires a period of incubation, where favorable conditions such as market selection, access to resources and incentives are provided, allowing for experimentation and learning until adoption and diffusion hurdles are overcome. It may also depart from contemporary SSCM thinking, as transformative OSCM will need to prioritize ecological requirements over social and economic challenges, as the legitimacy of much of these technologies are based on their ability to rectify climate change, but otherwise offer no other value proposition. However, without them, we will be gambling on adaptation and mitigation technologies that will unlikely meet the Paris Accord targets.

Empirical foundation: illuminating the underlining OSCM mechanisms of NETs

Biochar. During the interviews, experts agreed that biochar can contribute to negative emissions immediately, given that some business models have already been implemented, such as fertilizers and veterinarian products or as a biofilter for gas and water filtration. Regarding infrastructure, biochar can benefit from the huge global volume, agricultural land and heavy use of fertilizers, which it could potentially replace. However, crucial considerations are the ability to demonstrate that biochar can enhance soil productivity and agricultural yield and moreover to do so competitively in various environments, with minimal transaction and implementation costs for farmers and land managers (cognitive legitimacy). This could be further catalyzed through policy interventions and clear regulatory frameworks resulting in wider biochar application adaptation in various sectors, such as agriculture or construction.

Another issue that arose is the infrastructure needed for the technology to reach scale. Although biochar as a soil amendment would require minimal changes for potential customers, suppliers of biochar are different from incumbent fossil-based fertilizer firms.

Hence, such a substitution would probably necessitate a separate resource channel and supplier switching. Furthermore, short-term demand was identified, given that much of the required biomass is "*already spoken for*" (R019). Lastly, complementary innovators will need to be able to participate financially with the carbon-sequestration potential of biochar (and enhanced weathering), i.e. by obtaining carbon credits through monitor, report and verify frameworks.

Previous research (Low *et al.*, 2022; UK Centre for Ecology and Hydrology, 2021) located biochar at various Technology Readiness Levels [4] between 5 and 6, given its different applications of which some are already in use. Biochar technology is based on substantial research, including a variety of laboratory experiments and field trials undertaken globally. Hence, biochar is not perceived as a radical technology but rather as a slow transition toward negative emissions in a "*very low-tech manner*" (R015; R019).

The presently limited knowledge of how the various layers of soils and their constituent organisms interact vis-à-vis the long-term sequestration of CO_2 represents an obstacle for commercializing biochar as a negative emissions technology and as such there are risks of potential unintended consequences. They are however mostly perceived as problematic for large-scale biochar applications, as indicated by R114: "*I do think the problem is scale and the way it's being done. I think, from our perspective, doing the type of biochar at a small scale* [. . .] *has nothing to do with geoengineering.*" In general, unintended consequences for biochar are relatively minor and uncomplex as they are usually spatially contained. Reputation risks associated with this technology and its applications are rare.

After more research on potential soil problems has been conducted, relatively straightforward application pathways could be imagined through learning and experimentation, increasing biochar's cognitive legitimacy. For example, through a matrix that offers a "*best-practice guide*" that "*says you have this climate, this soil, you want to grow this or that, then you have to apply that rock powder, that biochar to optimize the carbon storage in the plant and in the soil*" (RO15). However, biochar solutions require sustainable OSCM practices, such as the use of clean energy and short transportation routes between production and application locations, otherwise, their negative emissions purpose would be significantly undermined.

For carbon accounting, mixed views were observed among the experts, regarding the ability to monitor, report and verify how much CO_2 is stored by biochar. Compared to the other two cases, biochar's carbon accounting is relatively simple, however, adding a long-term perspective raises questions about the *permanence of carbon storage by adding* "*huge uncertainty as to what is actually happening with carbon in the soils*" (R039). In addition to encouraging new technological innovations, such a gap could also be addressed by engaging new partners in operations and supply chains. For example, ongoing trials undertaken by Project Carbdown (CDI, 2021) aim to investigate how much the combined application of enhanced weathering and biochar on agricultural fields can promote CO_2 removal and sequestration to generate carbon credits. This project thus departs from quintessential academic procedures by including specialist IT infrastructure-monitoring and a field service software management firm to develop low-cost devices to enable real-time "smart monitoring" of CO_2 removal.

DACCS. The supply chain and infrastructure for DACCS need to be carefully designed, both up and downstream. DACCS facilities are often cited for reduced spatial use and locational flexibility compared to other forms of carbon removal, although experts stated that this is misleading. Depending on the variant (solid versus liquid sorbent), DACCS infrastructure and upstream supply chains must navigate "co-location" between renewable or fossil fuel energy sources, water and other inputs, while transportation (pipelines and/or vehicles), storage sites (terrestrial or undersea formations) and diverse carbon-product facilities are also factors (Low *et al.*, 2022). Solid sorbent DACCS could be located where renewables or waste heat are plentiful but unused, but perhaps at the expense of transport and storage. The range of co-locations that determine supply chains and capabilities is vast and currently immature and speculative.

From a downstream perspective, DACCS infrastructure needs to be built or repurposed from other industries such as petroleum, contingent on how the captured CO_2 is utilized. While biochar has direct use cases, DACCS' output is storable CO_2, a perceived waste that needs sequestering in currently limited underground geological formations (e.g. basalt): "w*ith the exception of North America, we've got* [. . .] *physically* [not] *in place right now*" (R077). However, experts also frequently referred to enhanced oil recovery (EOR) as a well-established business model and technical processes to use captured CO_2. EOR injects captured CO_2 into existing or depleted oil and gas fields to push out limited remnants, thereby lengthening its lifespan while sequestering CO_2. To date, EOR is the only industrial use of CO_2 reaching scalability. In the near term, EOR offers an opportunity to retrofit or shift the directionality of existing infrastructure, offering immediate learning and cost-reduction opportunities for sequestering CO_2 in fossil fuel reservoirs. Interviewees stated that it is thus currently the only viable business model and "*there is no commercial benefit of any of these geological storage options if you exclude EOR*" (R106). However, experts were also skeptical regarding EOR durability, given impending peaks in fossil fuel production and the paradox situation where:

> [You] have paid the oil, gas, big energy companies trillions of dollars over the last couple of centuries to pull carbon out of the ground. You might pay the same companies trillions of dollars, through some carbon price scheme or some more direct incentive or through some kind of producer obligation, to put the stuff back in again. Of course, that, in a sense, is a paradox but it's also not an unreasonable scenario given that they have the skills, geological scientific skills [and] the knowledge (R094).

Indirect business models for DACCS have been subsumed under the term carbon capture and utilization (CCUS) that include applications that use captured CO_2 in second-life products, such as construction materials, food and beverages production or synthetic fuels. Thus, captured CO_2 "*can create a market, because it will be tied into utilization and that has a $1 trillion opportunity as a market – and that's huge*" (R052). However, DACCS is currently described as a technology that produces carbon waste with limited commercial viability, making it a "*political market*" (R106), meaning that regulatory frameworks and policy incentives are needed. Its success will thus be dependent on governance around future carbon pricing and accounting, with challenges over calculating life cycle emissions and gaps in monitoring, reporting and verification for carbon accreditation.

Low *et al.* (2022) and the UK Centre for Ecology and Hydrology (2021) located DACCS at Technology Readiness Levels 6–7. Besides EOR, DACCS illustrate technologies currently unproven at scale, except for some beacon applications by Climeworks in Iceland (Birnbaum, 2021). The current landscape sees a "*new phase of direct air capture companies* [. . .] *that are all about smaller modular and specific niche applications*" (R052). Modularity options are perceived by many experts as key for learning processes, innovation and scaling: "*modularity can happen within a large plant. So, if you modularize its components, then you have a modular supply chain and so you're still getting that benefit of standardization*" (R052). Others disagree, differentiating between capturing and storing, with the latter disadvantaged on scale economies when modularized. It further seems difficult to justify dedicated pipelines for smaller modularized facilities.

