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EDITORIAL

Revisiting the sustainability science research agenda

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Abstract
Identifying research gaps and priorities is paramount to advance sustainability science and contribute to a sustainable future. This editorial contributes to this effort by contemplating the sustainability science research agenda and aligning it with recent changes in global dynamics. Drawing on consultations with the editorial board members of the Sustainability Science journal and a review of relevant literature, we identified 12 key research topics. These topics are interpreted within a strategic framework encompassing three key themes: (1) goals that drive sustainability science, (2) approaches to attain these goals, and (3) tools to advance sustainability science research. In so doing, this editorial emphasizes a sustainable development agenda extending beyond 2030, fostering equity and justice, and tackling issues related to power dynamics and geopolitical conflicts. It underscores the significance of research approaches to attaining sustainability goals, in particular, theorizing, co-production of knowledge and action, attaining clarity in conceptual descriptions, and developing systems-oriented analytical frameworks. Additionally, it highlights the value of place-based approaches, learning from significant systemic shocks, and nurturing inner transformations. It also underlines the need to explore emerging technologies and data-intensive methodologies as a tool to address sustainability concerns. The systematic contemplation of the sustainability science research agenda presented in this editorial piece aims to invoke further discussion among researchers and practitioners about a fresh and relevant agenda that promotes the sustainable integration of nature and society.

Keywords Sustainability transformation · Research prioritization · Transdisciplinarity · Sustainable development · Expert consultation

Introduction

Addressing the most pressing global challenges of our time requires a concerted effort from researchers, policymakers, and local communities across sectors and contexts. Climate change, poverty alleviation, biodiversity loss, inequality reduction, water scarcity, and marine ecosystem conservation are formidable obstacles to global sustainability (Hamann et al. 2018; Ashford et al. 2020; Arnott and Lemos 2021). In response to these challenges, sustainability science has emerged as a vibrant field of research and innovation, aiming to assess threats posed by social-environmental changes and to co-creating effective solutions (Kates et al. 2001; Shrivastava et al. 2020; Clark and Harley 2020; Arias-Maldonado 2020; Folke et al. 2021). However, given the rapidly evolving nature of global crises, it is clear that the current research priorities within sustainability science need constant realignment and reconsideration to fully address the complexity and dynamics of global social and environmental change.

The development of sustainability science is characterized by its transdisciplinary nature and collaborative philosophy (Clark and Harley 2020; Tengö and Andersson 2022; Currie et al. 2024). Transdisciplinarity lies at its core, which involves engaging non-academic stakeholders in knowledge creation (Scholz and Steiner 2015; Rigolot 2020). By embracing transdisciplinary methodologies and fostering partnerships among diverse interests, sustainability

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science seeks to catalyze transitions to a sustainable global society (Takeuchi et al. 2017; Gaziulusoy and Erdoğan Öztekin 2019). One of the critical shifts in sustainability science is broadening the research focus to encompass social, economic, environmental, and institutional dimensions of change (Moran and Lopez 2016). This expansion acknowledges the interconnectedness of human societies with their environment and emphasizes the importance of holistic (Raymond et al. 2019; Ives et al. 2020; Clark and Harley 2020; Folke et al. 2021) and relational approaches (West et al. 2020; Walsh et al. 2021; West et al. 2024a, b) to problem-solving.

Despite these advancements, the COVID-19 pandemic, geopolitical conflicts, and economic instabilities underscore the necessity of adaptive and resilient sustainability approaches (Chaerani et al. 2023; Yuan et al. 2023; Zhao et al. 2022). Significant gaps remain in achieving the 2030 Agenda for Sustainable Development, necessitating a focus on practical and achievable goals (Leal Filho et al. 2020; UN 2022). Advancements in science and technology require ethical and environmental considerations to ensure alignment with sustainability principles (Goralski and Tan 2023). Unmet international commitments in climate and ecological emergencies further underscore the urgency of revisiting research. Constant realigning and reconsidering of the sustainability science research agenda is needed to ensure that scholars and practitioners can address the changing nature and dynamics of global sustainability challenges.

Sustainability science is a dynamic and evolving field that continuously adapts to new challenges and opportunities to contribute to societal pursuits toward a more sustainable future in the Anthropocene (Gibbons 2020). This means there is an ongoing need to identify research gaps and explore pathways to advance sustainability science. Recent studies have highlighted vital research priorities within sustainability science, emphasizing the need for transformative change across various domains (UN 2019; Wuelser et al. 2020; Clark and Harley 2020; Liu et al. 2021; Fu et al. 2021; Jacob et al. 2022; Pascual et al. 2023). These priorities span a range of topics, including human well-being, food systems, energy decarbonization, values of nature, and environmental governance.

Aligned with this need, select members of the editorial team of Sustainability Science have undertaken a collaborative effort to systematically reassess the field's current research priorities. This editorial responds to concerns about potential lacunas in current research agendas, offering a systematic consideration of the relevance and impact of sustainability science in addressing global challenges. Developed in partnership with the editorial board of the Sustainability Science journal (SustSci EBM), this initiative aims to identify new research topics and adjust the focus of sustainability science in response to recent changes in global social dynamics and emerging challenges. It leverages a literature review and discussions with the editorial board to pinpoint key research topics, categorize them into strategic themes, explore new areas, and promote cross-disciplinary approaches. The results of this effort are used to outline future research directions and to underscore the importance of integrating diverse perspectives and employing transdisciplinary methodologies.

The main body of this editorial is structured into two distinct sub-sections. The first section reveals the outcomes of the topic ranking conducted by the SustSci EBM and overviews the selected research topics, categorized into three primary themes. The second section explores emerging topics within sustainability science and the way forward.

Exploring a future research agenda in sustainability science

The methodology used to identify and prioritize research topics in sustainability science involved consulting with SustSci EBM and conducting a literature review, as detailed in supplementary material 1. Consultation sessions with SustSci EBM occurred during annual meetings from 2019 to 2022, gathering various prioritized research topics. A literature review was performed by searching the Scopus database using relevant keywords and examining recent publications from selected journals addressing emerging issues in sustainability science (Supplementary material 2). Through discussions, 12 potential research topics were identified. SustSci EBM ranked these topics through an online survey, which assessed their priority and suggested additional emerging topics. The editorial underwent two rounds of consultation with SustSci EBM, incorporating feedback to ensure alignment with current research priorities and to achieve rigorous revisions.

