The circular economy and climate change: the state of national and global evidence on mitigation potential

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The Circular Economy and Climate Change: The State of National and Global Evidence on Mitigation Potential

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Abstract

While global resource use and GHG emissions keep increasing, the circular economy (CE) has ascended to the forefront of global policy, business and research agendas. Through narrower, slower, and more closed material cycles, the CE aims to avoid waste and reduce virgin raw material demand, thereby potentially also mitigating energy demand and GHG emissions. We review 75 national to global studies modeling over 500 specific measures. Studies modeling narrower, slower, and more closed material cycles show a combined GHG mitigation potential of on average 17% (0–91%). When CE measures are complemented with energy efficiency and decarbonization of energy supply and industry, an average GHG mitigation potential of 50% (1–100%) is found. This indicates that the CE might have substantial mitigation potentials if combined wisely with other supply- and demand-side measures. Future research should strengthen the links between industrial ecology and economic modeling and fully implement open science principles. These improvements would pave the way toward a more robust, granular, and systemic understanding of the CE's potential and limits for climate change mitigation and sustainable resource use.

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1. INTRODUCTION

Global raw material extraction, waste, energy use, and greenhouse gas (GHG) emissions are steadily increasing (1–3). Subsequently, the climate crisis is intensifying, and carbon budgets remaining to limit global warming to 1.5–2°C above preindustrial levels are rapidly being used up (4, 5). GHG emissions due to materials production are estimated at 23–35% of global GHG emissions, the majority of which are occurring in industry and are driven by investments into material stocks of buildings, infrastructure, and machinery (6, 7). In the high-income countries, material stocks are slowly growing and ageing, increasingly requiring maintenance and replacement. In the middle- and lower-income countries, resource-intensive industrialization pathways and widespread underprovision with essential services drive further energy and material demand (8–10). Ongoing global stock expansion therefore results in greater material and energy demand and, subsequently, waste and GHG emissions. Materials-oriented GHG mitigation strategies such as the circular economy (CE) are therefore argued to be necessary to complement established supply- and demand-side measures aiming to improve energy efficiency and decarbonize energy supply, industrial processes, and land uses in the decisive decades for avoiding catastrophic climate change (1, 5, 11).

Although the CE concept is sometimes simply interpreted as more recycling, most academic and public interpretations see the CE as addressing the entire life cycle of materials, products, and provisioning systems (12–14). The CE interpreted as systems approach aims to transform how materials are extracted, processed, and used, via measures narrowing, slowing, and closing material cycles (12, 15–17). Such a systems-based interpretation of the CE begins with measures to reduce material demand and improve the resource efficiency of products and service provisioning systems (narrow), extend product and component lifetimes (slow), and increase recycling (close), thereby aiming to avoid raw material extraction and waste, reduce energy use, and help mitigate GHG emissions (18).

The CE has ascended to the forefront of global policy, business, and research agendas, with great expectations about its potential to help mitigate climate change and other environmental challenges (12). The prominence of the CE concept stems from its forward-looking focus on solutions to global environmental challenges (19), its reliance on the widely established metaphor of natural cycles (20), and its openness to multiple interpretations—from material cycles to sustainable business profits (21). These qualities attract diverse actors and interests under a broad, inclusive umbrella (17, 22). Depending on the interpretation of the concept (23, 24), some advocate the CE as an obvious win–win situation for sustainable development (15), whereas others call for careful assessments of the CE's potentials, including possible trade-offs and limitations (24–26). Practically, CE discussions connect existing concepts into a systems-oriented narrative that bridges policy silos and aims to inspire business and nonprofit activities (17).

Meanwhile, the CE seems to be consolidating into its own distinct research field (16) with increasingly shared concepts and overarching research questions (14, 24, 27). This is evidenced by a rapidly growing literature (12, 28)—over 160 reviews (27)—new journals and conferences around the CE, and scientific societies creating new sections, with new associations emerging. The body of CE research focusing on the GHG mitigation potentials due to specific products, technologies, sectors, and business models is also growing rapidly (27, 28). However, previous reviews and most empirical modeling studies suffer from ambiguous CE definitions and varying study scopes across a multitude of methods using variable system boundaries (29–34). These ambiguities inhibit cumulative insights into the CE's contribution to GHG emissions mitigation. Closely relevant reviews addressed CE potentials for GHG mitigation in the European construction sector (35), as well as progress in modeling the CE in macroeconomic optimization models (36, 37), or via input–output analysis (38). Subsequently, evidence synthesis as advanced herein will be increasingly relevant to provide robust and context-specific scientific recommendations for policy and business.

This review focuses on three aspects of the question of how and to what extent the CE can help mitigate GHG emissions. Section 2 conceptualizes the relation of the CE with climate change mitigation at the global level. Section 3 gives an overview of the global CE policy landscape, drawing on peer-reviewed and gray literature. Section 4 summarizes results from 75 quantitative prospective studies modeling the CE's potentials to contribute to climate change mitigation at the national to global level. We include studies addressing CE potentials for metals and ores, nonmetallic minerals, plastics, timber, paper, and natural fibers across multiple sectors and at the economy-wide level. Section 5 discusses main insights and implications for future research.

2. CONCEPTUALIZING THE CE AND CLIMATE CHANGE MITIGATION

The CE is usually understood as a systems concept, building on the widely accepted "reduce, reuse, recycle (3R)" waste avoidance hierarchy as well as eco-design principles (39). These 3Rs are nowadays differentiated into 10Rs: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recovery (18, 40). The CE builds on a rich intellectual history (17), from bio-mimicry (18, 39) to extended producer responsibility (41) and resource- and material efficiency (31, 42), as well as sufficiency (43, 44) (see the **Supplemental Appendix Section 4** for an overview). The 10R measures address the micro-level of products and the meso-level of business models and specific production–consumption systems (18, 23, 40). Implementing the 10R measures should lead to narrower, slower, and more closed material cycles at the macro-level of the entire economy (18). Narrower cycles are to be achieved via smarter product use and manufacture (refuse, rethink, reduce). Slower material cycles are to be achieved by extending the lifespan of products and their parts (reuse, repair, refurbish, remanufacture, repurpose). More closed material cycles are to be achieved via the useful application of end-of-life and waste materials (recycle, recovery).

Supplemental Material >

The CE literature distinguishes sociotechnical and socioecological material cycles, roughly corresponding to nonrenewable (metals, nonmetallic minerals, fossil energy carriers) and renewable resources (biomass) (14, 23, 45). Nonrenewable materials are to be managed in sociotechnical cycles in which waste is avoided and the value of materials, products, and components is maintained for as long as possible, through slower and more closed material cycles. Renewable biomass materials are also to be kept in use for as long as possible, mainly via cascading uses from high value to lower value applications. For renewable materials and socioecological cycles, the aim of the CE includes the redesign of land systems to restore biosphere integrity and bring biogeochemical flows of phosphor and nitrogen back into the safe operating space of the Earth System (46, 47). Although narrower, slower, and more closed material cycles aim to avoid waste and reduce virgin raw material demand, they can also play an important role in reducing energy use and GHG emissions from energy supply and industrial processes as well as agriculture, forestry, and other land uses (AFOLU) (18).

Meanwhile, climate change mitigation measures have mainly focused on supply-side measures, aiming to improve energy efficiency across sectors, decarbonizing the energy system and industry, as well as making land use less GHG intensive (5). Policies usually target energy supply and energy-intensive sectors in industry, housing, and transport, as well as AFOLU (4, 48). Policy goals commonly include expanding renewable energy supply, adopting energy-efficient and carbon-free technologies, increasing public transport, modal shifts and shifting electric vehicles, electrifying energy demand, and increasingly carbon capture and storage (CCS) (4, 5). Uncertain and risky negative emission technologies including CCS have become central in scenarios limiting global warming to 1.5–2°C above preindustrial levels (4, 5). Common policies for AFOLU include improved land management (e.g., reduced methane emissions by improved manure management), carbon sequestration (e.g., re- and afforestation), and land conversion (e.g., reduced deforestation and degradation) (5). Recently, demand-side measures aiming to avoid-shift-improve (ASI) upon GHG-intensive activities, products, and services are coming into focus (5, 11). The ASI framework originates in transport studies and is increasingly used in demand-side climate change mitigation research, being positioned as a complement to established supply-side approaches helping reduce the reliance on CCS and other negative emissions technologies (11, 49). Clearly there are conceptual overlaps between ASI and the 3Rs and 10Rs in the CE, but these concepts originate from different research communities. For the analytical purpose of this review, we therefore conceptualize ASI as aiming at energy use and GHG emissions, whereas the CE primarily considers materials and products.