DACCS can thus be characterized as relying on a mix of established (EOR) and new science, where experts describe it as radical and potentially disruptive, especially if more solid sorbent innovation emerges. The costs of high- and low-temperature chemical reagents need to be reduced through scale economies. Interviewees stated that high-temperature solvents are more readily available from existing supply chains, whereas low-temperature solid sorbents require certain nanomaterials which "[. . .] *don't have supply chains yet.* [. . .] *Someone must build* [these]. *The first thing you'd see if solid sorbents are going to win is you'll see a Gigafactory equivalent of the supply chain to make those things*" (R086). Solid sorbents also contain more cost uncertainties and therefore require dedicated rather than retrofitting existing production processes and supply chains.

During the interviews, potential unintended consequences for the technologies' legitimacy were raised, such as "hazardous siting" (Hunold and Young, 1998) and "not in my back yard" (NIMBY). Pollutive industrial facilities have historically been located amongst marginalized communities (e.g. hazardous siting) with lower environmental, health and labor standards, and whose presence sometimes serves to depress standards through socioeconomic interdependence. Unintended consequences, such as carbon leakages from storage facilities are also a concern. In this context, the social acceptability and legitimacy of DACCS might be significantly low due to the NIMBY phenomenon, where concerns about health, pollution and social equity are subsumed with more general, even superficial concerns about the presence of any kind of change in an established culture and landscape. NIMBY could thus limit the storage location choice for DACCS, as "*some regions have less easy access to geological potential for sequestration"* (R014).

Regarding reputation risks, experts reiterated that low-temperature, solid sorbent DACCS relies upon a scaled renewable energy economy that does not yet exist. Until then, there will be trade-offs rather than synergies between DACCS and other energy needs, which could undermine the technology's legitimacy. Moreover, experts frequently highlighted the reputation risks of being associated with fossil fuels through EOR, which "*may kill* [DACCS] *companies, or may hurt them significantly*" (R082). Conversely, experts emphasize that EOR offers policy opportunities for transitioning local communities dependent on the petroleum sector. If DACCS prolongs fossil fuel infrastructures in such communities, their gradual retirement might allow workers to transition from carbon extraction to sequestration, mitigating societal inequities while maintaining social cohesion and creating business opportunities.

OAE. Currently, OAE infrastructure is lacking, but a major advantage is that the technology offers almost unlimited CO_2 storage potential. Unlike terrestrial enhanced weathering cases, no related supply chains exist, which leads some experts to speculate that OAE will be "*more of a local to regional operation if it can get to that scale, and not a global solution*" (R060). Another stated: "*to have an impact you would build up an industry like the global coal industry. So, you would move a lot of stones and I do not think that's so realistic*" (R008). One potential solution to scale up OAE infrastructure and logistics was mentioned by R015 and colleagues, who alluded to the possibility of "*ships which have the minerals and maybe also a CO2 source on board.* [. . .] *Because we have so many ships travelling, they can release, always, a little bit* [mineral products for OAE] *while travelling,*" which however was skeptically considered due to the "*need* [for] *the entire world shipping fleet to ship the stuff around*" (R060).

Like DACCS, there are currently no clear business models for OAE and indeed might be more difficult to imagine, according to the experts. One major difference with DACCS is that OAE does not allow for CCUS. OAE-removed CO_2 is stored in oceans, making utilization difficult. However, two currently hypothetical business models were discussed. The first alluded to the generally "dirty" shipping industry and that "*to make ships CO2 neutral, if you take 5–10% of the volume of a large ship* [. . .] *you can store the mineral products, lime, and you have a reactor. Then you can use the CO2 from the engine and then you neutralize it. The CO2 will be transferred into alkalinity* [which] [. . .] *helps to take up more CO2 from the atmosphere. So, you could, in theory, make ships CO2 neutral*" (R015). Others mentioned how the dredging industry might "*open up a whole market*" for carbon removal that avoids the land-use conflicts, along with being "*well-positioned to actually become a seller as well as a developer of these carbon-negative projects,*" with some dredging companies already looking into this option (R080). This might be an upcoming development, given that "*the naval sector has been kept out of the Kyoto and Paris accords*"; "*but the IMO, the International Maritime Organization of the UN has already said that* [they] *need to have* [their] *game in order,* [. . .] *so, the naval sector is scrambling now to come up with interesting ideas*" (R080).

Nevertheless, besides these to unrealized business models, OAE presents a "political market" like DACCS reliant on policy incentives and regulatory frameworks, such as carbon taxation: "*Nobody is going to pay you to do ocean alkalization right now, so, if there's not a carbon tax or some company isn't willing to pay to remove their legacy CO2*" (R036).

Another important factor is that OAE technology is currently unproven, difficult to test *in situ* and draws on relatively new science. Thus, consistent with our experts, previous research characterized OAE at TRL3 (Low *et al.*, 2022), versus terrestrial counterparts, which is classified at TRL5 given the stronger evidence regarding benefits and risks, e.g. in agricultural soils. Accordingly, "*there's still an innovation gap there that really needs to be filled*" (R036), and ongoing experiments and field trials are needing to run the gamut of research, development and deployment activities, with current projects simultaneously undertaking laboratory toxicity experiments, weathering process modelling and real-world field trials. This is best reflected by the multi-stage "project roadmap" put forward by Project Vesta (https://www.vesta.earth), a prominent OAE project.

Given these technological uncertainties, experts indicated that OAE probably faces significant unintended consequences: "*When you're plonking enhanced rock dust down on the ground, you know where you've put it, and it pretty much stays there. When you're doing that in the ocean, there's no telling where that's going to end up*" (R037). Experts emphasized that OAE is much more difficult to contain than land-based technologies, given the oceans' fluidity, calling for international regulation "*because you're adding something in the ocean that's not going to stay within your territorial waters, so there are cross-boundary effects*" (R036).

Problems linked to limited *in situ* experimentation, potential detrimental unintended consequences and thus reduced learning opportunities lead to low cognitive and socio-political legitimacy as indicated by the experts:

> It's just not at the level of granularity where you feel comfortable to know what was happening and make an informed decision or be able to have an informed discussion with potential stakeholders around what the implications may be (R004).

> What does the public want? People, I think, are very skeptical of dumping anything that seems like chemicals into the ocean, so I think that's going to constrain it. We need a lot more experimentation – laboratory, and perhaps even some very small-scale field trials – before we can really start to get a handle on that (R060).

Reputation risks have thus been linked to the implementation of OAE, due to public opposition and the potential contradiction of the technology's purpose without sustainable OSCM practices. Shipping and dredging industries are usually blamed for high net carbon emissions and high energy density. Moreover, the reliance on mining to provide vast amounts of basalt, lime and other rocks faces other sustainability issues, creating reputation risks. This multitude of risks and uncertainty is further exacerbated by highly complex and uncertain carbon accounting.

Table 7 summarizes our findings for each case and how they relate to our second-order themes, details of which will be discussed next.

Propositions: beyond the "new normal"

While a sense of urgency is emerging, there remain considerable challenges over how rectifying climate change can be operationalized, given the scale of the required investments and the need for global cooperation amongst a wide range of stakeholders. Currently, it remains uncertain how much it will cost to reverse climate change, and how it will be regulated and incentivized. As a result, the industry is still speculating on what business models may be suitable.