The rankings for each topic are presented using a linear scale ranging from 1 (lowest priority) to 5 (highest priority). Figure 1 displays the rankings of 12 identified research topics based on scoring by 68 SustSci EBM. The highly-ranked topics were "Sustainability development—looking beyond 2030" (average ranking of 4.1) and "Fostering equity and justice" (average ranking of 4.06). Following were "Theorizing in sustainability science" (average ranking of 3.94) and "Co-production of knowledge and action" (average ranking of 3.93). Topics with lower average rankings included "Conceptual clarity for operationalizing phenomena" (average ranking of 3.06), "Harnessing emerging technologies for a sustainable future" (average ranking of 3.34), and "Learning from large systemic shocks" (average ranking of 3.38). The remaining topics ranged from 3.42 to 3.49 on average. As all 12 topics received rankings above the average (2.5),

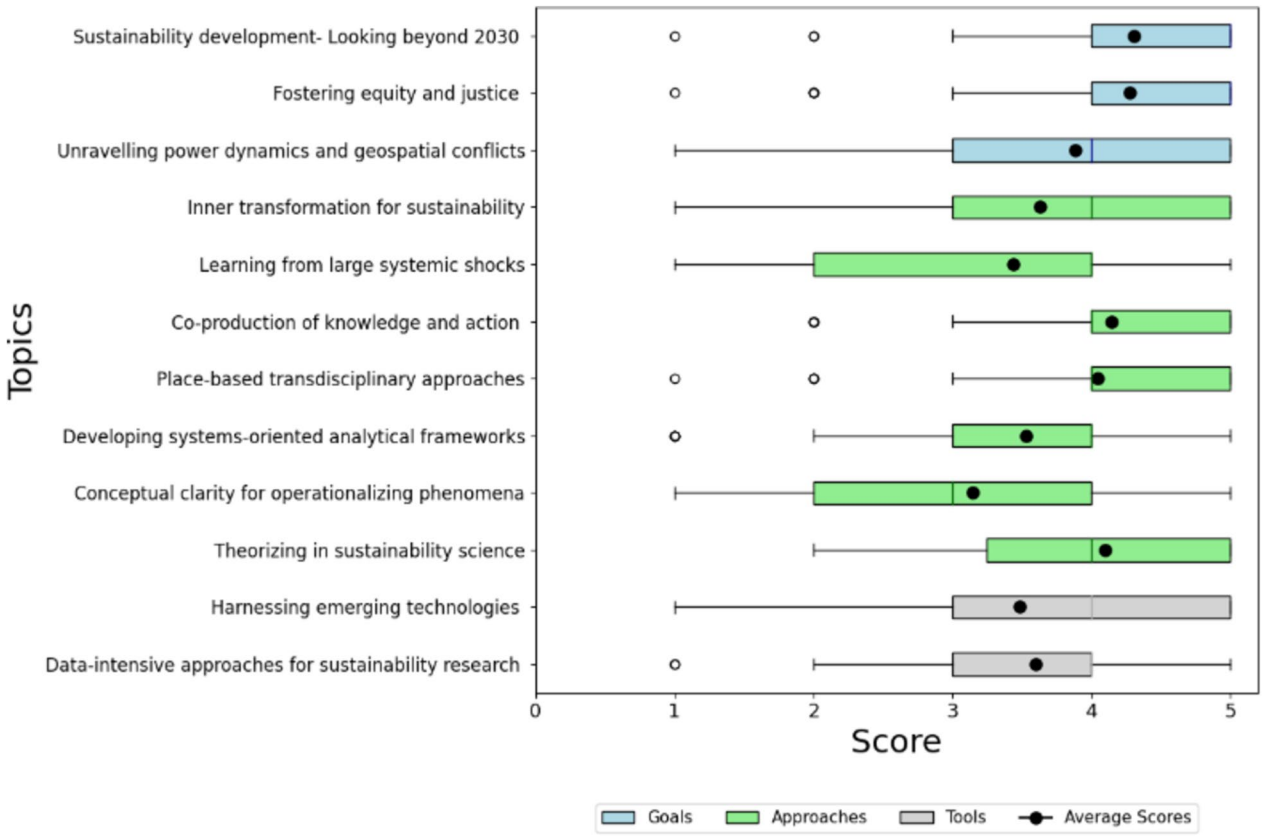

Fig. 1 The scores of 12 selected research topics in sustainability science. Points located beyond the whiskers are considered outliers. The lower and upper lines represent the minimum and maximum data ranges, while the box encapsulates the interquartile range, encompassing the middle 50% of the data. The sky-blue color highlights the theme related to the goals sustainability science seeks to contribute to, while the light green color denotes the theme focusing on approaches to achieve sustainability goals. Additionally, the grey color signifies the tools utilized to advance research in sustainability science

they were retained as priorities in the sustainability science agenda without further reprioritization.

Reviewing the selected topics in the context of sustainability science reveals three main themes (including subthemes) based on conceptual inter-relations (Fig. 2). The three main themes are: (i) goals to which sustainability science seeks to contribute; (ii) research approaches to support achieving these goals; and (iii) tools to propel research forward beyond 2030.

Within the category of the goals addressed by sustainability science, "Sustainable development—Looking beyond 2030" received a notable score of 4.1, followed closely by "Fostering equity and justice" at 4.06 (Fig. 1). "Unraveling power dynamics and geopolitical conflicts" received a comparatively lower score of 3.65. Regarding approaches to achieving sustainability, "Theories in sustainability science" received a score of 3.94, followed closely by "Co-producing knowledge for sustainability" at 3.93. "Place-based approaches" garnered a score of 3.87, while "Inner sustainability transformation" scored 3.46. Further down the list were "Systems-oriented analytical frameworks" with a score of 3.42 and "Learning from COVID-19" with 3.38. "Conceptual clarity in sustainability science" received a score of 3.06. Regarding tools advancing research, data-intensive approaches scored 3.49, and leveraging emerging technologies received a score of 3.34, reflecting their comparable importance in the research landscape. The ranking allows us to sequence topics within each theme, prioritizing those with higher scores first.