Here, we provide a first quantitative orientation for how the CE could contribute to climate change mitigation (**Figure 1**, compiled from References 7 and 8). We locate the CE via the 10Rs and narrow–slow–close outcomes vis-à-vis latest assessments of global material cycles and sectoral global GHG emissions (**Figure 1**). In the year 2020 (8), 94.7 Gt/year of primary metals and ores, biomass, nonmetallic minerals, and fossil energy carriers were extracted, of which 39.8 Gt/year were used for energy supply, food, and feed, whereas the remaining 64.3 Gt/year were used as technical materials for producing and constructing material stocks of buildings, infrastructure, machinery, and other short-lived goods (**Figure 1*b***). Only 9.5 Gt/year of materials were recycled. The headline indicator circular material use rate (50) quantifies the amount of recycled secondary materials (9.5 Gt/year) in total material inputs into the economy (104 Gt/year), suggesting that the global economy is only 9% circular (8). Similar or even lower circular material use rates are found in country-level studies (50–55). Reasons for the low circular material use rate include ongoing stock growth requiring large amounts of primary resources and the large share of fossil fuels in energy supply, as well as relatively low recycling rates for most materials except iron and steel as well as paper.

To relate material cycles to GHG emissions, we also show sectoral direct on-site emissions and the GHGs from electricity and heat demand of these sectors, as covered in emissions reporting[1] (**Figure 1*c***). Materials-related emissions amount to 25–35% of global GHG emissions in 2019, the majority of which are occurring in industry and are driven by investments into material stocks of buildings, infrastructure, and machinery (6, 7). These emissions occur during the refining of ores into metals (8%), the production of chemicals and plastics (7%), the calcination of cement (3%), and during waste management (4%), as well as along complex global production networks (6, 7). These large materials-related emissions give a first illustration of the potentials of the CE to contribute to climate change mitigation via narrower, slower, and more closed material cycles.

2.1. Agreements and Tensions About the CE

Although there is no widely accepted authoritative definition of the CE so far, there are several important points of agreement across most CE definitions (14). These are that the principal aim of the CE is sustainable development, that a fundamental transformation of the economy is required, that the 10R framework is a useful heuristic to conceptualize CE measures, and that policy, business, consumers, and academia are together required as coordinated enablers of a CE transition. Competing definitions and remaining tensions about the CE are because of (16, 57, 58) multiple contributing research fields that so far lack a shared ontological basis, as well as because the CE is a strongly transdisciplinary concept driven by nonscientific stakeholders, from nonprofit organizations such as the Ellen MacArthur Foundation and consulting firms, as well as businesses interests and policy makers. Finally, different paradigmatic worldviews implicitly shape CE discussions, similar to agreements and tensions about the concept of sustainable development (23, 59, 60).

[1]These allocations of GHG emissions are called scope 1 for direct on-site emissions and scope 2 for the emissions occurring in the supply of electricity and heat. Not shown here is a scope 3 allocation, which would cover all upstream and downstream emissions.

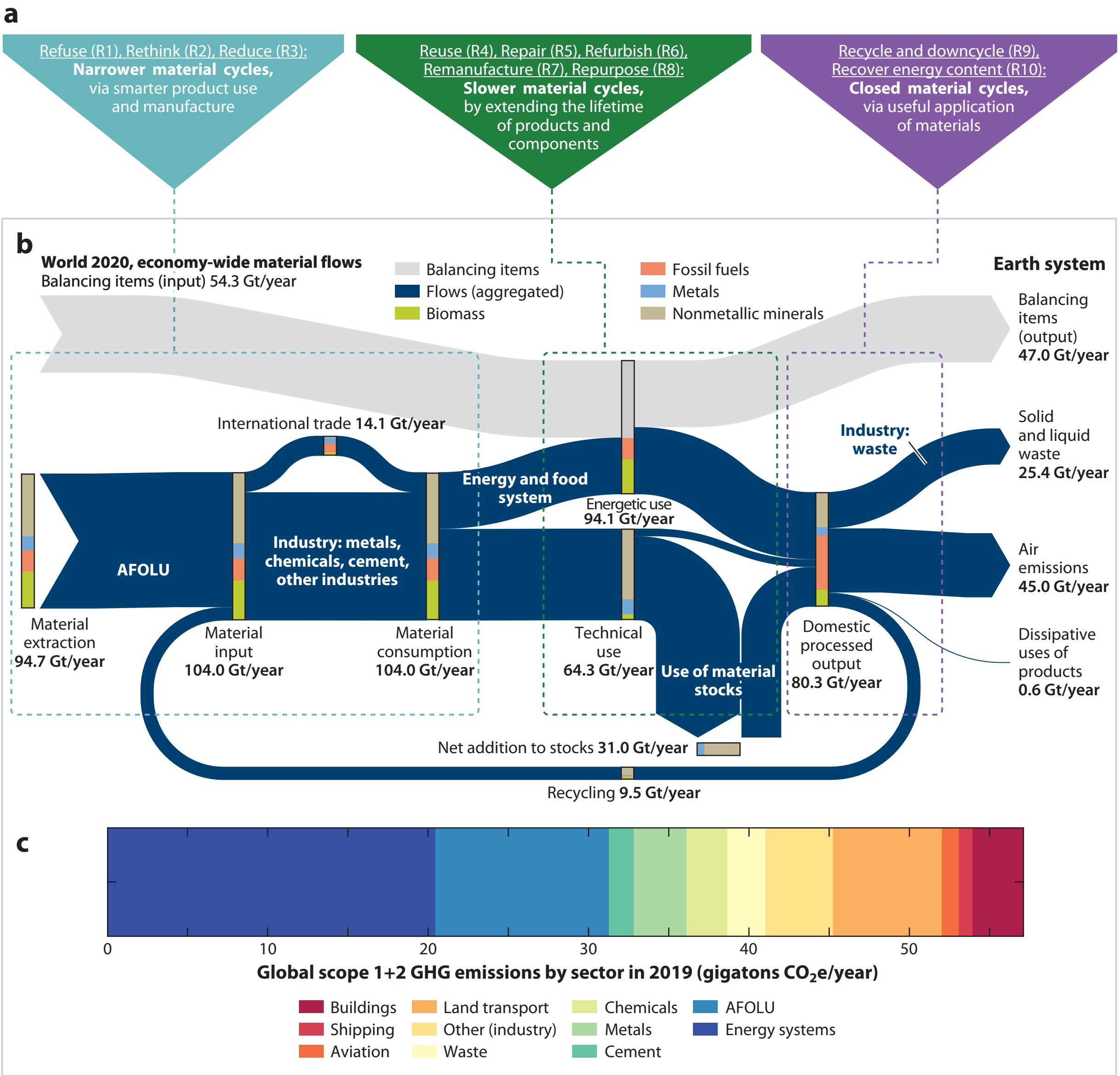


Figure 1

Situating the circular economy and its aim to narrow, slow, and close material cycles vis-à-vis global material cycles, energy use, and GHG emissions. (*a*) Locating the micro-/meso-level 10R measures (40) and their envisioned macro-level outcomes of narrower, slower, and more closed material cycles. (*b*) Global economy-wide resource use patterns and the resulting waste and emissions, differentiating resources used for energy provision, food, and feed, from the materials processed into long-lived material stocks and short-lived products. Data taken from Reference 8. (*c*) Global GHG emissions by sector including upstream emissions from electricity and heat provision. Data taken from References 7 and 56. Abbreviations: AFOLU, agriculture, forestry, other land use; GHG, greenhouse gas; Gt, gigatons (10^9 metric tons).