Table 8 summarizes the three approaches to how OSCM can respond to climate change. While contemporary approaches to incorporating sustainability in OSCM may be useful and necessary for adaptation and mitigation, it may not be sufficient for some emerging NETs. Given their novelty, some of these technologies will likely struggle due to poorly defined

Table 7. Summary of findings for the three selected NETs

Second order themes	Biochar	DACCS	OAE
Infrastructure	Can currently be facilitated via established OSCM practices	Needs to be built or repurposed from other industries (e.g. oil and gas)	Needs to be built, but has almost unlimited CO2 storage potential
Technological readiness and radicalness	Established and in use; based on established science	Niche applications and some proven technologies; mix of established and new science	Technology has yet to be proven, difficult to test *in situ* and draws on relatively new science
Establishing legitimacy through learning	Opportunities to improve economics and cognitive legitimacy	Need to establish socio-political legitimacy first (e.g. currently a waste, not a value-input)	Need to establish both socio-political and cognitive legitimacy since the technology is unproven
Regulatory regime	Evolving, but currently limited to specific sectors	Needs to be established: dependent on future carbon pricing regulations	Needs to be established: dependent on future carbon pricing regulations; complexity due to ocean rights
Policy incentives	Initially as catalyst to get started (transitions literature)	Essential and likely needed in the long term, as there is otherwise no market	
Business models	Established and based on dual use	Needs to be established and dependent on policy (incentives and policy)	Currently hypothetical; dependent on policy (incentives and policy); differs from DACS in that it does not allow for captured CO_2 use
Uncertainty/ unintended consequences	Relatively minor; relatively uncomplex and spatially controlled	Relatively high Negative: Leakages, hazardous siting, NIMBYetc. Positive: May allow resource-based regions to transition away from, e.g. oil and gas dependency; captured CO2 can be used for other applications	High: Very complex Negative: Unknown ecosystem impacts; geopolitical (e.g. storage ownership) issues; requires yet to be established international governance regime
Carbon accounting	Comparatively simple but with contradictory views	Relatively complex	Highly complex
Reputation risk	Will be undermined without sustainable OSCM practices	Partnering with O&G could undermine initial socio-political legitimacy; will be undermined without sustainable OSCM practices (e.g. transportation, energy use, etc.)	Likely will be met with major opposition (lacks legitimacy); will be undermined without sustainable OSCM practices; cannot exist without transitional sustainable OSCM (shipping, mining, etc.)

Source(s): Authors' own creation

markets and lack of infrastructure and partnerships. As such, they will require radically new supply chain reconfigurations.

The relationship between climate change and OSCM is paradoxical. Past behavior contributed toward exacerbating climate change (Dooley *et al.*, 2019; Gopalakrishnan *et al.*, 2021) so there is a sense of culpability. Conversely, OSCM will be widely affected by climate

Table 8. Summary of OSCM approaches to climate change

Issues	Adaptation	Mitigation	NETs
Strategic stance	Reactive (“wait and see”) strategy to climate change in anticipation (or after) of it happening	Proactive; responding to normative and regulatory pressures to address climate change beforehand	Embracing climate change as core to new business opportunities
Climate change assumptions	Cannot be reversed, so we need to learn to cope	Can be reversed to manageable levels through retrofitting	Can only be reversed through new carbon capture (and storage) means
Objective	Survival by reorienting to the “new normal”	Reduce emissions while maintaining economic viability and legitimacy	Reverse climate change under the assumption that mitigation is inadequate
Starting point	Retrofitting existing supply chains		Radical infrastructure and supply chain reconfiguration
Supply chain changes	Relocating supplier locations, processes, products and services, etc.	Incrementally improve environmental performance while maintaining economic viability	Must start with environmental (carbon negative) criteria and then incrementally improve economic performance through learning
Approach to innovation	Incremental	Mostly incremental	Radical
Financial risk	Moderate (i.e. new partners, locations etc.)	Relatively low; mitigation costs passed on to consumers or suppliers; incrementally reduced through learning	High; new unproven technologies, poorly defined markets and infrastructure, partnerships, etc.
Reputation and litigation risk	Focusing only on cognitive legitimacy may result in future litigation, boycotts, supplier preference delisting, etc.	Focus on socio-political legitimacy reduces perception of culpability	High, if unintended consequences not considered
Policy issues	Established regulations that must be met	Established regulations that must be met, but often prepared to address new regulations	Policy intervention needed for new regulatory regimes and incentives that will provide the basis for business models
OSCM approach	Traditional OSCM approaches	Traditional OSCM + Sustainable OSCM	Traditional OSCM + Sustainable OSCM + Transformative OSCM

Source(s): Authors’ own creation

change in terms of supply issues (Alves *et al.*, 2017; Ghadge *et al.*, 2020; Kara *et al.*, 2021), demand, consumer behavior and regulatory uncertainty (Chen and Wang, 2016; Drake, 2018; Sunar and Plambeck, 2016). In response, firms will need to embark on adaptation strategies, allowing them to shift into the “new normal.” However, none of these practices are necessarily linked to sustainability but rather utilize proven generic OSCM techniques and strategies which contribute little to the implementation of true sustainability (Pagell and Shevchenko, 2014). Such a stance may maintain cognitive legitimacy but does nothing for socio-political legitimacy (Aldrich and Fiol, 1994; Hall *et al.*, 2014, 2019), and thus the shadow of culpability remains.

Whereas adaptation is a reactive response to climate change, a more proactive response is mitigation. Although numerous studies emphasize mitigation in the OSCM literature, most are focused on reducing emissions assessment (Alvarez *et al.*, 2018; Rizet *et al.*, 2012), typically through established practices such as collaboration, engagement and supplier information exchange (Dahlmann and Roehrich, 2019; De Stefano and Montes-Sancho, 2024; Jira and Toffel, 2013) and local sourcing and production (Nieuwenhuis *et al.*, 2012). All have been shown to reduce emissions and will be necessary but perhaps insufficient to reverse climate change, where firms face trade-offs between different sustainability dimensions, such as labor productivity and carbon neutrality (Sartal *et al.*, 2020). Indeed, while mitigation clearly involves sustainability (Atasu *et al.*, 2020), these improvements are mostly incremental and constrained by economic pressures. They thus reflect many of the shortcomings frequently criticized in the SSCM literature (Gold and Schleper, 2017; Montabon *et al.*, 2016 Pagell and Shevchenko, 2014; Pagell and Wu, 2009; Sarkis, 2021).

One insight discussed from our study suggests that while adaptation can be achieved through traditional OSCM approaches, it does little to protect the firm from reputational damage and nothing to rectify climate change. Such a "business as usual for the new normal" (Wright and Nyberg, 2017) approach will undoubtably be under fire if other firms must carry the burden. Climate change thus sharpens the arguments extolling the virtues of adopting sustainable OSCM practices.

P1. Traditional OSCM will have limited positive effects on stopping or reversing climate change, which will in turn damage the reputation of firms.

To facilitate the development of negative emissions technologies, OSCM must transcend incrementalism and establish the necessary infrastructure. We therefore propose the concept of transformative OSCM, which recognizes the need for policy interventions to address ambiguous commercial incentives, while simultaneously prioritizing the critical challenge of our era. Consequently, it underscores the need for novel OSCM infrastructure and business models as integral components of this transformative process. Unlike contemporary sustainable OSCM approaches, transformative OSCM recognizes the need for robust mechanisms to foster the emergence of new technologies in industry sectors driven by social mandates but lacking clear commercial incentives. We thus postulate:

P2. Transformative OSCM, encompassing policy mechanisms and novel business models, will facilitate the development of negative emissions technologies.

A relatively new discourse calls for an understanding of the unanticipated outcomes of OSCM (Matos *et al.*, 2020). We responded by showing that, given the need for more radical technologies and practices, transformational OSCM will likely create detrimental unanticipated outcomes if not managed carefully, although this is contingent on the nature of the technology (Harvey, 2023). For example, in our cases, biochar appears less likely to create unanticipated outcomes compared to the others. An important implication for decision-makers is that without careful management, NETs could lose their socio-political legitimacy long before a viable business model can be established, as most technologies' main purpose is rectifying an environmental problem rather than exploiting an established and clearly defined market. Business models are already being developed, some of which may be questionable as they depend on collaboration among partially controversial stakeholders, such as petroleum companies for DACCS. Unintended consequences such as association with fossil fuels can significantly influence the creation of business models and the building of OSCM infrastructure, necessary for wide-spread adoption of these technologies, especially in the absence of more stable government incentives and regulatory frameworks:

P3. Lack of policy incentives and regulatory frameworks can create a negative (unintended) impact on OSCM infrastructure for negative emissions technologies.

Lastly, counter to much of the sustainable OSCM literature that emphasizes the importance of balancing the triple bottom line, the significant complexity and distinctive features of emerging NETs require prioritization of environmental parameters, given that their legitimacy is solely based on rectifying a major environmental crisis. These findings further reiterate the perspective of an ecologically dominant logic, as advocated for by Montabon *et al.* (2016).