Theme 1: the goals to which sustainability science seeks to contribute

This theme centers on the aspirations and extended vision of the post-2030 sustainable development agenda. It underscores the role of sustainability science to contribute to setting the sustainable development agenda to extend beyond 2030, fostering equity and justice, and tackling issues related to power dynamics and geopolitical conflicts (Fig. 2). Envisioning the post-2030 sustainable development agenda requires the perspective needed to foster equity and justice. Addressing power dynamics and conflicts is essential to

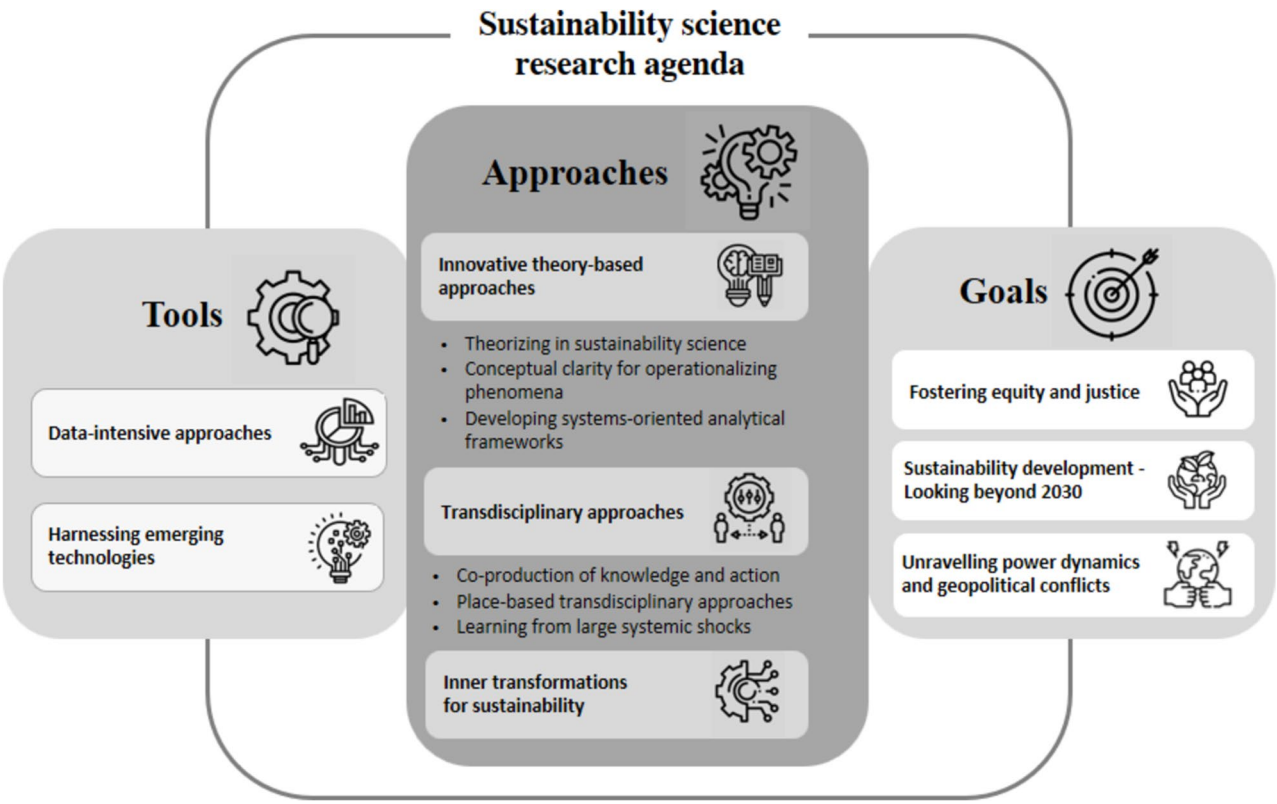

Fig. 2 An overview of the selected research topics categorized within three key themes: (i) the goals that sustainability science seeks to address; (ii) the approaches employed to achieve these goals; and (iii) the tools that can drive advancements in sustainability research (Source: developed by authors)

creating conditions that enable equity and justice, ultimately contributing to a more sustainable and just world.

Sustainable development—looking beyond 2030

The United Nations introduced the SDGs to tackle sustainable development issues and create a better world for both present and future generations (UN 2015). Comprising 17 goals with 169 targets, the SDGs touch on all aspects of human life and interact in complex ways (Nilsson et al. 2018). The SDGs are in force from 2015 to 2030, guiding political and civil society actions to tackle pressing challenges such as climate change, poverty reduction, biodiversity loss, and social inequality (UN 2015).

However, achieving these goals by 2030 remains uncertain due to various barriers and crises. These challenges include resistance from vested interests, the vagueness of some goals and targets, collective action problems, trade-offs between the goals and targets, financial constraints, and setbacks due to an unprecedented COVID-19 pandemic (Leal Filho et al. 2020; UN 2022; Chaerani et al. 2023; Yuan et al. 2023; Goralski and Tan 2023; Zhao et al. 2022). Moreover, emphasizing economic growth within the formulation of the SDGs creates a barrier to sustainability (Eisenmenger et al. 2020; Menton et al. 2020). This perspective aligns with the degrowth literature, which argues that prioritizing continuous economic expansion often leads to environmental degradation and social inequities (Parrique 2023). Prioritizing and understanding the impacts of achieving or falling short of the SDGs, sufficiency in relation to sustainable consumption, and the management of synergies and trade-offs among SDGs are areas that require further investigation (Weitz et al. 2018; Gasper et al. 2019; Ait Sidhoum et al. 2022; Anderson et al. 2022a, b). Failing to address these gaps hinders progress toward equitable development. Moreover, the metrics used to monitor the achievement of the SDGs do not accurately reflect the degree to which their attainment signifies progress toward sustainable development (Clark and Harley 2020).