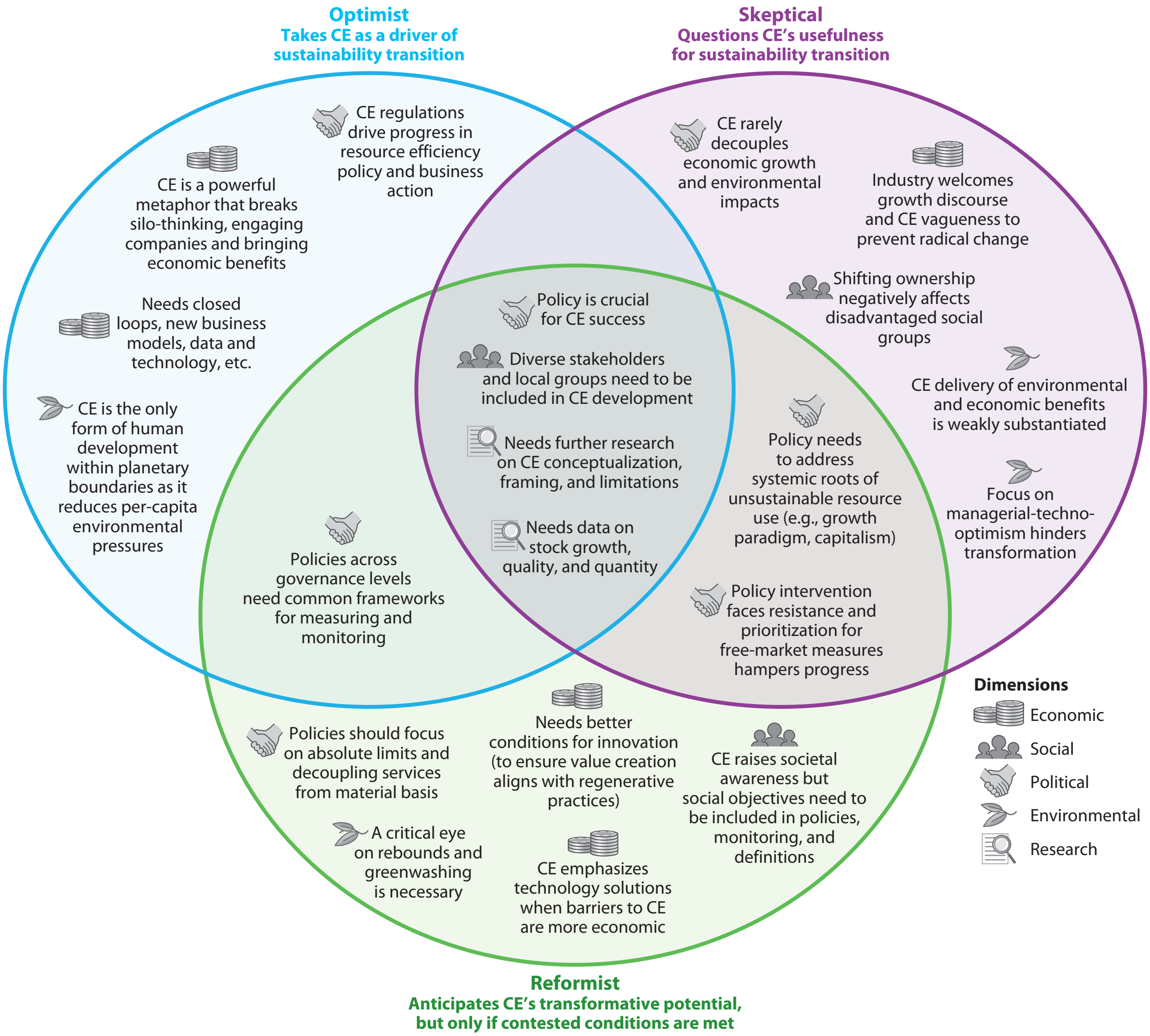


Figure 2

Three narratives about the circular economy (CE) and the key points of agreements as well as tensions underlying the assessment of academic experts of how and if the CE can contribute to sustainable development and climate change mitigation. Figure adapted from Reference 24.

Leipold et al. (24) empirically synthesized prevalent agreements and tensions about the CE into three diverging narratives reflecting different paradigmatic worldviews about the CE, extended upon early conceptual considerations (23) (**Figure 2**). They (24) distinguish a techno-optimist narrative that treats the CE as synonymous with innovation, entrepreneurship, and sustainability, as well as a reformist transformative narrative accepting the CE's potentials while highlighting potential limits and trade-offs with other socioeconomic goals as well as emphasizing the need for strong policy guardrails. The third worldview identified by Leipold et al. (24) is a skeptical narrative that emphasizes how the CE distracts from the contradiction of endless economic growth on a finite planet, how it can easily be misused for greenwashing, and that it might reinforce structural inequalities and exploitative relationships. All narratives do agree that strong policy and governance and a diversity of stakeholder voices are crucial for the success of a CE, as well as that biophysical monitoring and assessment methods need to be advanced (24). From Leipold et al.'s study on worldviews and narratives about the CE (24) and the wider literature, we also summarize seven key tensions about the CE's potential below (Sections 2.1.1–2.1.7).

2.1.1. Decoupling economic growth from resource use and greenhouse gas emissions is/is not possible with regulatory reforms. Whether economic growth can coexist with ecological limits is a key tension in the CE discourse. While optimist CE narratives promote efficiency and technological solutions to do more with less, especially skeptical positions argue that the CE sustains business-as-usual (BAU) growth models without structurally challenging them (20, 26, 61).

2.1.2. Encouraging entrepreneurship and innovation will/will not benefit the environment. Optimists claim that CE entrepreneurship and innovation will benefit the environment while skeptics and reformists argue that so far innovation has accelerated economic growth, usually resulting in rebound effects that ultimately increase resource use (62, 63). All narratives do agree that regulation and strong governance are necessary to ensure that the CE is aligned with sustainable development and to prevent misleading claims.

2.1.3. The environmental benefits of CE implementation strategies are/are not proven. Optimists argue that CE measures are a win–win situation for environmental and economic goals while skeptics and reformists point out that problem-shifts and rebound effects are widespread. The environmental and GHG mitigation benefits of specific CE measures are tricky to assess, with conflicting evidence (29). This is partly because of different research assumptions and data sources, and partly because measures often focus on optimizing specific aspects of production–consumption systems, without addressing the entire business model and life cycle of products. For example, increasing paper recycling without ensuring a carbon-free energy supply might increase overall GHG emissions along the entire paper life cycle (64).

2.1.4. Efficiency, not sufficiency, will primarily create a sustainable CE. CE optimists promote efficiency and technical solutions, focusing on supply-side measures such as optimizing resource use and improving recycling processes. In contrast, reformists and skeptics argue that such technology-focused solutions alone are not enough and that complementary demand-side measures are necessary to reduce consumption and shift production patterns (61, 65).

2.1.5. Justice and equity are/are not a prerequisite for an environmentally sustainable CE. Although much of the current CE debate has ignored issues of justice and equity (27), skeptics argue especially that production and consumption drive historical and current inequalities, so addressing these concerns through resource redistribution is essential for a CE to contribute to sustainable development. Justice is crucial to ensure that all stakeholders are included, resources are distributed fairly, and those harmed by CE strategies are compensated (66, 67). This is particularly important in today's globalized supply chains, where any ambitious CE measure will likely have repercussions globally (68, 69).

2.1.6. An environmentally sustainable CE should be achieved locally, not globally. Especially skeptics and some reformists argue that the CE needs to be localized with shorter supply chains and regional production as well as reuse and recycling to minimize environmental impacts and strengthen local communities. Optimists tend to argue that the CE needs to focus on globalized supply chains, as those are seen as beneficial for the common good and achieving economic efficiency. This tension is especially relevant in the Global South, which often supplies raw materials to the Global North (8, 52), raising questions about fair CE implementation worldwide.

2.1.7. An environmentally sustainable CE should focus on the common good, not on profitability. Optimists tend to see profitability and market growth as primary drivers for CE implementation, together with policy and governance. Reformists tend to argue that CE measures and circular business models can be less profitable economically while yielding larger social and environmental benefits. Skeptics emphasize that CE should help promote social and environmental justice (67), even if this comes at the expense of short-term profits.

In summary, though a consensus definition would be important for policymaking and businesses to orientate and evaluate their efforts, a truly final definition might be elusive, owing to the transdisciplinary nature of the CE as a concept and its implications for specific sectors and sociocultural contexts (14, 24). We do note that the CE discussion is increasingly moving beyond a product-centric resource efficiency perspective toward embracing the complexity involved in implementing the CE for sustainable development and considering potential trade-offs among social, ecological, and economic goals.

3. THE CE IN THE GLOBAL POLICY LANDSCAPE

CE policies originate in waste- and materials-oriented thinking, with climate change mitigation only recently becoming a major new emphasis. The first explicit CE policies originated in Japan in the 1990s, operationalizing the 3Rs heuristic into the sound material-cycle society concept (70). Shortly after, the CE was taken up in Chinese policy, focusing on industrial symbiosis and waste management (71). In 2015 and 2018, the European Union (EU), enacting their first CE policies (72), mainly aimed at improving resource efficiency, avoiding waste, improving end-of-life waste management, and increasing recycling; there was little direct reference to GHG mitigation. Recently, countries in North America (73), Latin America and the Caribbean (74), and several Asian countries (75) have also started developing CE policies. At least 75 national calls to action, roadmaps, and operational strategies were identified as of 2024, and at least 10 more are being developed (76, 77).

As of 2024, the CE has come center stage in the global policy discussion, for example, in the United Nations Environment Assembly (UNEA) 5.2 resolution on the CE (78), the G20 Resource Efficiency Dialogue (**https://g20re.org/**), and the G7 Alliance on Resource Efficiency (**https://www.g7are.com/**). There, the CE is interpreted as a tool for addressing the triple planetary crisis of pollution, climate change, and biodiversity loss at the global level, potentially also alleviating materials criticality and supply security. In 2024, the UNEA-6 Ministerial Declaration called on Member States and United Nations observer states to develop resource efficiency and CE strategies (79). Multiple regional roadmaps and coordination efforts are being established, e.g., in the EU, Africa and the Association of Southeast Asian Nations (ASEAN) countries (76). Meanwhile, the Global Environment Facility and the Multilateral Development Banks have initiated various CE financing initiatives (80).