P4. NET business models are solely dependent on tackling an environmental crisis and thus require an ecologically dominant logic that may unbalance triple bottom line approaches.

Contributions and conclusions

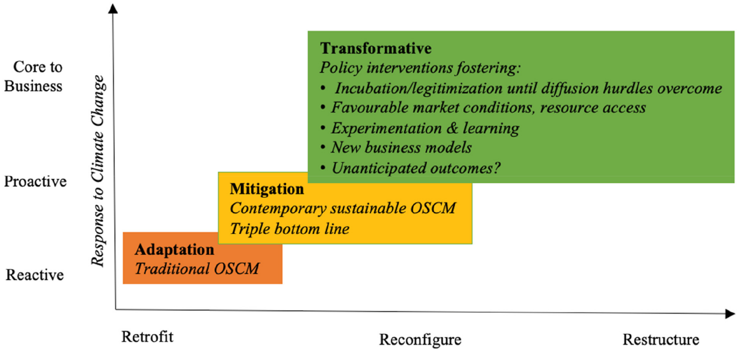
With the shift from polarized debate to implementation, scientific communities have identified a plethora of new technologies, techniques and policies for meeting emissions targets, but none will meet their potential without effective OSCM (Helper *et al.*, 2021). In response, we identified how OSCM can be adjusted to meet CO_2 reduction targets, recognizing that adaptation and mitigation are necessary but unlikely sufficient. We contribute to theory by developing transformative OSCM as a mechanism that directly embraces the climate challenge through NETs. New policy mechanisms will be needed to regulate and incentivize the development of business models, which in turn will provide the infrastructure and supply chains necessary for such technologies to live up to their potential for stabilizing climate change.

Figure 2 summarizes our conceptualization of transformative OSCM. On the *y*-axis we distinguish how firms and their supply chains respond to climate change. It builds on seminal approaches to environmental management, i.e. whether reactive, proactive or core to the business model, as is the case for NETs. The *x*-axis represents the required degree of OSCM change, which ranges from retrofitting, to reconfiguring to entirely new restructuring. The size of the boxes represents the scale of the challenges, as well as the business opportunities that these challenges present.

Adaptation can be both reactive or proactive, but still uses traditional OSCM practices, where for example firms can retrofit in response to, or in anticipation of, climatic disruptions (Wieland *et al.*, 2023). Such a response to climate change however does nothing to reduce CO_2 and thus is represented here in orange. Mitigation, represented here in light green, is more proactive, where the aim is to reconfigure OSCM practices with the ultimate aim of net zero (Atasu *et al.*, 2020). However, the overarching value proposition of the firm remains the same and rectifying climate change is not core to the business. That is not to say that such approaches are obsolete – indeed, they are absolutely necessary but unlikely sufficient.

In contrast, transformative OSCM's primary purpose is to reduce CO_2 and as a result, the response to climate change is core to the business. Building on Wieland (2021), transformative OSCM here applies insights from the transitions literature (Geels, 2002, 2004; Geels *et al.*, 2018) that calls for policy interventions that foster incubation that allow for experimentation and learning, such as early favourable market conditions and resource access. It also draws on the technology and operations management literature (Hall *et al.*, 2014; Matos and Hall, 2007) that emphasized the importance of legitimization processes to overcome complex hurdles and the unanticipated outcomes they may subsequently create (Matos *et al.*, 2020).

Transformative OSCM may be radical (Henderson and Clark, 1990; Wieland *et al.*, 2023), where new supply chains are forged, necessitating complex and resource-intensive alterations



Source(s): Authors' own creation

Figure 2. Conceptual model of OSCM approaches to the climate crisis

that can only become viable if the focus is shifted to environmental benefit. This phenomenon is for example evident in solid sorbents-based DACCS, where the integration of renewable energy sources requires the creation of new supply chains and industrial systems. Transformative OSCM innovation can also manifest via architectural innovation, where new OSCM approaches are required without significantly altering the individual components of the supply chain. Biochar, liquid-sorbent-based DACCS, and OAE are examples of technologies that utilize existing industrial systems but require a transition from prioritizing economic viability to emphasizing environmental benefits. These radical or architectural OSCM changes are difficult to identify and challenging to enact without the implementation of supportive policies.

Limitations and further research

This research was based on a preliminary study exploring new technologies for what has recently become a universally acknowledged crisis. As such, we acknowledge that our study has some inherent limitations and point out ways these can be addressed. The methodological challenges we encountered when researching early-stage technologies will diminish as NETs are further developed and implemented. Future research should leverage both qualitative and quantitative studies as new data becomes available to examine the nuances of transformative OSCM implementation, including addressing any unanticipated negative outcomes. Although data collected from the interviewees allowed for depth and breadth of analysis, other stakeholders who may be affected by the technology, such as farmers as users of biochar, are absent. Although we interviewed experts from 34 different disciplines, given the breath of the problem and the variety of potential technologies, data collection could include other stakeholders, as well as experts from related disciplines such as environmental law and political science. Future research should address these broader perspectives, which may raise other relevant issues and unintended consequences of NETs. A further limitation is the context under which issues identified in the data may (or may not) manifest. These could include, for example, socio-economic, geographical and temporal contexts, cultural, values and norms in different parts of the Globe and how these could hinder to promote of transformative OSCM. For example, future research could investigate the supportive policies needed to facilitate transformative OSCM in complex contexts, such as the Global South, which often operates under weak institutions and corruption.

A perhaps controversial but important area for further OSCM research is whether attempts to balance the needs and demands of the many have resulted in the state of procrastination and lethargy in addressing such an important problem. Counter to much of the discourse (including our own previous studies), the significant complexity, scale and urgency of the climate crisis requires prioritization of the environmental parameter. Additionally, most emerging NETs have limited utility without a strong focus on the environmental parameters, thus requiring focusing efforts in this area. It is thus worth exploring in greater detail how transformative OSCM may align with this prioritization, the requisite capabilities and the potential incumbency resistance such efforts may face. Such issues may sound daunting, but reinforce the need, and importance, for further OSCM research.

Lastly, all carbon removal technologies are linked to an ongoing debate on mitigation deterrence, or the moral hazard, in which the promise of eventual carbon removal creates systemic disincentives to undertake costly, substantial emissions reductions in OSCM. A broad assessment of unanticipated outcomes is thus an important area for future research. As noted by Nelson and Winter (1982), innovation resolves some problems but also creates new ones that must also be addressed. Past innovators, some of which pioneered the technologies that have contributed towards the climate crisis, could perhaps be judged as not responsible through ignorance, given that climate science was not understood. However, today we no longer have this excuse, and as such we have an obligation to search for how our efforts may result in detrimental outcomes and ways in which they can be avoided. Previous research has attempted to address this concern by bringing together technology developers with those responsible for commercialization, organizational issues and societal impacts at the early stages of the innovation process (Hall *et al.*, 2014, 2019; Hall and Martin, 2005). Such an approach can explore how diverse secondary stakeholders may affect or be affected by NETs, as well as the impacts it could potentially have on the environment.

Notes

1. See Smith *et al*. (2024) for a detailed overview of the current state of CDR.
2. We use "sustainability" as the main terminology throughout, although it might better be qualified as "environmental sustainability" and "environmentally sustainable." While environmental sustainability is intrinsically linked to a low-carbon economy, this cannot necessarily be said for social sustainability.
3. Although the same dataset has been used by the authors in other publications (blinded to protect anonymity), none focused on OSCM. Along with the distinct research questions addressed here, this provided ample uniqueness of analysis and theory building to develop a completely new paper (Kirkman and Chen, 2011).
4. Technology Readiness Levels (TRLs) is a method to define the level of technology maturity that considers different organizational and financial modes of technological development (Héder, 2017). Levels range from 1 (basic principles observed and reported) to 7 (adequacy validated).

References

Aldrich, H.E. and Fiol, C.M. (1994), "Fools rush in? The institutional context of industry creation", *Academy of Management Review*, Vol. 19 No. 4, pp. 645-670, doi: 10.5465/amr.1994.9412190214.

Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herndon, S.C., Jacob, D.J., Karion, A., Kort, E.A., Lamb, B.K., Lauvaux, T., Maasakkers, J.D., Marchese, A.J., Omara, M., Pacala, S.W., Peischl, J., Robinson, A.L., Shepson, P.B., Sweeney, C., Townsend-Small, A., Wofsy, S.C. and Hamburg, S.P. (2018), "Assessment of methane emissions from the US oil and gas supply chain", *Science*, Vol. 361 No. 6398, pp. 186-188, doi: 10.1126/science.aar7204.

Alves, M.W.F.M., Lopes de Sousa Jabbour, A.B., Kannan, D. and Chiappetta Jabbour, C.J. (2017), "Contingency theory, climate change, and low-carbon operations management", *Supply Chain Management*, Vol. 22 No. 3, pp. 223-236.

Anderson, N., Bergman, R. and Page-Dumroese, D. (2017), "A supply chain approach to biochar systems", in Bruckman, V., Apaydın Varol, E., Uzun, B. and Liu, J. (Eds), *Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation*, Cambridge University Press, Cambridge, pp. 25-45.

Atasu, A., Corbett, C., Huang, X. and Toktay, L. (2020), "Sustainable operations management through the perspective of manufacturing & service operations management", *Manufacturing and Service Operations Management*, Vol. 22 No. 1, pp. 146-157, doi: 10.1287/msom.2019.0804.

Augustine, G., Soderstrom, S., Milner, D. and Weber, K. (2019), "Constructing a distant future: imaginaries in geoengineering", *Academy of Management Journal*, Vol. 62 No. 6, pp. 1930-1960, doi: 10.5465/amj.2018.0059.

Bag, S., Rahman, M.S., Rogers, H., Srivastava, G. and Pretorius, J.H.C. (2023), "Climate change adaptation and disaster risk reduction in the garment industry supply chain network", *Transportation Research Part E*, Vol. 171, 103031.

Bals, L. and Tate, W. (2018), "Sustainable supply chain design in social businesses: advancing the theory of supply chain", *Journal of Business Logistics*, Vol. 39 No. 1, pp. 57-79, doi: 10.1111/jbl.12172.

Baum, C.M., Low, S. and Sovacool, B.K. (2023), "Coupling for climate intervention: sectoral and sustainability couplings for carbon removal and solar geoengineering pathways", *Technological Forecasting and Social Change*, Vol. 194, 122734, doi: 10.1016/j.techfore.2023.122734.

Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., Mercure, J.F., Pollitt, H., Holden, P.B., Edwards, N.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I.A., Hansen, J. and Banwart, S.A. (2020), "Potential for large-scale CO2 removal via enhanced rock weathering with croplands", *Nature*, Vol. 583 No. 7815, pp. 242-248, doi: 10.1038/s41586-020-2448-9.

Bijma, J., Smet, I., Hagens, M., Hartmann, J., Steffens, R. and Paessler, D. (2021), "Field trials of enhanced weathering combined with corn farming in Germany", *Goldschmidt2021 Virtual Conference*, 4-9 July 2021, available at: https://2021.goldschmidt.info/goldschmidt/2021/meetingapp.cgi/Paper/5745 (accessed 12 June 2024).

Birnbaum, M. (2021), "The world's biggest plant to capture CO2 from the air just opened in Iceland", *Washington Post*, available at: https://www.washingtonpost.com/climate-solutions/2021/09/08/co2-capture-plan-iceland-climeworks (accessed 12 June 2024).

Bloomberg (2020), "Carney calls net-zero greenhouse ambition 'greatest commercial opportunity'", Bloomberg, available at: https://www.bloomberg.com/news/articles/2020-11-09/carney-calls-net-zero-ambition-greatest-commercial-opportunity#xj4y7vzkg (accessed 12 June 2024).

Bloomberg (2023), "The US could remove 1 billion tons of carbon from the air — for $130 billion", Bloomberg, available at: https://www.bloomberg.com/news/articles/2023-12-11/united-states-carbon-removal-infrastructure-could-cost-130-billion (accessed 12 June 2024).

Burke, M., Hsiang, S.M. and Miguel, E. (2015), "Global non-linear effect of temperature on economic production", *Nature*, Vol. 527 No. 7577, pp. 235-239, doi: 10.1038/nature15725.

Carleton, T.A. and Hsiang, S.M. (2016), "Social and economic impacts of climate", *Science*, Vol. 353 No. 6304, aad9837, doi: 10.1126/science.aad9837.

Carlin, D. (2021), "The $100 Trillion investment opportunity in the climate transformation", *Forbes.com*, available at: https://www.forbes.com/sites/davidcarlin/2021/06/02/the-ieas-net-zero-climate-pathway-is-a-100-trillion-investment-opportunity/?sh=46e10c7e5597 (accessed 12 June 2024).

CDI [Carbon Drawdown Initiative] (2021), "Introducing 'Project Carbdown': our first 'enhanced weathering' field trial aims to remove CO_2 from the atmosphere", available at: https://www.carbon-drawdown.de/blog/2021-01-14-introducing-project-carbdown (accessed 12 June 2024).

Chen, X. and Wang, X. (2016), "Effects of carbon emission reduction policies on transportation mode selections with stochastic demand", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 90 No. 1, pp. 196-205, doi: 10.1016/j.tre.2015.11.008.

Cobo, S., Galán-Martín, Á., Tulus, V., Huijbregts, M.A.J. and Guillén-Gosálbez, G. (2022), "Human and planetary health implications of negative emissions technologies", *Nature Communications*, Vol. 13 No. 1, p. 2535, doi: 10.1038/s41467-022-30136-7.

Conway, D., Archer van Garderen, E., Deryng, D., Dorling, S., Krueger, T., Landman, W., Zhu, T., Lebek, K., Osborn, T., Ringler, C., Thurlow, J. and Dalin, C. (2015), "Climate and Southern Africa's water-energy-food nexus", *Nature Climate Change*, Vol. 5 No. 9, pp. 837-846, doi: 10.1038/nclimate2735.

Corbett, C.J. and Klassen, R.D. (2006), "Extending the horizons: environmental excellence as key to improving operations", *Manufacturing and Service Operations Management*, Vol. 8 No. 1, pp. 5-22, doi: 10.1287/msom.1060.0095.

Corbin, J. and Strauss, A. (2015), *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*, 4th ed., Sage, Thousand Oaks, CA.

Corley, K.G. and Gioia, D.A. (2011), "Building theory about theory building: what constitutes a theoretical contribution?", *Academy of Management Review*, Vol. 36 No. 1, pp. 12-32, doi: 10.5465/amr.2009.0486.

Costantini, V., Crespi, F., Marin, G. and Paglialunga, E. (2017), "Eco-innovation, sustainable supply chains and environmental performance in European industries", *Journal of Cleaner Production*, Vol. 155 No. 2, pp. 141-154, doi: 10.1016/j.jclepro.2016.09.038.

Dahlmann, F. and Roehrich, J.K. (2019), "Sustainable supply chain management and partner engagement to manage climate change information", *Business Strategy and the Environment*, Vol. 28 No. 8, pp. 1632-1647, doi: 10.1002/bse.2392.

Davoudi, S., Brooks, E. and Mehmood, A. (2013), “Evolutionary resilience and strategies for climate adaptation”, *Planning Practice and Research*, Vol. 28 No. 3, pp. 307-322, doi: 10.1080/02697459.2013.787695.

De Stefano, M.C. and Montes-Sancho, M.J. (2024), “Complex supply chain structures and multi-scope GHG emissions: the moderation effect of reducing equivocality”, *International Journal of Operations and Production Management*, Vol. 44 No. 5, pp. 952-986, doi: 10.1108/ijopm-11-2022-0759.

Dooley, K.J., Pathak, S.D., Kull, T.J., Wu, Z., Johnson, J. and Rabinovich, E. (2019), “Process network modularity, commonality, and greenhouse gas emissions”, *Journal of Operations Management*, Vol. 65 No. 2, pp. 93-113, doi: 10.1002/joom.1007.