As we approach 2030, setting the sustainable development agenda beyond 2030 is essential to address the complex challenges facing humanity and the planet. Sustainability science scholars play a vital role in this endeavor by synthesizing diverse data sources to formulate coherent global targets based on their understanding of the social-environmental interdependencies (Reyers and Selig 2020) and producing long-term scenarios to evaluate their effects (Moallemi et al. 2020). Their engagement extends

to devising holistic, systemic, and relational strategies to establish effective governance and institutional accountability mechanisms to overcome implementation hurdles (Biermann et al. 2023; Pradhan 2023; West et al. 2024a, b), to establishing reliable financing mechanisms, fostering international cooperation and partnerships, and investing in education and infrastructure (Leal Filho et al. 2023). Investigation of SDGs gaps and transdisciplinary collaboration helps sustainability scientists to critically assess governance efforts that promise to deliver a sustainable and prosperous future (Moallemi et al. 2020).

Fostering equity and justice

Achieving equitable and just outcomes for present and future generations involves understanding the interplay of economic drivers and environmental conflicts to address the unequal distribution of resources and benefits within and between societies (Leach et al. 2018; Temper et al. 2018; Scheidel et al. 2018; Bennett et al. 2019; Scheidel et al. 2018). Recognizing the rights of non-human entities, future generations, and the interdependence of ecosystems is indeed essential for sustainability (O'Connor and Kenter 2019; Anderson et al. 2022a, b).

Fostering equity and justice in sustainability science entails considering and integrating multiple justice dimensions, such as distributive, procedural, contributive, and environmental justice, into research, policies, and actions (Menton et al. 2020; de Herve et al. 2023; Boonstra and Söderberg 2024) as well as their academic structures and institutions. Despite progress in incorporating equity and justice into sustainability science and research practices, a significant research gap persists, particularly in examining equitable outcomes across various scales (Hamann et al. 2018; Biermann and Kalfagianni 2020).

Sustainability science can play a pivotal role in addressing the imperative for justice in sustainability. By conducting transdisciplinary research, sustainability science scholars can elucidate the complex interplay between political economy, resource distribution, and environmental sustainability (Wiedmann et al. 2020; Kaul et al. 2022). Through comprehensive analyses and integration of world-system analysis with planetary boundaries, sustainability scientists can offer insights into transitioning to renewable energies and mitigating climate change (Gielen et al. 2019; Kim and Kotzé 2021). Moreover, sustainability science can investigate the political and institutional factors perpetuating inequities, examining power dynamics and decision-making processes to identify opportunities for transformative change toward greater equity (Patterson et al. 2017; Temper et al. 2018; Scheidel et al. 2018; Bennett et al. 2019).

Unraveling power dynamics and geopolitical conflicts

Understanding and addressing power dynamics and geopolitical conflicts is crucial due to their profound influence on resource control, social marginalization, and decision-making exclusion (Boonstra 2016). These dynamics often lead to social-environmental injustices and exacerbate geopolitical tensions, particularly in regions with contested natural resources (Schellens and Diemer 2020). However, a notable research gap exists regarding effective solutions to rectify these power imbalances and promote equitable resource governance.

Power disparities intertwined with geospatial conflicts intensify social and economic strains and hinder progress toward SDGs globally (UN 2020, 2022). For instance, wars like those in Ukraine, Russia, Palestine, and Israel have resulted in humanitarian crises, impacted energy availability, and caused environmental pollution (Osendarp et al. 2022; Dell'Angelo et al. 2023; Akgül-Açıkmeşe and Özel 2024). Similarly, conflicts in Africa and the Middle East have impeded SDG achievements, including poverty reduction, access to clean water and energy, and environmental sustainability (Kumar and Roy 2018; Solomon et al. 2018; Pereira et al. 2022).

Addressing these issues necessitates a collaborative approach involving governments, international organizations, civil society, businesses, academia, and other stakeholders. The focus should be on fostering inclusive and equitable resource governance to mitigate power imbalances (Egid et al. 2021; Ratner et al. 2022). Moreover, orienting power dynamics towards equity and justice requires integrating disciplines such as political ecology, environmental justice, and governance studies (Clark and Miles 2021; Patterson et al. 2017; Malešević, 2022). Scholars in sustainability science can contribute significantly by employing data-driven modeling to analyze energy transition scenarios and their impacts on social-environmental justice outcomes. They also play a pivotal role in identifying effective practices for conflict-sensitive conservation and advocating for policy interventions based on empirical evidence (UN 2020, 2022). To bridge the research gap, future studies should focus on integrating approaches/disciplines to develop practical frameworks and policy recommendations that promote fair and sustainable resource management amidst geopolitical conflicts. This approach can pave the way for more just transitions and resilient societies worldwide.

Theme 2: approaches for achieving the sustainability

Transdisciplinary approaches in sustainability science are essential for identifying effective and sustainable solutions involving, among other things, technology, public policies,

human rights, and global constraints (Knapp et al. 2019; Hölsgens et al. 2023; Scholz and Steiner 2023). The second theme encompasses approaches for achieving sustainability and can be organized into three sub-themes (Fig. 2).

Sub-theme 1: innovative theory-based approaches in sustainability science

Theorizing in sustainability science Sustainability science aims to comprehend social-ecological interactions by employing theoretical frameworks to gather and generate knowledge that can help guide interactions toward sustainable outcomes (Raymond et al. 2019; Lang and Wiek 2022). Theorizing in sustainability science involves developing and applying theories to address the multifaceted challenges and causal complexity of sustainable development, consolidate understanding, extract insights, and advance transformative action toward more sustainable and equitable futures (Schlüter et al. 2022). However, theory building in sustainability science faces various challenges, including integrating transdisciplinary perspectives, grappling with complexity and context specificity, embracing long-term processes, ensuring practical applicability, establishing empirical foundations, and balancing quantitative and qualitative methodologies (van Riper et al. 2018; Purvis et al. 2019).

Sustainability scholars often utilize diverse theoretical frameworks, each with its own limitations, prompting exploration into more integrated approaches that consider power dynamics and the array of values attributed to nature (Purvis et al. 2019; van Kerkhoff 2014). Nevertheless, the emphasis on action-oriented outcomes sometimes sidelines the significance of theory building, potentially hindering the depth of understanding and the potential for impactful interventions (Waring et al. 2015; Cumming and Peterson 2017; Bodin et al. 2019; Meyfroidt et al. 2018; Lang and Wiek 2022). Exploring avenues of solution-oriented research and methodological innovation holds promise for addressing sustainability challenges (Pereira et al. 2020a, b). Theoretical abstractions must be effectively connected with practical relevance to make theories more useful in dissecting complex sustainability issues and catalyzing transformative action (Austin and McBeath 2022).