CE policies so far mainly target brokering, fiscal instruments, research, as well as producer and product requirements, and business support, as well as circular resource and waste management (76). Examples are the 2nd European Union Circular Economy Action plan (81) and the US REMADE Institute,[2] as well as multiple efforts in China and other Asian countries (82–85). Specific measures range from shifting taxation, digital product passports, requirements for

[2]The REMADE Institute was founded in 2017 and is the only national institute and a public-private partnership established and funded in part by the US Department of Energy's Office of Advanced Materials and Manufacturing Technologies with an initial investment of $140 million (**https://remadeinstitute.org/about/**).

material efficiency of products, and the promotion or even requirement for recycled secondary resource use, as well as "right to repair" legislations. This momentum has led to industrial efforts in developing global and nationally relevant standards (86, 87).

Most CE policy still operates nationally, with little consideration for coordination and the substantial differences between the Global North and South (22, 74, 76). An increased recognition of resource security concerns potentially addressable via CE strategies has become relevant recently (88). For example, Japan published a growth-oriented resource autonomy economic strategy and revised its plans for a sound material-cycle society accordingly. China (71, 84) aims to establish circular industries, improve capacity for resource circulation, and improve its resource productivity to ensure a stable resource supply. Meanwhile, many countries in the Global South (74) are struggling with uncontrolled waste dumps and widespread informal recycling, primarily attempting to establish proper waste management and recycling systems (89). Importantly, most countries fail to consider the unintended consequences of national CE policies on key trading partners, particularly those in the Global South (52, 68).

Regarding climate change mitigation, the First Global Stocktake of Nationally Determined Contributions for climate change mitigation showed that the CE is being interpreted as a means to strengthen GHG mitigation efforts (90, 91). In the investment taxonomies of the EU (92) and the ASEAN countries (93), the CE is positioned as an environmental objective to be achieved simultaneously with climate change mitigation. However, methods to quantify GHG mitigation due to CE measures have not been fully developed yet, and the official monitoring of the relationships among material cycles, CE measures, and GHG mitigation are not well established. National monitoring of economy-wide material cycles and derived CE indicators such as the "circular material use rate" are used in Japan, China, and the EU (50, 54, 70, 71, 94). The monitoring systems for energy use and GHG emissions are being done completely separately, which means that monitoring systems for materials, energy, and GHGs are not systematically integrated. This severely limits the understanding of the interrelations among material cycles, energy use, and GHG emissions for national policy and monitoring (70).

In summary, while policy makers around the world expect substantial contributions of the CE for climate change mitigation, these contributions are not yet properly measured nor ensured. Only a small number of countries have quantitative circularity targets, which are often not linked to either proposed actions or GHG reductions in a science-based manner (76). Research efforts are ongoing to address some of these methodological and data challenges, for example, in several Horizon Europe research projects, as well as by statistical agencies and the United Nations. Translating those efforts into official long-term mandates for data gathering and monitoring is crucial to ensure that progress and setbacks can be identified. Evaluating CE policy outcomes is therefore going to be an important future research frontier.

4. ASSESSING THE EMPIRICAL NATIONAL-TO-GLOBAL LITERATURE

Here, we summarize quantitative results from 75 studies collected through October 2024, originating from 8 modeling traditions drawing on industrial ecology and ecological economics (MEFA, material and energy flow analysis; LCA, life cycle assessment; IOA, input–output analysis), and different strands of traditional environmental and energy economics [partial and general equilibrium models, nonequilibrium models, econometric models, and integrated assessment models (IAMs)]. Industrial ecology models emphasize biophysical consistency and usually simulate potential futures in a what-if setting based on exogenous assumptions on, for example, technical potentials or otherwise grounded changes in production and consumption patterns. Economic models typically employ normative assumptions about increasing utility and minimizing costs. See References 95–98 for discussions of the theoretical paradigms underpinning these traditions and the caption of **Figure 3**, which has explanations of the abbreviations. Details about the 75 reviewed studies are found in the **Supplemental Appendix** and **Supplemental Data**.

Supplemental Material >

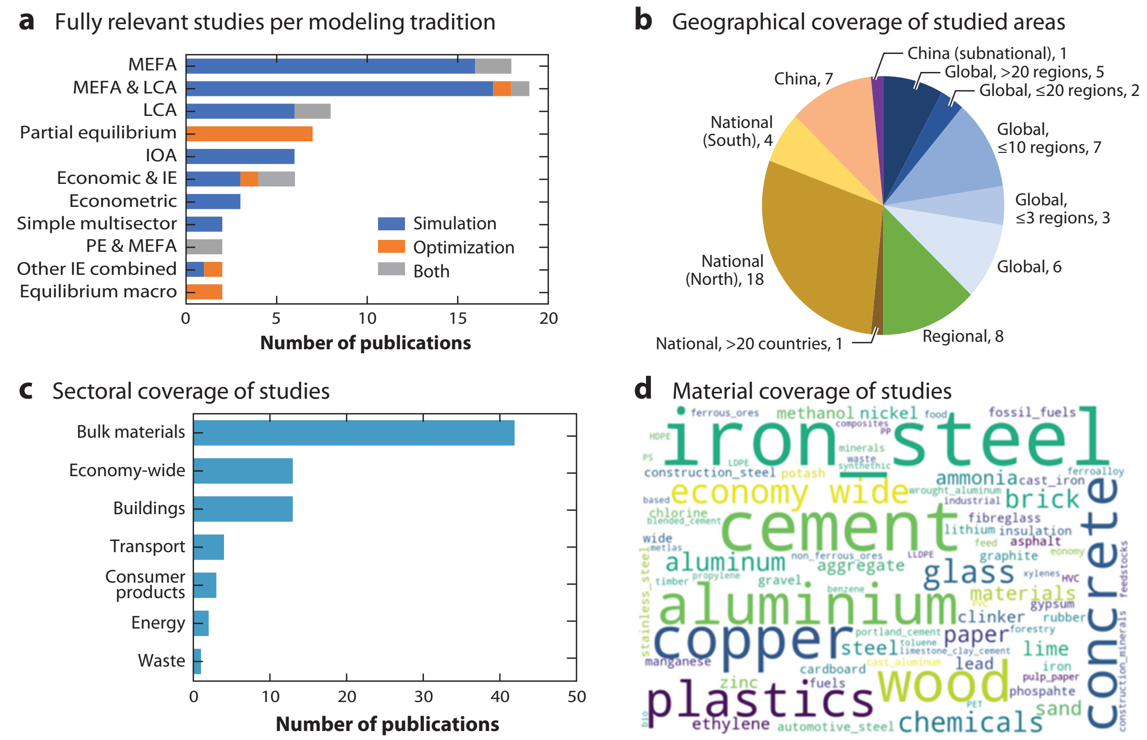
4.1. Overview of the National to Global Quantitative Evidence Base

We find 28 studies that combine two or more modeling traditions, most of them linking MEFA with LCA (**Figure 3*a***). Some 8 studies combine an economic with an industrial ecology model. About 70% of the studies simulate CE measures vis-à-vis a base year or a BAU scenario. Another 20% optimize economic costs or environmental performance compared to BAU growth pathways. Around 10% of studies combine both simulation and optimization approaches, by either soft-coupling or integrating cost-optimizing models with those from industrial ecology (e.g., MEFA with a computable general equilibrium, or CGE, model and other submodules), using simulation to model resource flows and then optimizing versus a certain goal, such as carbon budgets (9), or optimizing production systems (99). Most studies focus on the global level (36), with about half modeling one global region while the other half distinguishes among two to twenty-six world regions (**Figure 3*b***). Most of the remaining studies focus on the national level (31), primarily on countries of the Global North (18) and China (7). Only 4 studies specifically investigate Global South countries (Brazil, Colombia, Cuba, and India). Additionally, 8 studies focus on specific regions, and 1 study has provincial resolution for China.

Most studies (42) model the bulk material industries of metals (18), chemicals and plastics (9), cement and concrete (7), and other industries such as paper, wood, and waste (13) (**Figure 3*c***). Some 13 studies conduct economy-wide modeling using single IOA or CGE models, or their combinations with MEFA. Several studies focus on materials for either buildings (11 studies) or a combination of buildings, transport, and other sectors (3 studies), or specifically on transport (1 study). The most prominent materials modeled are iron and steel, cement and concrete, copper and aluminum, wood, plastics, chemicals, glass, and economy-wide material flows (**Figure 3*d***).

No single study fully addresses all four robustness criteria (**Figure 3*e***). However, there are many studies covering a combination of three criteria. We find that about 55–68% of the studies are physically stock-flow consistent, ensure mass and energy balances, and conduct uncertainty/sensitivity analyses (**Figure 3*e***). These are crucial concerns about the robustness of any study aiming to consistently show how changes to socioeconomic material cycles and material stocks affect GHG emissions from energy supply and industrial processes (95). Only 9 studies or 13% of the literature sample addresses how direct and indirect rebound effects from efficiency gains can result in increases of energy and material use. Rebound effects are widely discussed in the CE literature (62, 100), but they are not yet well addressed in macro-level modeling studies. Approaches from industrial ecology (e.g., MEFA, IOA) generally perform well regarding mass and energy balances and stock-flow consistency, whereas the rebound effect is only addressed via economic models, or combinations thereof. Although 59% of the studies conduct some sensitivity and uncertainty testing, there is clearly room for improvement across all studies (**Figure 3*e***). Finally, 65–73% of the 75 studies are open access and have supplemental information and data in some form, whereas only 26% provide open code (**Figure 3*e***).