Drake, D.F. (2018), “Carbon tariffs: effects in settings with technology choice and foreign production cost advantage”, *Manufacturing and Service Operations Management*, Vol. 20 No. 4, pp. 667-686, doi: 10.1287/msom.2017.0674.

DuHadway, S., Mena, C. and Ellram, L.M. (2022), “Let the buyer beware: how network structure can enable (and prevent) supply chain fraud”, *International Journal of Operations and Production Management*, Vol. 42 No. 2, pp. 125-150, doi: 10.1108/ijopm-05-2021-0310.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O. (2000), “Climate extremes: observations, modeling, and impacts”, *Science*, Vol. 289 No. 5487, pp. 2068-2074, doi: 10.1126/science.289.5487.2068.

Eisenhardt, K.M. and Graebner, M.E. (2007), “Theory building from cases: opportunities and challenges”, *Academy of Management Journal*, Vol. 50 No. 1, pp. 25-32, doi: 10.5465/amj.2007.24160888.

Elias, M., Sanchez, D.L., Saksa, P., Hunt, J. and Remucal, J. (2024), “Market analysis of coupled biochar and carbon credit production from wildfire fuel reduction projects in the western USA”, *Biofuels, Bioproducts and Biorefining*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1002/bbb.2614.

Erhun, F., Kraft, T. and Wijnsma, S. (2021), “Sustainable triple-a supply chains”, *Production and Operations Management*, Vol. 30 No. 3, pp. 644-655, doi: 10.1111/poms.13306.

Eskandarpour, M., Dejax, P., Miemczyk, J. and Péton, O. (2015), “Sustainable supply chain network design: an optimization-oriented review”, *Omega*, Vol. 54, pp. 11-32, doi: 10.1016/j.omega.2015.01.006.

Financial Times (2023), “Is 1.5C still realistic? The crumbling consensus over key climate target”, *Financial Times*, available at: https://www.ft.com/content/450a59bb-7c83-4d04-851f-0bbc120c09f7 (accessed 12 June 2024).

Florida, R. (1996), “Lean and green: the move to environmentally conscious manufacturing”, *California Management Review*, Vol. 39 No. 1, pp. 80-105, doi: 10.2307/41165877.

Geels, F.W. (2002), “Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study”, *Research Policy*, Vol. 31 Nos 8-9, pp. 1257-1274, doi: 10.1016/s0048-7333(02)00062-8.

Geels, F.W. (2004), “From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory”, *Research Policy*, Vol. 33 Nos 6-7, pp. 897-920, doi: 10.1016/j.respol.2004.01.015.

Geels, F.W., Schwanen, T., Sorrell, S., Jenkins, K. and Sovacool, B.K. (2018), “Reducing energy demand through low carbon innovation: a sociotechnical transitions perspective and thirteen research debates”, *Energy Research and Social Science*, Vol. 40, pp. 23-35, doi: 10.1016/j.erss.2017.11.003.

Geffen, C.A. and Rothenberg, S. (2000), “Suppliers and environmental innovation: the automotive paint process”, *International Journal of Operations and Production Management*, Vol. 20 No. 2, pp. 166-186, doi: 10.1108/01443570010304242.

Ghadge, A., Wurtmann, H. and Seuring, S. (2020), “Managing climate change risks in global supply chains: a review and research agenda”, *International Journal of Production Research*, Vol. 58 No. 1, pp. 44-64, doi: 10.1080/00207543.2019.1629670.

Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013), "Seeking qualitative rigor in inductive research: notes on the Gioia methodology", *Organizational Research Methods*, Vol. 16 No. 1, pp. 15-31, doi: 10.1177/1094428112452151.

Gold, S. and Schleper, M.C. (2017), "A pathway towards true sustainability: a recognition foundation of sustainable supply chain management", *European Management Journal*, Vol. 35 No. 4, pp. 425-429, doi: 10.1016/j.emj.2017.06.008.

Gopalakrishnan, S., Granot, D., Granot, F., Sošić, G. and Cui, H. (2021), "Incentives and emission responsibility allocation in supply chains", *Management Science*, Vol. 67 No. 7, pp. 3985-4642, doi: 10.1287/mnsc.2020.3724.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N. and Noble, I. (2013), "Policy: sustainable development goals for people and planet", *Nature*, Vol. 495 No. 7441, pp. 305-307, doi: 10.1038/495305a.

Grötsch, V.M., Blome, C. and Schleper, M.C. (2013), "Antecedents of proactive supply chain risk management – a contingency theory perspective", *International Journal of Production Research*, Vol. 51 No. 10, pp. 2842-2867, doi: 10.1080/00207543.2012.746796.

Gualandris, J., Branzei, O., Wilhelm, M., Lazzarini, S., Linnenluecke, M., Hamann, R., Dooley, K.J., Barnett, M.L. and Chen, C.M. (2024), "Unchaining supply chains: transformative leaps toward regenerating social–ecological systems", *Journal of Supply Chain Management*, Vol. 60 No. 1, pp. 53-67, doi: 10.1111/jscm.12314.

Gupta, M.C. (1995), "Environmental management and its impact on the operations function", *International Journal of Operations and Production Management*, Vol. 15 No. 8, pp. 34-51, doi: 10.1108/01443579510094071.

Hall, J. (2000), "Environmental supply chain dynamics", *Journal of Cleaner Production*, Vol. 8 No. 6, pp. 455-471, doi: 10.1016/s0959-6526(00)00013-5.

Hall, J. and Martin, M.J.M. (2005), "Disruptive technologies, stakeholders and the innovation value-added chain: a framework for evaluating radical technology development", *R&D Management*, Vol. 35 No. 3, pp. 273-284, doi: 10.1111/j.1467-9310.2005.00389.x.

Hall, J., Bachor, V. and Matos, S. (2014), "Developing and diffusing new technologies: strategies for legitimization", *California Management Review*, Vol. 56 No. 3, pp. 98-117, doi: 10.1525/cmr.2014.56.3.98.

Hall, J., Matos, S. and Bachor, V. (2019), "From green technology development to green innovation: inducing regulatory adoption of pathogen detection technology for sustainable forestry", *Small Business Economics*, Vol. 52 No. 4, pp. 877-889, doi: 10.1007/s11187-017-9940-0.

Harvey, F. (2023), "Experts call for global moratorium on efforts to geoengineer climate", *The Guardian*, available at: https://www.theguardian.com/environment/2023/sep/14/experts-call-for-global-moratorium-on-efforts-to-geoengineer-climate (accessed 12 June 2024).

Héder, M. (2017), "From NASA to EU: the evolution of the TRL scale in public sector innovation", *The Innovation Journal*, Vol. 22 No. 2, pp. 1-23.

Helper, S., Gray, J.V., Hughes, M.M. and Roman, A.V. (2021), "Public policy and operations management", *Journal of Operations Management*, Vol. 67 No. 7, pp. 780-802, doi: 10.1002/joom.1160.

Henderson, R.M. and Clark, K.B. (1990), "Architectural innovation: reconfiguration of existing product technologies and the failure of established firms", *Administrative Science Quarterly*, Vol. 35 No. 1, pp. 9-30, doi: 10.2307/2393549.

Holgado, M., Blome, C., Schleper, M.C. and Subramanian, N. (2024), "Brilliance in resilience: operations and supply chain management's role in achieving a sustainable future", *International Journal of Operations and Production Management*, Vol. 44 No. 5, pp. 877-899, doi: 10.1108/ijopm-12-2023-0953.

Howard-Grenville, J., Buckle, S.J., Hoskins, B.J. and George, G. (2014), "Climate change and management", *Academy of Management Journal*, Vol. 57 No. 3, pp. 615-623, doi: 10.5465/amj.2014.4003.

Hunold, C. and Young, I.M. (1998), "Justice, democracy, and hazardous siting", *Political Studies*, Vol. 46 No. 1, pp. 82-95, doi: 10.1111/1467-9248.00131.

IPCC [Intergovernmental Panel on Climate Change] (2007), *Climate Change: 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, and New York, NY.