Achieving effective theorizing in sustainability science requires bridging disparate theoretical traditions, which involve collaborative and participatory processes with stakeholders, experimentation, and learning from practical experiences (Nagatsu et al. 2020). These approaches should encompass the intricacies of social-environmental interactions, acknowledging the interdependencies across different scales of analysis (van Riper et al. 2018; Kenter et al. 2019; Li et al. 2021; Bodin et al. 2019). Embracing diverse theoretical and methodological approaches while prioritizing communication can facilitate the understanding and reconciliation of contrasting theoretical lenses (Kenter et al. 2019). Theorizing should be complemented by empirical evidence, practical concepts, and adaptable tools open to diverse perspectives, revisions, and constructive criticism (Schlüter et al. 2022). Collaboration with stakeholders and continual learning from practical experiences further enrich the application of theoretical frameworks in driving transformative action towards more sustainable and equitable futures.

Systems-oriented frameworks to address complex sustainability challenges Systems-oriented frameworks provide a structured and integrated approach to addressing complex sustainability challenges (Da Costa Junior et al. 2019; Laimon et al. 2022; Sriraman and Raghunathan 2023). The systemic basis of the nexus approach, for example, analyses the interdependencies between different systems, such as energy, water, and food, and how to account for these when developing strategies to achieve sustainable outcomes (Namany et al. 2019). Similarly, the systemic nature of the telecoupling approach highlights the interconnectedness of different systems across geographic locations (Kapsar et al. 2019; Zhang 2023; Liu 2023). Moreover, based on political economy ecological economics links environmental impacts, social outcomes, and financial stability to sustainably transform the economy by exploring degrowth scenarios (Demaria et al. 2013; Asara et al. 2015; Hardt and O'Neill 2017).

Traditional linear approaches to sustainability address single sustainable development challenges exclusively, neglecting the interconnectedness of social and environmental factors (Liu et al. 2015; Selin and Selin 2023). In contrast, systems-oriented frameworks recognize the complex feedback loops and relationships between these factors, emphasizing the need for integrated solutions that address the root causes of sustainability challenges (Ballew et al. 2019; Gómez et al. 2020; Voulvoulis et al. 2022; Selin and Selin 2023). While existing systems-oriented frameworks are valuable, there is a need to develop additional research tools and methods that are adaptable and inclusive for diverse sustainability challenges.

In addressing complex sustainability challenges, scholars can leverage its core action of knowledge production and co-production through diverse forms of research. Inclusive and participatory systems-oriented analytical approaches engage local communities and incorporate their perspectives into research endeavors (Little et al. 2019). By actively involving researchers and stakeholders from various sectors and integrating a wide range of knowledge sources, including Indigenous and local knowledge, sustainability science can ensure the relevance, inclusiveness, and effectiveness of its frameworks (Selin and Selin 2023).

Enhancing conceptual clarity in sustainability science for effective operationalization Enhancing conceptualization has the potential to improve the quality and impact of sustainability research (Usman Khizar et al. 2022). By achieving clarity in sustainability concepts, researchers can better communicate their findings, facilitate knowledge exchange, and enhance the applicability of their research outcomes. Well-defined concepts allow for consistent interpretation and measurement, enabling comparison and synthesis of research findings across studies and contexts. Clarity also fosters a shared understanding of concepts among researchers, policymakers, and stakeholders, promoting more effective communication and collaboration in addressing sustainability challenges. Operationalizing abstract concepts furthermore helps bridge the gap between theory and practice, enabling practical applications that inform decision-making and policy development for sustainability efforts (Nagatsu et al. 2020).

Enhancing conceptual clarity in sustainability science centers on the importance of clear and well-defined concepts in sustainability research (Nagatsu et al. 2020). Due to the multidisciplinary nature of sustainability studies, researchers often draw upon abstract concepts from diverse disciplines and apply them in various contexts (Brandt et al. 2013; Kiatkoski Kim et al. 2022). However, the lack of clear definitions and inconsistent use of concepts can lead to confusion and misinterpretation, ultimately resulting in ineffective research outcomes.

To address these issues, sustainability science researchers must strive to develop better and more precise definitions of key concepts to facilitate their operationalization in sustainability research (Black et al. 2023). For instance, sustainability can be defined in multiple ways depending on the researcher's perspective and the context of people-nature relations (Anderson et al. 2022a, b). Conceptual mapping, systematic reviews, and expert consultations are valuable tools for clarifying and defining abstract concepts based on empirical evidence, theoretical frameworks, and stakeholder engagement (Nagatsu et al. 2020). By engaging in a "conceptual refinement" process, researchers can arrive at more precise and consensus-based definitions, contributing to better operationalization and measurement of concepts in sustainability studies.

Sub-theme 2: transdisciplinary approaches

Co-production of knowledge and action for sustainability transformations Knowledge co-production, a collaborative approach between stakeholders and researchers, is essential in sustainability science and practice. It involves generating socially relevant and scientifically reliable knowledge about empirical phenomena (Kliskey et al. 2023). Co-creation of knowledge encompasses various approaches and terms, such as "transdisciplinary," "participatory research," "action research," "stakeholder engagement," "collaboration," "community-based research," "cooperative inquiry," "co-design," "inclusive research," and "citizen science," among others. These methodologies share the common principle of active and collaborative knowledge generation involving diverse stakeholders. The collective creation of knowledge within sustainability science underscores the significance of integrating a broad spectrum of knowledge and perspectives to tackle intricate sustainability challenges (Shrivastava et al. 2020). This cooperative process increases the practical relevance of scientific knowledge by considering its real-world applications (Durose et al. 2022). Engaging diverse societal actors in connecting research and practice is essential for propelling sustainability transformations based on rigorously researched holistic, inclusive solutions (Pereira et al. 2018; Chambers et al. 2022; Ordonez-Ponce 2023).

The connection between knowledge and society is intricately woven, underscoring how existing social frameworks influence the knowledge we seek and endorse while concurrently, specific societal constructs are moulded by prevailing scientific knowledge. Scholars are challenged to balance "methodological groundedness" and "epistemological agility" to navigate tensions that may arise in these collaborative processes (Haider et al. 2018), particularly concerning perceived limitations of various knowledge sources (Chambers et al. 2022).