Overall, we find that interdisciplinary combinations of models from industrial ecology and economics, followed by energy system modeling (partial equilibrium), are on the rise, which is beneficial for combining the strengths of each tradition, particularly as economics (e.g., CGE) and partial equilibrium models have a long history of supporting climate mitigation. We also find



e Studies complying with robustness criteria and FAIR principles

Share of studies per tradition complying with robustness criteria
Low — High

Robustness criteria and FAIR principles

Modeling traditions	Mass and energy balances	Rebound	Uncertainty/ sensitivity	Physical stock-flow consistency	Open access	Supplementary information	Supplementary data	Open code
MEFA	76%	6%	83%	67%	56%	67%	56%	22%
MEFA + LCA	94%	0%	67%	93%	74%	89%	68%	37%
LCA	50%	0%	50%	29%	63%	63%	38%	13%
Partial equilibrium	25%	33%	43%	25%	50%	57%	14%	0%
IOA	0%	17%	33%	0%	50%	67%	50%	17%
Economic model + IE	100%	50%	33%	67%	67%	83%	17%	0%
Econometric	50%	33%	100%	0%	67%	100%	0%	0%
Simple multisector	0%	0%	0%	0%	100%	0%	0%	0%
PE + MEFA	100%	50%	50%	100%	50%	50%	100%	50%
Other IE combined	100%	0%	50%	50%	100%	50%	0%	0%
Equilibrium macro	0%	0%	50%	0%	100%	50%	0%	0%
Total	68%	13%	59%	55%	65%	73%	50%	26%

Figure 3

Overview of the reviewed modeling studies quantifying how CE measures can support GHG mitigation at national to global levels. (*a*) Studies grouped by modeling tradition, as described by Wiedenhofer (2024). (*b*) Geographic coverage of the reviewed studies. (*c*) Sectoral coverage of the studies. (*d*) Materials coverage in the studies. (*e*) Compliance with robustness criteria, by modeling tradition. Implementation of open science principles, as studies, results, and model code should be findable, accessible, interoperable, and reusable (FAIR) (52). For details of each study, see the **Supplemental Data**. Abbreviations: CE, circular economy; CGE, computable general equilibrium; Economic + IE, combinations of economic and industrial ecology models; GHG, greenhouse gas; IE, industrial ecology; IOA, input–output analysis; LCA, life cycle assessment; MEFA, material and energy flow analysis; Other IE combined, other industrial ecology models combined; PE, partial equilibrium.

Supplemental Material >

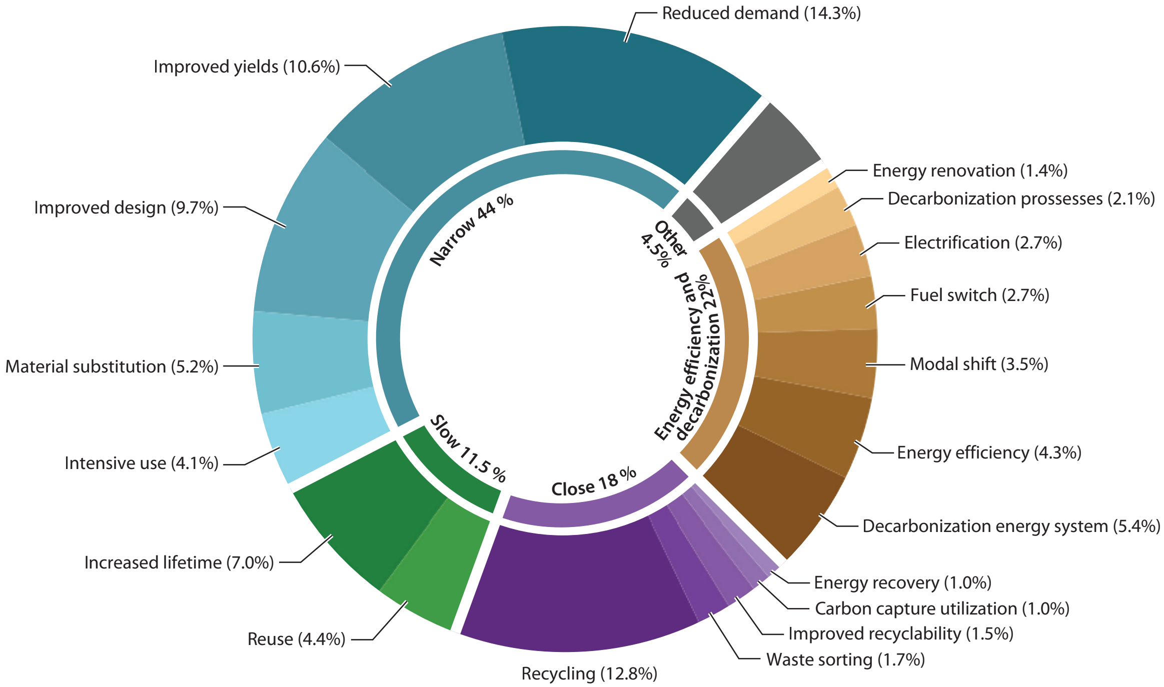


Figure 4

Overview of the circularity measures modeled in the 75 fully relevant studies. Color schemes correspond to the categories of measures: narrow (*blue*), slow (*green*) and close (*purple*), as well as decarbonization and energy efficiency (*brown*). A few measures are not clearly associated with any group and are classified as other (*gray*). The detailed measures are shaded accordingly and give their total count in a percentage. The **Supplemental Appendix Section 2** contains further documentation and more detailed figures.

a clear need for improvements regarding open science and findable, accessible, interoperable and reusable (FAIR) research (103), which would also facilitate synthesizing evidence and ensuring comparability of study results.

4.2. CE Measures Modeled in the National to Global Literature

Next, we summarize which measures are being modeled in order to understand how the CE is interpreted by modeling teams and to clarify the basis of the evidence summary in Section 4.3. We identified 517 specific measures modeled in the 75 reviewed studies. We harmonized those 517 specific measures into 24 types of measures and then grouped them along the main CE strategies: Those aiming to narrow, slow, and close material cycles, as well as those aimed at improving energy efficiency and decarbonizing the energy system and industrial processes. Further information and documentation can be found in the **Supplemental Appendix Section 2**.

Supplemental Material >

About 44% of the modeled measures aim to narrow material cycles, whereas the rest are distributed more evenly across measures that slow (12%) and close (18%) material cycles (**Figure 4**). Measures aimed at energy efficiency and decarbonization of energy and industry (22%) are the second-most applied group. The most frequently applied measures are reduced_demand (14%), recycling (13%), improved_yields and less production waste (11%), improved_design (10%), increased_lifetime (7%), and material_substitution (5%). Most studies model 1–6 measures, whereas a few model bundles of up to 40 measures (2, 101, 102).

In summary, we see that the 75 reviewed modeling studies address the entire life cycle of materials and products and that energy efficiency and decarbonization are used as complementary strategies in nearly all studies. For future evidence synthesis, an agreed upon CE framework is an important next step, which would help clearly delineate and group specific measures—for example, by adopting the narrow–slow–close grouping of CE measures advanced herein (see the **Supplemental Appendix** for details). Furthermore, a clear delineation of CE measures from other supply- and demand-side measures will be important for better understanding their interactions and potential synergies and trade-offs. Key material–energy–GHG interactions remain little explored. Material substitutions can have ill effects, for example, with timber versus other biomass-based materials or in the chemical sector, which produces not only plastics but also fertilizers and other organic chemicals, that need to be accounted in the face of a potential fossil fuel phase-out.

Supplemental Material >

4.3. Quantitative Evidence Summary of CE Potentials for Greenhouse Gas Mitigation

Finally, we show modeled mitigation potentials for materials, energy, and GHG emissions summarized from the 75 reviewed studies. The left-hand side of **Figure 5** shows results only addressing material cycles via narrow–slow–close CE measures (96 data points). Combined CE measures complemented with energy efficiency and decarbonization are shown on the right-hand side (102 data points). Due to limited FAIR data on baselines and scenarios results, even after contacting individual authors directly, we can only provide a semi-harmonized and high-level evidence summary of mitigation potentials, which does not fully disentangle the granular contributions of each specific measure. Details are available in the **Supplemental Appendix** and **Supplemental Data**.

Across the 75 studies, we find that the combined modeling of CE measures yields an average mitigation potential of 17% (0–91%, 19 data points) (**Figure 5**). When energy efficiency and decarbonization measures are modeled in combination with CE measures, an average GHG mitigation potential of 50% (1–100%, 90 data points) is achieved. In economy-wide studies, combined CE measures have an average GHG mitigation potential of 6% (0–27%, 24 data points), which in combination with energy efficiency and decarbonization increases to an average of 54% (9–100%, 11 data points).