IPCC [Intergovernmental Panel on Climate Change] (2019), “Annex I: glossary”, in van Diemen, R. (ed.), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)], doi: 10.1017/9781009157988.010.

IPCC [Intergovernmental Panel on Climate Change] (2023), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Core writing team, Lee, H. and Romero, J. (Eds), IPCC, Geneva, doi: 10.59327/IPCC/AR6-9789291691647.

Jacobsson, S. and Bergek, A. (2011), “Innovation system analyses and sustainability transitions: contributions and suggestions for research”, *Environmental Innovation and Societal Transitions*, Vol. 1 No. 1, pp. 41-57, doi: 10.1016/j.eist.2011.04.006.

Jira, C. and Toffel, M. (2013), “Engaging supply chains in climate change”, *Manufacturing and Service Operations Management*, Vol. 15 No. 4, pp. 559-577, doi: 10.1287/msom.1120.0420.

Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.L., Graber, E.R., Ippolito, J.A., Kuzyakov, Y., Luo, Y., Ok, Y.S., Palansooriya, K.N., Shepherd, J., Stephens, S., Weng, Z.H. and Lehmann, J. (2021), “How biochar works, and when it doesn’t: a review of mechanisms controlling soil and plant responses to biochar”, *GCB Bioenergy*, Vol. 13 No. 11, pp. 1731-1764, doi: 10.1111/gcbb.12885.

Kagawa, S., Suh, S., Hubacek, K., Wiedmann, T., Nansai, K. and Minx, J. (2015), “CO2 emission clusters within global supply chain networks: implications for climate change mitigation”, *Global Environmental Change*, Vol. 35 No. 1, pp. 486-496, doi: 10.1016/j.gloenvcha.2015.04.003.

Kamau, S., Karanja, N.K., Ayuke, F.O. and Lehmann, J. (2019), “Short-term influence of biochar and fertilizer-biochar blends on soil nutrients, fauna and maize growth”, *Biology and Fertility of Soils*, Vol. 55 No. 7, pp. 661-673, doi: 10.1007/s00374-019-01381-8.

Kara, M.E., Ghadge, A. and Bititci, U.S. (2021), “Modelling the impact of climate change risk on supply chain performance”, *International Journal of Production Research*, Vol. 59 No. 24, pp. 7317-7335, doi: 10.1080/00207543.2020.1849844.

Ketokivi, M. and Choi, T. (2014), “Renaissance of case research as a scientific method”, *Journal of Operations Management*, Vol. 32 No. 5, pp. 232-240, doi: 10.1016/j.jom.2014.03.004.

Kirkman, B.L. and Chen, G. (2011), “Maximizing your data or data slicing? Recommendations for managing multiple submissions from the same dataset”, *Management and Organization Review*, Vol. 7 No. 3, pp. 433-446, doi: 10.1111/j.1740-8784.2011.00228.x.

Klassen, R.D. and Vachon, S. (2003), “Collaboration and evaluation in the supply chain: the impact on plant-level environmental investment”, *Production and Operations Management*, Vol. 12 No. 3, pp. 336-352, doi: 10.1111/j.1937-5956.2003.tb00207.x.

Knight, L., Pfeiffer, A. and Scott, J. (2015), “Supply market uncertainty: exploring consequences and responses within sustainability transitions”, *Journal of Purchasing and Supply Management*, Vol. 21 No. 3, pp. 167-177, doi: 10.1016/j.pursup.2015.04.002.

Kumar, S., Narayanan, S. and Salvador, F. (2020), “Innovation in supply networks—a research framework and roadmap”, *Journal of Operations Management*, Vol. 66 Nos 7-8, pp. 754-767, doi: 10.1002/joom.1122.

Lee, L.H. (2004), “The triple-A supply chain”, *Harvard Business Review*, Vol. 82 No. 10, pp. 102-157.

Lehmann, J. and Possinger, A. (2020), “Pulling carbon from the sky is necessary but not sufficient”, *Nature*, Vol. 583 No. 7815, pp. 167-168.

Lehmann, J., Cowie, A., Masiello, C.A., Kammann, C., Woolf, D., Amonette, J.E., Cayuela, M.L., Camps-Arbestain, M. and Whitman, T. (2021), “Biochar in climate change mitigation”, *Nature Geoscience*, Vol. 14 No. 12, pp. 883-892, doi: 10.1038/s41561-021-00852-8.

Low, S., Baum, C.M. and Sovacool, B.K. (2022), “Rethinking net zero systems, spaces, and societies: hard versus soft alternatives for engineered and nature-based carbon removal”, *Global Environmental Change*, Vol. 75, 102530, doi: 10.1016/j.gloenvcha.2022.102530.

Madhu, K., Pauliuk, S., Dhathri, S. and Creutzig, F. (2021), “Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment”, *Nature Energy*, Vol. 6 No. 11, pp. 1035-1044, doi: 10.1038/s41560-021-00922-6.

Madonna, A., Boffelli, A. and Kalchschmidt, M. (2024), “Panarchy theory: myth or reality? Empirical evidence of the socio-ecological nature of supply chains”, *International Journal of Operations and Production Management*, Vol. 44 No. 8, pp. 1493-1521, doi: 10.1108/IJOPM-05-2023-0337.

Markard, J. (2011), “Transformation of infrastructures: sector characteristics and implications for fundamental change”, *Journal of Infrastructure Systems*, Vol. 17 No. 3, pp. 107-117, doi: 10.1061/(asce)is.1943-555x.0000056.

Markard, J., Raven, R. and Truffer, B. (2012), “Sustainability transitions: an emerging field of research and its prospects”, *Research Policy*, Vol. 41 No. 6, pp. 955-967, doi: 10.1016/j.respol.2012.02.013.

Matos, S. and Hall, J. (2007), “Integrating sustainable development in the supply chain: the case of life cycle assessment in oil and gas and agricultural biotechnology”, *Journal of Operations Management*, Vol. 25 No. 6, pp. 1083-1102, doi: 10.1016/j.jom.2007.01.013.

Matos, S.V., Schleper, M.C., Gold, S. and Hall, J.K. (2020), “The hidden side of sustainable operations and supply chain management: unanticipated outcomes, trade-offs and tensions”, *International Journal of Operations and Production Management*, Vol. 40 No. 12, pp. 1749-1770, doi: 10.1108/ijopm-12-2020-833.

Meixell, M.J. and Gargeya, V.B. (2005), “Global supply chain design: a literature review and critique”, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 41 No. 6, pp. 531-550, doi: 10.1016/j.tre.2005.06.003.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente Vicente, J.L., Wilcox, J. and del Mar Zamora Dominguez, M. (2018), “Negative emissions—Part 1: research landscape and synthesis”, *Environmental Research Letters*, Vol. 13 No. 6, 063001, doi: 10.1088/1748-9326/aabf9b.

Montabon, F., Pagell, M. and Wu, Z. (2016), “Making sustainability sustainable”, *Journal of Supply Chain Management*, Vol. 52 No. 2, pp. 11-27, doi: 10.1111/jscm.12103.

Nakano, K. (2021), “Risk assessment for adaptation to climate change in the international supply chain”, *Journal of Cleaner Production*, Vol. 319, 128785, doi: 10.1016/j.jclepro.2021.128785.

Narasimhan, R. and Talluri, S. (2009), “Perspectives on risk management in supply chains”, *Journal of Operations Management*, Vol. 27 No. 2, pp. 114-118, doi: 10.1016/j.jom.2009.02.001.

Naumov, S., Keith, D.R. and Sterman, J.D. (2023), “Accelerating vehicle fleet turnover to achieve sustainable mobility goals”, *Journal of Operations Management*, Vol. 69 No. 1, pp. 36-66, doi: 10.1002/joom.1173.

Nelson, R.R. and Winter, S.G. (1982), *An Evolutionary Theory of Economic Change*, Harvard University Press, Cambridge, MA.

Ng, A.K.Y., Wang, T., Yang, Z., Li, K.X. and Jiang, C. (2018), “How is business adapting to climate change impacts appropriately? Insight from the commercial port sector”, *Journal of Business Ethics*, Vol. 150 No. 4, pp. 1029-1047, doi: 10.1007/s10551-016-3179-6.