To drive forward the development of co-production methodologies, sustainability science researchers recognize a pressing need for inclusive and participatory approaches that incorporate decolonizing strategies, public engagement, and indigenous perspectives (Schneider et al. 2021; Chambers et al. 2022; Gram-Hanssen et al. 2022; Solman et al. 2021; Zelenski et al. 2023; West et al. 2024a, b). Scholars have pioneered diverse strategies and toolkits to tackle the intricacies of co-producing knowledge. These include post-normal science, expanded peer review communities, and varied toolkits for addressing disciplinary epistemologies and knowledge co-production (Funtowicz and Ravetz 1994; Ainscough et al. 2018; Pohl and Wuelser 2019). These strategies aim to unveil the underlying presumptions of disciplinary or stakeholder viewpoints, thereby resolving misconceptions and tensions arising from implicit assumptions. However, further progress necessitates robust testing and validation protocols for contributions from diverse stakeholders (Pohl and Wuelser 2019). Gaining more profound insights into cultivating transformative co-production processes, especially in the Global South, remains vital (Pereira et al. 2020a, b). Furthermore, formalized knowledge systems, including universities and research institutions, need to embrace open, diverse, and equitable collaboration to transcend mere knowledge generation to co-crafting wisdom concerning thriving in a time when humans have had a substantial impact on our planet

(Fazey et al. 2020). Such transformation would involve explicitly acknowledging and creating positions for experts trained to facilitate equitable integration and co-production across the diverse "science-society" interfaces (Wiek 2007; Brundiers et al. 2013; Hoffmann et al. 2022).

Place-based transdisciplinary approaches for addressing local and regional challenges Transdisciplinary approaches are pivotal in guiding endeavours to reshape societal values towards more comprehensive principles that support sustainability and promote justice and equity. These approaches help ground such values into various institutions (Wiedmann et al. 2020; Kaul et al. 2022; Pascual et al. 2023). Place-based transdisciplinary approaches in sustainability science focus on context-sensitive research considering characteristics and dynamics of social-ecological interaction in distinct geographies and locations (Staples et al. 2021; Chen et al. 2022). This involves understanding local and regional challenges and human–environment interactions in the context of socio-economically central and peripheral countries (Carpenter et al. 2012; Balvanera et al. 2017a).

Place-based transdisciplinary approaches are essential for generating relevant knowledge and building trust among researchers, decision-makers, and local communities (Balvanera et al. 2017a; Ramos-Mejía et al. 2018; Raymond et al. 2022). By focusing on specific social-ecological contexts, these approaches can address challenges such as urban stream ecological management, rural residents' value shifts, vulnerability to climate and flood changes, and ecosystem values integration in forest management (Lebel et al. 2011; Kenter et al. 2011; Ramos-Mejía et al. 2018; Graziano et al. 2019; Andrade et al. 2023). However, the challenge lies in generalizing insights in connection to other contexts, as knowledge co-production is an open-ended process influenced by stakeholder selection and socio-economic context (Adler et al. 2018; Kenter et al. 2019; Eigi-Watkin and Koskinen 2023). Addressing this challenge can involve cross-site comparisons and horizontal portability to contextualize and generalize in place-based studies (Balvanera et al. 2017b).

In fortifying place-based transdisciplinary research, sustainability science scholars recognize the importance of conducting empirical assessments of research methods for nature-society studies (Balvanera et al. 2017b; De Vos et al. 2019; Carr Kelman et al. 2023). Continuous evaluation and enhancement of research methodologies and approaches are essential for addressing the intricate sustainability challenges confronting diverse communities and regions (Horlings et al. 2020). Exploring cross-site comparisons and adopting global-level approaches fosters knowledge development concerning social-environmental connections and inspires alternative pathways toward global sustainability (Balvanera et al. 2017a; Knapp et al. 2019; Martín-López et al. 2020). In navigating the tensions that may arise between locally focused, context-sensitive sustainability approaches and global-level strategies, adopting a "glocal" perspective becomes essential. This approach prioritizes adaptability, participatory decision-making, knowledge exchange, customized implementation, ongoing monitoring, and policy alignment to synchronize local priorities with global sustainability goals (Persson and Erlandsson 2014).

Learning from large systemic shocks Learning from large systemic shocks like pandemics is an essential component of transdisciplinary approaches because it involves the coordinated effort of experts from various fields to understand the complex, interconnected nature of these shocks and their impact on sustainability. Shocks like pandemics, economic crises, or extreme climate events have widespread social-environmental consequences (Lenzen et al. 2020) and, in some cases, are necessary for adapting to change (Erwin et al. 2021). The COVID-19 pandemic is a pertinent example of a large systemic shock that has reverberated globally, highlighting the urgency of addressing sustainability challenges and opportunities (Tonne 2021; EEA 2021; Pradhan et al. 2021). Analyzing the impacts and responses to such shocks provides valuable insights into vulnerabilities and weaknesses in existing systems (Folke et al. 2016; Haldon et al. 2020).

Analyzing large systemic shocks offer an opportunity to learn from experiences and better prepare for future challenges (Haldon et al. 2020; Rockström et al. 2023). These shocks can reveal gaps in governance structures, social inequalities, and environmental vulnerabilities, underscoring the need for transformative changes in policies and practices (Jones and Hameiri 2022). By studying the adaptive capacities of different communities and nations in the face of such shocks, researchers can identify best practices and strategies to build resilience and improve sustainability in the long run (Cumming and Peterson 2017; Leach et al. 2018; Brundiers 2018). Moreover, the lessons learned from these shocks can inform the development of more robust and inclusive policies that promote sustainable development issues during crises (Galaz et al. 2021; Tonne 2021; Mugabe et al. 2022).