GHG mitigation potentials of CE measures for specific sectors are varied but can be substantial, depending on the scenario assumptions. For metals, we find potentials between 3 and 81%, for cement and concrete between 0 and 81%, and for chemicals and plastics between 4 and 91%, whereas for other industries we find potentials between 42 and 52%. For buildings-related GHG emissions, we find potential reductions of 1–50%, and for transport-related emissions 0–85%. Likewise, for studies reporting combined findings for transport, buildings, and some small other associated sectors, we find potentials from 1 to 76%.

Almost all studies providing granular and FAIR data are for buildings (103–107). For example, Zhong et al. (106) estimate GHG mitigation potentials of embodied emissions of up to 41% for global buildings through floor area reduction (cumulative 2020–2060 versus BAU). Pauliuk et al. (103) find potential GHG reductions of 19% including operational emissions for global residential buildings [cumulative 2016–2050 versus a BAU in the "middle of the road" SSP2 (shared socioeconomic pathways 2) scenario]. Song et al. (108) find that slowing and closing bulk material cycles is insufficient to achieve deep decarbonization in China, arguing that strong demand-side measures must accompany the CE to reach net-zero emissions. Especially for nonmetallic minerals, these authors (108) find that recycling can increase energy use and emissions because of

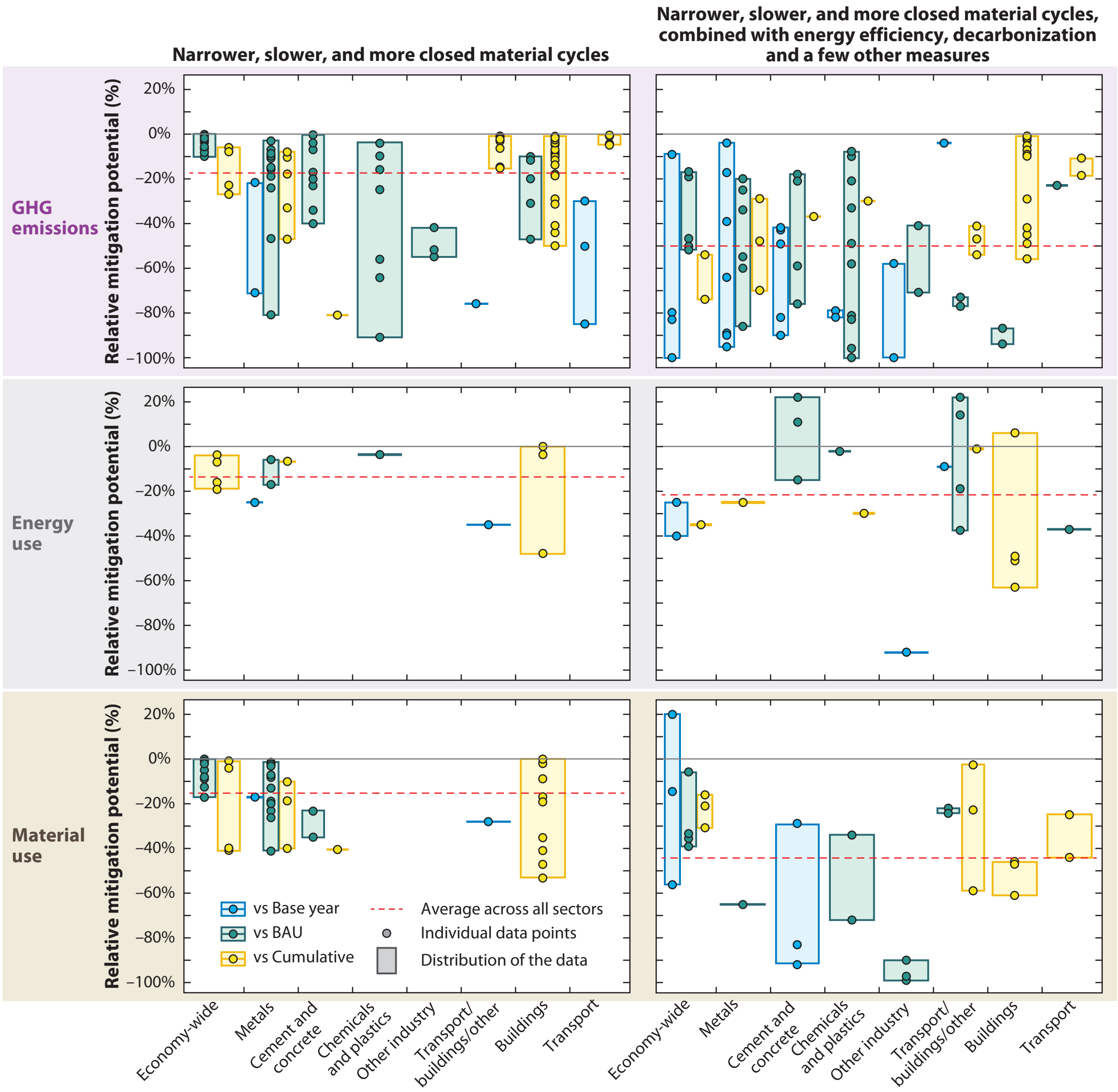


Figure 5

Synthesis of mitigation potentials for greenhouse gas (GHG) emissions, as well as energy and material use summarized from the 75 studies. Negative values indicate mitigation potentials, whereas positive values show potential increases. The left-hand column shows mitigation potentials only from CE measures aiming to narrow, slow, and close material cycles. The right-hand column shows mitigation potentials from the combined modeling of CE measures complemented with energy efficiency and decarbonization measures. Results are presented across three different temporal scopes, due to the heterogeneity of evidence: (1) "vs base year" reports the potential vis-à-vis a historical base year, (2) "vs BAU" reports annual potentials compared to a business-as-usual (BAU) scenario, and (3) "vs cumulative" reports potentials as cumulative for the entire prospective time period compared to a BAU scenario. The mitigation potentials should be interpreted as approximate estimates drawn from comparing heterogeneous groups, baseline data, and scenarios assumptions. Red dashed lines indicate average mitigation potential across all sectors and studies.

energy-intensive reprocessing. These authors (108) also show that wealthier Chinese provinces could close material cycles decades earlier than less-developed ones, due to higher end-of-life material availability, suggesting that context-specific CE strategies are necessary. Berrill et al. (109) show that for buildings in the USA, renovation and electrification reduce emissions more than rebuilding, as new homes generate higher embodied emissions and tend to be larger, offsetting efficiency gains. As operational emissions decline, embodied emissions dominate, highlighting the need for smaller homes and low-carbon materials. Mastrucci & Rao (110) demonstrate that the substitution of GHG-intensive materials can help attain decent living standards in India with substantially reduced emissions and energy consumption while also lowering construction costs.

Examples for trade-offs between more closed cycles via increased recycling and decarbonizing energy supply are found for plastics (99, 111) and shifting chemical feedstocks (112) from fossil fuels to carbon capture and utilization (CCU). For example, replacing all chemical feedstock by CCU would require low-carbon electricity amounting to up to 55% of the globally projected electricity generation in 2030. Although CCU could reduce annual GHG emissions by up to 3.5 Gt CO_{2e} in 2030, it would also compete for low-carbon electricity that could be used for impactful GHG mitigation measures, such as heat pumps and electric vehicles; similar issues are found for very high plastics recycling rates (99, 111).

For energy use, we find an average mitigation potential of 14% (0–48%, 13 data points) from the combined modeling of CE measures (**Figure 5**). When modeling CE measures together with energy efficiency and decarbonization, we find energy use mitigation potentials of 22% (+22–92%, 23 data points). Importantly, some studies suggest that energy use for concrete and steel production, as well as buildings and infrastructure, might increase in absolute terms even with CE measures, energy efficiency, and decarbonization. For example, Gaspard et al. (102) find an increase of 6% for French buildings, de Souza & Pacca (113) find an increase of 11–22% for steel and cement industries in Brazil, and Haas et al. (124) find an increase of 14–22% for buildings, transport, and electricity sectors in Austria. These findings reflect that energy use is a prerequisite for production and consumption and that many CE measures might require similar energy use compared to primary materials production.

Metals and especially iron and steel cycles are of significant interest in the CE literature, because the steel industry is responsible for approximately 7% of global GHG emissions and is considered a challenging sector to decarbonize (114). Although the industry has well-established recycling routes via electric arc furnaces, future demand for steel is projected to more than double in the coming decades (3). Global progress in decarbonizing the steel sector has largely stagnated since 1995 (115). Technological efficiency improvements have been offset by the growth of carbon-intensive steel production, particularly in China. Some potentials for narrower steel cycles through avoiding waste are still available, for example, avoiding the 26% of liquid steel that is currently lost as process scrap and never reaches final products (116). The literature therefore suggests that it is essential to narrow metal cycles by rapidly stabilizing per capita metal stock levels (1, 117), as well as reducing the GHG emission intensity of production, particularly within fast-growing middle-income countries (118, 119).