Nieuwenhuis, P., Beresford, A. and Choi, A.-Y. (2012), “Shipping or local production? CO2 impact of a strategic decision: an automotive industry case study”, *International Journal of Production Economics*, Vol. 140 No. 1, pp. 138-148, doi: 10.1016/j.ijpe.2012.01.034.

Ozkan, M., Akhavi, A.-A., Coley, W.C., Shang, R. and Ma, Y. (2022), "Progress in carbon dioxide capture materials for deep decarbonization", *Chem*, Vol. 8 No. 1, pp. 141-173, doi: 10.1016/j.chempr.2021.12.013.

Pagell, M. and Shevchenko, A. (2014), "Why research in sustainable supply chain management should have no future", *Journal of Supply Chain Management*, Vol. 50 No. 1, pp. 44-55, doi: 10.1111/jscm.12037.

Pagell, M. and Wu, Z. (2009), "Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars", *Journal of Supply Chain Management*, Vol. 45 No. 2, pp. 37-56, doi: 10.1111/j.1745-493x.2009.03162.x.

Pankratz, N.M.C. and Schiller, C.M. (2022), "Climate Change and adaptation in global supply-chain networks", in *Finance and Economics Discussion Series 2022-056*, Board of Governors of the Federal Reserve System, Washington, available at: https://doi.org/10.17016/FEDS.2022.056 (accessed 25 May 2024).

Plambeck, E.L. (2012), "Reducing greenhouse gas emissions through operations and supply chain management", *Energy Economics*, Vol. 34 No. 1, pp. S64-S74, doi: 10.1016/j.eneco.2012.08.031.

Rapley, T.J. (2001), "The art (fulness) of open-ended interviewing: some considerations on analysing interviews", *Qualitative Research*, Vol. 1 No. 3, pp. 303-323, doi: 10.1177/146879410100100303.

Realff, M.J., Min, Y.J., Jones, C.W. and Lively, R.P. (2021), "Perspective – the need and prospects for negative emission technologies – direct air capture through the lens of current sorption process development", *Korean Journal of Chemical Engineering*, Vol. 38 No. 12, pp. 2375-2380, doi: 10.1007/s11814-021-0957-3.

Rizet, C., Browne, M., Cornelis, E. and Leonardi, J. (2012), "Assessing carbon footprint and energy efficiency in competing supply chains: review – case studies and benchmarking", *Transportation Research Part D: Transport and Environment*, Vol. 17 No. 1, pp. 293-300, doi: 10.1016/j.trd.2012.01.002.

Sarkis, J. (2021), "Supply chain sustainability: learning from the COVID-19 pandemic", *International Journal of Operations and Production Management*, Vol. 41 No. 1, pp. 63-73, doi: 10.1108/ijopm-08-2020-0568.

Sartal, A., Rodríguez, M. and Vázquez, X.H. (2020), "From efficiency-driven to low-carbon operations management: implications for labor productivity", *Journal of Operations Management*, Vol. 66 No. 3, pp. 310-325, doi: 10.1002/joom.1060.

Saunders, L.W., Brooks, J.P., Merrick, J.R.W. and Autry, C.W. (2020), "Addressing economic/environmental sustainability trade-offs in procurement episodes with industrial suppliers", *Production and Operations Management*, Vol. 29 No. 5, pp. 1256-1269.

Smith, S.M., Geden, O., Gidden, M.J., Lamb, W.F., Nemet, G.F., Minx, J.C., Buck, H., Burke, J., Cox, E., Edwards, M.R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B.S., Roe, S., Schenuit, F., Schulte, I. and Vaughan, N.E. (2024), (Eds), *The State of Carbon Dioxide Removal 2024*, 2nd ed., doi: 10.17605/OSF.IO/F85QJ.

Sovacool, B.K., Baum, C.M. and Low, S. (2023), "Reviewing the sociotechnical dynamics of carbon removal", *Joule*, Vol. 7 No. 1, pp. 57-82, doi: 10.1016/j.joule.2022.11.008.

Sovacool, B.K., Baum, C.M., Cantoni, R. and Low, S. (2024), "Actors, legitimacy, and governance challenges facing negative emissions and solar geoengineering technologies", *Environmental Politics*, Vol. 33 No. 2, pp. 340-365, doi: 10.1080/09644016.2023.2210464.

Strefler, J., Amann, T., Bauer, N., Kriegler, E. and Hartmann, J. (2018), "Potential and costs of carbon dioxide removal by enhanced weathering of rocks", *Environmental Research Letters*, Vol. 13 No. 3, 034010, doi: 10.1088/1748-9326/aaa9c4.

Sunar, N. and Plambeck, E. (2016), "Allocating emissions among co-products: implications for procurement and climate policy", *Manufacturing and Service Operations Management*, Vol. 18 No. 3, pp. 414-428, doi: 10.1287/msom.2015.0572.

Teece, D.J. (1987), *The Competitive Challenge: Strategies for Industrial Innovation and Renewal*, Ballinger Pub., Pensacola, FL.

UK Centre for Ecology and Hydrology (2021), “Greenhouse gas removal methods and their potential UK deployment”, available at: https://assets.publishing.service.gov.uk/media/616ff80ce90e07197b571c95/ggr-methods-potential-deployment.pdf (accessed 12 June 2024).

Van Wassenhove, L.N. (2018), “Sustainable innovation: pushing the boundaries of traditional operations management”, *Production and Operations Management*, Vol. 28 No. 12, pp. 2930-2945, doi: 10.1111/poms.13114.

Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., Sophia van der Voort, T., Malarvizhi, P., Yi, S., Gebert, J. and Aravind, P. (2021), “Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations”, *Frontiers in Energy Research*, Vol. 9, 710766, doi: 10.3389/fenrg.2021.710766.

Voss, C., Johnson, M. and Godsell, J. (2015), “Revisiting case research in operations management”, *22nd International Annual EurOMA Conference*.

Weber, K.M. and Rohracher, H. (2012), “Legitimizing research, technology and innovation policies for transformative change: combining insights from innovation systems and multi-level perspective in a comprehensive ’failures’ framework”, *Research Policy*, Vol. 41 No. 6, pp. 1037-1047, doi: 10.1016/j.respol.2011.10.015.

WEF (World Economic Forum) (2021), “Net-zero challenge: the supply chain opportunity”, available at: https://www3.weforum.org/docs/WEF_Net_Zero_Challenge_The_Supply_Chain_Opportunity_2021.pdf (accessed 12 June 2024).

Wheelwright, S.C. and Clark, K.B. (1992), *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency and Quality*, The Free Press, New York.

Wieland, A. (2021), “Dancing the supply chain: toward transformative supply chain management”, *Journal of Supply Chain Management*, Vol. 57 No. 1, pp. 58-73, doi: 10.1111/jscm.12248.

Wieland, A., Stevenson, M., Melnyk, S.A., Davoudi, S. and Schultz, L. (2023), “Thinking differently about supply chain resilience: what we can learn from social-ecological systems thinking”, *International Journal of Operations and Production Management*, Vol. 43 No. 1, pp. 1-21, doi: 10.1108/ijopm-10-2022-0645.

Wright, C. and Nyberg, D. (2017), “An inconvenient truth: how organizations translate climate change into business as usual”, *Academy of Management Journal*, Vol. 60 No. 5, pp. 1633-1661, doi: 10.5465/amj.2015.0718.

Appendix
Interview guidelines

1. What are critical innovation gaps? Which particular options have high or low innovation potential (e.g. learning potential)?
2. What energy systems or other sociotechnical systems could or should be coupled?
3. What business models and markets could these technologies create or disrupt?
4. Which serious risks (e.g. social, political, military, ethical, environmental, etc.) may arise?
5. What are the synergies and trade-offs for other societal objectives and the SDGs?
6. What particular vulnerable groups could be affected, positively or negatively?
7. Who are the relevant (or most important) actors (or stakeholders/networks)?

Corresponding author
Martin C. Schleper can be contacted at: martin.schleper@neoma-bs.fr