Collaboration among sustainability science scholars from various disciplines helps to analyze the complexities of large systemic shocks and their cascading effects. Data-driven analyses and modeling techniques can help understand the interactions between different factors and predict potential future shocks, enabling proactive policy interventions. Engaging with local communities and stakeholders affected by these shocks is essential to ensure that research and responses are contextually appropriate and socially just. By promoting continuous learning and adaptation, the knowledge gained from large systemic shocks can drive a new approach to disaster preparedness and positive

transformations toward a more sustainable and resilient global society (Brundiers and Eakin 2018; Barouki et al. 2021; Kadykalo et al. 2022). This approach aligns with the principles of adaptive governance for social-ecological systems during periods of abrupt disruption, which emphasizes collaboration among various entities and envisions crises as opportunities for transformative change toward a more desirable state (Folke et al. 2005).

Sub-theme 3: inner transformations for sustainability

Inner transformation encompasses diverse dimensions of human existence and interactions, including consciousness, mindsets, values, worldviews, beliefs, emotions, spirituality, and the connection between humans and nature (Woiwode et al. 2021). Recognizing and addressing inner dimensions can help foster sustainable practices and achieve sustainable development. Inner transformation for sustainability highlights the importance of personal and shared values, emotions, and attitudes in promoting sustainable behavior and driving transformative change (Woiwode et al. 2021). It explores the role of an individual's inner world, including personal and community values, cultural heritage, beliefs, worldviews, and attitudes, in promoting sustainable behavior and driving collective and systems change (Woiwode et al. 2021). Research has shown that individuals who perform prosocial behavior and subscribe to environmental values are more likely to engage in sustainable practices (Thøgersen and Noblet 2012), especially when those values are considered across scales (van Riper et al. 2019). Inner dimensions and transformation play a vital role in fostering consciousness, relationships with others, the environment, and oneself (Woiwode et al. 2021; Cooper and Gibson 2022; Gomes Junior et al. 2023).

While sustainability transitions research has begun to acknowledge the importance of addressing inner elements, further investigation is required to comprehend the significance of emotions and moods in transformative change (Ryan 2016). Emotions significantly influence human behavior, and positive emotions like joy and awe are associated with sustainable behaviors (Zelenski and Desrochers 2021; Thiermann and Sheate 2021). Negative emotions such as guilt and worry that are associated with moral obligation can also energize behavior change (Shipley and van Riper 2022). However, consequences of the ecological crisis, such as 'ecological grief' when experienced in excess, can significantly de-motivate sustainability efforts as it can affect individuals' willingness and ability to engage in pro-environmental behaviors and support conservation and sustainability initiatives (Pihkala 2022). Furthermore, environmental value conflicts can generate neutral and negative emotions such as avoidance and anguish, but there remains a limited understanding of how these emotions influence resolving conflicts (Isacs et al. 2023). Examining human speciesism is another crucial area of research in sustainability science (Swartz and Mishler 2022). Human speciesism entails believing in human superiority over other species and hinders sustainable practices and ethical frameworks for sustainability (Hopster 2019). The IPBES values Assessment also calls for broader recognition of non-anthropocentric worldviews (Anderson et al. 2022a, b), including through its adoption of the Life Framework of Values, which emancipates holistic frames of human-nature relations (Kenter and O'Connor 2022; Willemen et al. 2023).

Sustainability science researchers can strive to account for inner transformation through a multifaceted research approach, encompassing transdisciplinary research, cultural awareness, and ethical considerations (Moore and Milkoreit 2020; Wamsler et al. 2021; Woiwode et al. 2021). Their collaborative efforts bridge the gap between research, policy, and practice, offering opportunities to introduce a concerto of inner transformations for sustainability (Cooper and Gibson 2022; Gomes Junior et al. 2023). By delving deeper into the role of personal values and human-nature relationships in sustainability, researchers can develop effective strategies for transformative change toward a sustainable future.

Theme 3: tools to propel the research forward

The third theme summarizes the research priorities related to specific tools to propel research forward, which include data-intensive approaches and harnessing emerging technologies to contribute to a sustainable future (Fig. 2).

Data-intensive methods for sustainability research and decision-making

The proliferation of data availability has catalyzed the adoption of data-intensive methods in sustainability, garnering support from diverse stakeholders (Asokan et al. 2020). These approaches, encompassing big data and citizen science data, hold immense promise in propelling sustainability initiatives forward by furnishing invaluable information and insights (Sauermann et al. 2020; Sakti and Takeuchi 2020).

Nevertheless, realizing the full potential of data-intensive approaches entails addressing several challenges (Asokan et al. 2020; Sauermann et al. 2020; Garrigós-Simón et al. 2021). A pivotal challenge is ensuring the compatibility of diverse data sets collected through distinct methodologies to facilitate integration and processing (Asokan et al. 2020). Additionally, the heterogeneous nature of sustainability definitions and values poses a significant obstacle across disciplines, stakeholders, cultures, and contexts (Kenter et al. 2019). Recognizing this, the IPBES Values Assessment offers an inclusive typology of values, which holds promise in bridging disparate knowledge traditions, including