Enhanced recycling becomes the major strategy once sufficient material stocks are accumulated and coming to their end of life to supply recycling. However, achieving a CE at the regional or national level is challenging, because no single country possesses the complete set of technologies as well as fully decarbonized energy systems for high recycling without GHG emissions (69, 120). Advanced recycling technologies that can efficiently process scrap metal may be unavailable or unaffordable in regions with underdeveloped infrastructure, leading to lower recovery rates and poorer quality of recycled metals. The metal cycle extends beyond national borders and operates on a global scale; approximately two-thirds of global metal ore extraction are destined for international trade (8). In addition, manufactured products and scrap often cross borders multiple times. For example, Serrenho et al. (121) find that regardless of changes in the United Kingdom's iron and steel industry, GHG mitigation requires addressing the United Kingdom's reliance on net steel imports from other carbon-intensive producers. Therefore, a net-zero GHG CE for metals seems more sensible on a global scale (120, 122).

Nonmetallic construction minerals are quite different in this regard, as large volumes and high weight are prohibitive for large-scale long-distance transport, making regionalized recycling networks a much more useful strategy (123). The feasibility of reusing or recycling demolition waste largely depends on the distance between supply sources and end-use sites because of the high (environmental) cost of transportation.

Despite limitations in the evidence base, we conclude that CE measures alone can have substantial GHG mitigation potentials, which more than double on average when modeled in combination with energy efficiency and the decarbonization of energy supply and industrial processes (**Figure 5**). The large ranges of mitigation potentials found across the 75 studies (**Figure 5**) indicate three important challenges: First, because some studies provide more detailed results than others, the ranges of mitigation potentials shown suffer from reporting bias, as some individual measures might have small mitigation potentials, whereas combined CE scenarios have in total higher potentials. Second, the much smaller potentials of slowing material cycles via lifetime extensions might also be biased because of the limited evidence about individual measures across all studies; this is a challenge in clearly attributing mitigation potentials across multiple measures and crucially so because most scenarios run until the year 2050. Third, a substantial portion of GHG mitigation benefits may occur later, especially for already long-lived stocks like buildings and infrastructure (105, 124). Although energy efficiency and decarbonization are crucial complementary strategies (**Figure 5**), the lack of detailed scenario results from the reviewed literature inhibits fully disentangling the contributions of each materials-oriented circularity measure, vis-à-vis other supply- and demand-side measures for climate change mitigation. Therefore, implementing FAIR data standards is crucial for facilitating robust and granular evidence synthesis in the future.

5. DISCUSSION

5.1. Greenhouse Gas Mitigation Potentials from Narrow–Slow–Close CE Measures

This quantitative review of 75 national to global level modeling studies exploring over 500 individual measures shows large GHG mitigation potentials of narrow–slow–close CE scenarios across a large spectrum of sectors, product groups, and materials (**Figures 4** and **5**). Energy efficiency and decarbonization of energy supply and industry emerge as clearly complementary strategies, which help bring sectors closer to net-zero GHG emissions. Net-zero GHG energy supply is repeatedly identified as a condition of the possibility for a net-zero CE in the future. For example, increased paper (64) and plastics (99, 111) recycling, as well as replacing chemical feedstocks from fossil fuels with carbon captured and utilized (112), might not mitigate GHG emissions as long as the industry's energy supply is not decarbonized. Importantly, trade-offs can occur when the GHG mitigation potentials of high recycling rates require substantial amounts of low-GHG electricity supply, which might also be used to decarbonize other sectors more effectively (111, 112).

Most materials cannot be recycled without material and quality losses (26, 61). Plastics and paper degrade with each reprocessing, and recycling of metals involves losses and requires substantial energy, which still comes largely from nonrenewable sources. Hence, closed material cycles are most usefully understood as an aspirational theoretical benchmark (125). Clearly, there are large untapped potentials due to low recycling rates for many materials and countries. Many of the reviewed studies emphasize that beyond closing loops, narrowing via demand reduction and resource-efficient product design and provisioning are crucial for a CE to reduce GHG emissions.

5.2. Future Research Needs to Robustly Quantify Mitigation Potentials of CE

We identify three future research needs emerging from the following limitations. First, more robust and granular modeling of the CE's potentials for GHG mitigation requires addressing the dynamic interconnections of materials cycles, waste, energy, and material stocks and linking them to models depicting socioeconomic dynamics (32, 95, 96, 126). Single modeling approaches do not provide a sufficiently comprehensive and robust multidimensional assessment of the CE for climate mitigation (95, 96, 126). IOA and LCA do not reflect the dynamics of energy transitions and CE measures, including the deployment of new technologies and improved processes over time. MEFA models do not endogenously capture the trade-offs between material flows and the necessary adjustments in energy systems. IAMs and CGE models—extensively used to support macro-level mitigation decisions and policies—frequently lack biophysical consistency and usually do not present the necessary value-chain granularity. Second, data limitations regarding economy-wide material cycles (127, 128) and the absence of harmonized classification systems for materials, as already available for energy, hamper current CE assessments. Information on material and energy trade-offs, product maintenance costs, recycling limits based on regional or national scrap quality and quantity, and consumer behavior—including willingness to change habits and the magnitude of rebound effects—often are scattered across detailed studies with variable system boundaries or are completely unavailable. Third, an often overlooked issue is transport and trade. Circular supply chains frequently involve fragmented shipments, multiple handling points, and possible additional transport steps (e.g., from consumers to collection, sorting, and recycling units), the impacts of which on GHG emissions are yet unclear. Similarly, the implications of CE measures in certain world regions on key trading partners and across global supply chains are not properly addressed in the reviewed literature.

Five research efforts therefore seem essential, which are being addressed in ongoing projects around the world, including Horizon Europe–funded work.[3] First, ongoing efforts aim to integrate industrial ecology with a variety of economic- and processed-based IAMs, aiming to capture the complexities associated with material cycles and stocks, as well as rebound effects and other socioeconomic implications, and the technology shifts needed for climate mitigation (32, 129–131). Based on aligned system boundaries, industrial ecology and economic approaches could then provide multidimensional assessments of biophysical and socioeconomic costs, benefits, and trade-offs of different CE transformation pathways (49, 95).

Second, expanding biomass use to substitute GHG-intensive materials such as concrete and steel is widely discussed and modeled, however, often with overly simple assumptions. Currently, material uses of biomass for construction and various products (timber, paper, fibers) play a minor role compared to biomass use as energy carrier and for food and feed (8, 132). Biomass does have the potential to be biodegradable and carbon neutral within limits, although intensifying land use and growing biomass demand are already creating a critical land squeeze (133, 134). Further work is necessary to understand an environmentally sustainable level of biomass extraction and

[3]For example, see **https://circomod.eu**, **https://circeular.org**, **https://co2nstruct.dtu.dk**, **https://mapsresearch.eu/**, and **https://www.realpostgrowth.eu/**.

land use (47, 133, 134). This includes the carbon opportunity costs of harvesting timber for the construction of buildings versus the growth of natural carbon stocks in forests (104, 135–137). It also pertains to the carbon opportunity costs and net GHG benefits of more circular/cascading biomass use, e.g., prioritizing reuse of timber over burning for energy, or leaving forests to grow (35, 138–140).

Third, common conceptual frameworks as proposed herein are required to facilitate the synthesis of study results into overarching insights. This starts with establishing standardized data exchange protocols and a data ontology (30, 141), as well as creating comprehensive, robust and open databases on historical material flows and stocks across various products and sectors (142–145). Necessary data to represent higher-tier R-measures aiming to narrow and slow are often insufficient, requiring work-intensive surveys and field work. Integrating empirically driven and context-specific micro- and meso-level research into macro-level modeling is a key task here. Ongoing efforts by the industrial ecology community (145, 146), the Integrated Assessment Modeling Consortium (IAMC; **https://www.iamconsortium.org**), the International Transport Energy Modeling (iTEM) network (**https://transportenergy.org/**), and the Energy Demand changes Induced by Technological and Social innovations (EDITS) network (**https://iiasa.ac.at/projects/edits**) are working on such ontologies and templates, aiming to facilitate contributions to the 7th Intergovernmental Panel on Climate Change (IPCC) assessment and beyond. Herein, we advanced the narrow–slow–close grouping of the many possible specific CE measures and the clear delineation from energy efficiency and decarbonization as a first step toward such a framework.

Fourth, linking CE scenarios to the latest shared socioeconomic pathways (SSPs), as for example in Reference 147, as well as ongoing efforts toward developing a new postgrowth SSP (148), would help to show the wider relevance of CE measures in the context of various other supply- and demand-side measures being explored. The SSPs are a common framework connecting research on mitigation, adaptation, and impacts, and since their inception in 2014 they have been developed further (149, 150), with substantial quantitative updates[4] released in 2024. Developing additional, regionally specific CE pathways, grounded in empirical evidence, could improve transparency and integrate micro- and meso-level empirical research into macro-level models. This would facilitate future evidence synthesis for policy, as well as for assessment reports conducted by the IPCC or the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Finally, another important avenue for macro-level CE research is to deepen the engagement with environmental-economic monitoring and reporting frameworks. Statistical agencies are increasingly compiling CE-relevant information to provide progress toward policy targets. These efforts build on economy-wide material flow accounting as part of the System of Environmental-Economic Accounts, which are already used to monitor the circular material use rate of nations and the global economy (50, 52–54, 132). Here, it is important to see that energy and emissions monitoring have a relatively long history and by now provide relatively granular and consistent data, as the accounting is hosted by international bodies such as the International Energy Agency, the International Renewable Energy Agency, the Food and Agriculture Organization, and the United Nations Framework Convention on Climate Change. In comparison, economy-wide monitoring of material cycles, stocks, and circularity is relatively young (127, 128). Therefore, the biophysically consistent integration of materials–energy–GHG monitoring is therefore another important research frontier.

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[4]Refer to **https://depts.washington.edu/iconics/** and **https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update/**.

5.3. Policy Implications for Realizing the Greenhouse Gas Mitigation Potentials of the CE

Despite the promising GHG mitigation potential found (Section 4), the CE risks fragmentation and misuse without clear boundaries and careful assessment of trade-offs. Although the CE concept bridges academia, business, and policy like few other sustainability concepts (16), its broad appeal is both a strength and a challenge. The CE draws in diverse interests and perspectives, which can lead to fragmented implementation or even co-optation by powerful actors. The disagreements outlined in Section 2.1 and the research gaps in Section 5.2 reveal key compromises and risks in CE strategies. Beyond thermodynamic and biophysical limits, meaningful assessments must also account for critical societal and (geo)political trade-offs.

A fundamental societal risk is increasing global consumption and rebounds undermining the promise of absolute and deep decoupling of resource use from economic growth (13, 151, 152). Although some CE strategies can extend product lifetimes or improve materials efficiency, these gains are often outweighed by increasing global consumption. For instance, technological efficiency improvements in the steel sector have been offset by the growth of high-carbon intensity steel production, particularly in China. Researchers therefore warn of rebound effects: Efficiency gains that lead to price reductions can lead to higher consumption and negate the climate benefits (62, 108).

Geopolitical tensions and trade-offs across spatiotemporal scales further constrain a CE global vision. As more countries implement circular strategies, global demand for secondary materials and recyclable inputs could intensify. This risks stripping local communities—especially in resource-rich but economically disadvantaged regions—of the materials they need to build up their own economic systems (52). Conversely, efforts to achieve local self-sufficiency could challenge global supply chain dependencies. To add to the complexity, current patterns of resource flows between the Global North and South perpetuate colonial extractivist dynamics. Access to CE technologies is not evenly distributed. Wealthier countries and groups often have better infrastructure for repair, recycling, or reuse while others become hotspots for dumping waste or extracting raw materials (52, 153–155).

How can scientific evidence help to design policies that avoid these societal and political trade-offs and risks? Our analysis suggests some immediate policy implications. Binding resource reduction targets, for instance, should complement existing recycling and reuse goals to avoid rebound effects. Furthermore, divestment from linear production and consumption systems and investments in new infrastructures and technologies—in the Global North and South—are needed. Any public funding for CE initiatives should be tied to social co-benefits, such as improved labor conditions or reduced extraction from the Global South. CE regionalization strategies could support repair centers, regional recycling infrastructure, or bio-based loops that strengthen local economies and communities while reducing environmental pressures. Finally, establishing a common vocabulary and data infrastructure is essential. One way forward could be the creation of an independent CE accountability body—one that sets standards to develop evaluation frameworks and monitors net sustainability gains across environmental, social, and economic dimensions. This body could be supported by systemic, transdisciplinary CE research, embedding questions of power, equity, and cultural practice into how we design and evaluate CE policies.

6. CONCLUSIONS

The 75 reviewed modeling studies exploring the CE at national to global levels show great climate change mitigation potentials, especially if CE measures are complemented with energy efficiency and decarbonization. We find that the CE can potentially reduce material use and GHG emissions more than energy use, whereas mitigation potentials are less clear. At the same time, we summarized a set of biophysical, social, and (geo)political trade-offs and risks inherent in many CE strategies. These trade-offs and risks inform a set of interconnected future research needs, which are being addressed in multiple large-scale research projects around the world. Currently, the lack of consistent baseline information and scenario data poses challenges for granular evidence synthesis and specific science-based policy recommendations. We therefore highlight the need for more open science, FAIR data, and interdisciplinary collaborations linking industrial ecology with traditional and heterodox economic approaches to facilitate more policy-relevant evidence synthesis in the future.

Finally, we emphasize that evidence synthesis needs to go hand in hand with adequate policy processes, embedding questions of power, equity, and cultural practice into the design and evaluation of CE policies. A politically transparent and coordinated approach to these trade-offs and risks is not something that is just nice to have; it is a prerequisite for an environmentally and socially sustainable CE. Ultimately, the macro-level climate benefits of a CE depend on who controls the loops, who benefits, and who pays the price.

SUMMARY POINTS

- The circular economy (CE) is a materials-oriented strategy that aims to narrow, slow, and close economy-wide material cycles, avoiding waste and reducing primary material demand, and thereby mitigate energy demand and GHG emissions.
- The CE is complementary to and partially integrates other materials-, energy- and GHG-oriented supply- and demand-side mitigation strategies, such as material efficiency, avoid–shift–improve, energy efficiency, and material substitution, as well as dietary change, sustainable land use, degrowth, and postgrowth.
- Although CE policy originates from a few pioneering countries originally focusing on resource efficiency and avoiding waste, in 2024 more than 79 countries reference the CE within their Paris Agreement Nationally Determined Contributions (NDCs) to climate change mitigation.
- Competing interpretations of the CE's potentials and limits, combined with the lack of a generally accepted definition, result in tensions about how to operationalize, analyze, and implement the CE in a systems-oriented manner.
- Neither concrete measures nor monitoring systems to ensure climate change mitigation through circularity at the national level have been developed yet.
- Studies modeling national to global material cycles find substantial GHG mitigation potentials of on average 17% (0–91%) from measures solely narrowing, slowing, and closing material cycles.
- When CE measures are modeled in combination with energy efficiency and decarbonization of energy supply and industry, GHG mitigation potentials reach on average 50% (1–100%).
- There are significant variations in the materials, energy and GHG mitigation potentials reported across national-to-global-level studies due to ambiguous system definitions arising from diverse disciplinary backgrounds and the inherent complexities involved in

modeling the numerous interdependencies among material cycles, energy systems, and GHG emissions across sectors and supply chains.

FUTURE ISSUES

- Agreed upon CE frameworks and indicators are required to show CE potentials, trade-offs, and synergies for climate change mitigation at national levels, ideally extending upon established economy-wide CE monitoring frameworks in the European Union, China, and Japan.
- The unintended consequences of national CE policies on key trading partners, particularly those in the Global South, as well as the dependence on global coordination and collaboration to achieve domestic CE goals should be addressed more explicitly in future work.
- Ensuring biophysical consistency in the analysis of economy-wide material cycles, energy use, material stocks, and GHG emissions is crucial for understanding how CE measures interact with socioeconomic dynamics as well as other supply- and demand-side GHG mitigation measures.
- It is crucial to clearly define and report the specific modeled measures and their respective materials, energy, and GHG mitigation potentials ideally in a standardized format to facilitate disentangling the respective contributions and trade-offs among CE measures as well as energy efficiency and decarbonization efforts.
- Understanding GHG mitigation potentials from socioecological biomass cycles requires systematically assessing trade-offs between ecosystems and socioeconomic systems over time, which substantially increases modeling complexity and is currently oversimplified in most life cycle assessment studies.
- Shared concepts and scenario narratives, as well as open science principles and findable, accessible, interoperable, and reusable research data (FAIR), ideally in widely used data exchange formats, are needed to facilitate the combination of models, the comparison of results, and the synthesis of evidence.
- Connecting CE scenarios with the shared socioeconomic pathway framework is important so that the Intergovernmental Panel on Climate Change and other assessment efforts can integrate the potentials of the CE into evidence synthesis.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

D.W. contributed to the article's conceptualization, methodology, investigation, resources, writing of the original draft, review and editing, visualization, supervision, project administration, and funding acquisition. H.W. contributed to the article's investigation, methodology, formal analysis, data curation, visualization, and writing of the original draft. S.L. and C.A.-S. contributed to the article's investigation and writing of the original draft. T.W. and G.A.A.-H. contributed to the article's investigation, data curation, and review and editing. S.G. contributed to the article's investigation, formal analysis, data curation, visualization, and writing of the original draft. O.Y.E., M.Z.-Z., and P.F. contributed to the article's investigation, data curation, and writing of the original draft. L.K. contributed to the article's investigation, data curation, and review and editing. W.H. contributed to the article's conceptualization, investigation, and writing of the original draft. J.S. contributed to the article's conceptualization, methodology, formal analysis, investigation, data curation, visualization, supervision, writing of the original draft, and review and editing.

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