Table 1 Brief notes on emerging frontiers in sustainability science

Research topics	Brief notes
Exploring intersectionality for a sustainable future	Intersectionality is a framework for understanding how different social identities—such as race, gender, class, ethnicity, and other factors—intersect to create unique experiences of oppression, privilege, and discrimination (Crenshaw 1989; Davis 2008; Kaijser and Kronsell 2014). Intersectionality involves analyzing how different social identities intersect in relation to sustainability challenges. Considering these intersections is vital for effective policy and program design (Nash 2008; Ryder and Boone 2019; Amorim-Maia et al. 2022; Bryan et al. 2023). Accounting for intersectionality in the research design aligns with the goals of sustainability science to investigate approaches that can foster equity and justice and thus inform the policy and program designs mentioned above
Social tipping points in the pursuit of sustainability	Social tipping points are moments in social-ecological systems where a small change triggers a rapid, non-linear shift in the social system, driven by self-reinforcing feedback loops, often leading to a new, irreversible state (Milkoreit et al. 2018; Otto et al. 2020a, b). These tipping points are key to understanding how minor changes can rapidly and dramatically alter social structures, behaviours, and outcomes, particularly in the context of sustainability and environmental challenges. Identifying and analyzing these tipping points is essential for driving transformative change (Otto et al. 2020a, b; Stadelmann-Steffen et al. 2021; Lenton et al. 2022; Chapman et al. 2022; Gupta et al. 2023; Rockström et al. 2023; Rammelt et al. 2023). Incorporating social tipping points into research endeavors would align with research priorities, particularly when integrated into the further development of system-based frameworks designed to tackle intricate sustainability challenges
Transformative action for sustainability	Transformative action for sustainability refers to profound system-wide reorganization across technological, economic, and social factors, including paradigms, goals, and values towards sustainable and equitable futures (IPBES 2019; Salomaa and Juhola 2020; Fougères et al. 2022). It entails restructuring social-environmental systems to address the root causes of unsustainability. To foster transformative action, policymakers and stakeholders need to adopt evidence-based decision-making and integrate scientific knowledge with practical implementation. Researchers, policymakers, and stakeholders need to collaborate closely, ensuring that scientific findings and recommendations are effectively translated into practical actions and policies (Wiek et al. 2012; Sarewitz et al. 2012; Nevens et al. 2013; Fedele et al. 2019; Bush and Doyon 2021; Zeigermann 2021; Tengö and Andersson 2022; Sandberg and Tienari 2022; Du et al. 2023). The goal of co-creating transformative action for sustainability would be shaped by insights derived from internal changes and would guide approaches for attaining sustainability goals, particularly in advancing methodologies centered on solutions-oriented research (Lang and Wiek 2022)
Cross-cutting issues in sustainability science	Cross-cutting issues to develop sustainable solutions involves researching sustainable finance instruments, ethics, gender equity, and acknowledging researcher values (Ziolo et al. 2019; Joaquin and Biana 2020; Leal Filho et al. 2022; Kenter et al. 2016), aligning with the research priority of promoting equity and justice
Innovations in sustainability education	Promoting innovations in sustainability education is essential for enhancing a sustainable future. This involves embedding global sustainability principles, transformative learning, valuing and caring for local contexts, and inventive pedagogical methods in sustainability education (Evans 2015; Brundiers and Wiek 2017; Horbacauskiene 2019; Kioupi and Voulvoulis 2019; Redman and Wiek 2021; Brundiers et al. 2021; Liu et al. 2022; Hurlimann et al. 2023). Aligning educational efforts with practical sustainability goals drives meaningful change and equips individuals with essential research skills. The synergy between education and research is crucial for progress in sustainability science, linking education, research, and practical action

scientific, indigenous, and local knowledge (Pascual et al. 2023; Raymond et al. 2023). On the other hand, unequal global representation of data and knowledge further exacerbates disparities, favoring more high-income countries (Herrera et al. 2023). This imbalance perpetuates unequal power dynamics and impedes meaningful stakeholder participation. Moreover, incomplete data, particularly regarding social and economic aspects, hampers a comprehensive understanding of sustainability issues (Blazquez and Domenech 2018).

To address data-intensive challenges in sustainability, researchers in the field can lead by fostering transdisciplinary collaboration, developing frameworks for data compatibility, and promoting inclusivity and equitable representation among diverse stakeholders (Tengö et al. 2021; Muller

et al. 2022; Pascual et al. 2023; Raymond et al. 2023). By recognizing and respecting different value lenses and integrating various knowledge traditions, researchers can enhance the validity of research outcomes and drive progress in sustainability research and decision-making.

Harnessing emerging technologies for a sustainable future

Harnessing emerging technologies in sustainability focuses on evaluating the potential benefits and drawbacks of new and emerging technologies for sustainability (Gulsrud et al. 2018). Integrating digital technologies with sustainable development and governance can enhance social welfare, measure the impacts of SDGs, and increase the sustainability and resilience of business supply chains (ElMassah and Mohieldin 2020; Browning et al. 2020; Bai et al. 2020; Galaz et al. 2021; Chauhan et al. 2022a; Samuel et al. 2022; Kazancoglu et al. 2023).

As technology continues to transform our world, conducting ongoing research and development is crucial to establishing policies that promote sustainability and guidelines for their use (Vinuesa et al. 2020). Understanding the trade-offs between the benefits and risks of emerging technologies is important for developing policies that promote sustainability (Chauhan et al. 2022b). This requires researchers to be aware of the social and ethical consequences of technological progress and consider how it affects social-environmental contexts and interactions (Kendal 2022). To assess these implications, a broader framework, such as the social-environmental-technological perspective, may be needed to encompass the multifaceted interactions between society, nature, and technology (McPhearson et al. 2022).

Sustainability science researchers can focus on exploring the potential of retroinnovation and emerging technologies, such as digital technologies, artificial intelligence (AI), and virtual reality, to support research on sustainability and human well-being (Switalski et al. 2021; Dwivedi et al. 2022; Piscicelli 2023). For example, virtual reality as a tool to simulate the multiple benefits that people can derive from nature, including emotional well-being, stress reduction, and environmental stewardship, is an area for further investigation (Browning et al. 2020; Dwivedi et al. 2022). This exploration should include a thorough understanding of potential drawbacks and unintended consequences to develop strategies for responsible and sustainable use of these tools as data collection and analysis instruments and in real-world practice applications.

Emerging frontiers and the way forward

In addition to the abovementioned ranked topics, SustSci EBM proposed five additional areas for future research in sustainability science. These include (a) exploring intersectionality for a sustainable future, (b) social tipping points, (c) transformative action, (d) cross-cutting issues, and (e) innovations in sustainability education. Table 1 highlights each topic, and the explanatory details are presented in supplementary material 3. Exploring these areas in conjunction with the research topics above will add further theoretical and methodical rigor to sustainability science.

Given the transdisciplinary nature of sustainability science, the boundaries of the discipline are malleable and emergent. Due to the ever-changing nature of sustainability, establishing a fixed theoretical framework or tradition remains a work in progress. Therefore, journals such as Sustainability Science must continue recognizing and incorporating emerging topics.

By outlining the prioritized research topics, this editorial stimulate future discussion in sustainability science, serving as a roadmap for subsequent studies striving to create a more sustainable future. Continuous efforts to update and revisit research agendas for sustainability science are essential to meet persistent and new challenges rooted in dynamic interactions between humans and nature. We hope this editorial will stimulate ongoing and future research activities in sustainability science, which, in turn, will necessitate future prioritization efforts, ultimately contributing to the advancement of sustainability science.

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Declarations

Conflict of interest The authors declare no conflicts of interest or competing interests.

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