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The connection between Sustainable Development Goals (SDGs) and forest operations research

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ABSTRACT

In this study, a worldwide bibliometric analysis was used to examine the status and development trends of research related to the United Nation's Sustainable Development Goals (SDGs) in the field of sustainable forest operations (SFO). The aim was to quantify the extent to which SDG targets are considered, directly or indirectly, in the assessment of SFO in the literature from the period 2017–2022. Nine of 17 SDGs and 17 of 169 SDG targets were found to be highly relevant for quantifying SFO. Cluster analysis revealed interconnections among SDGs and SDG targets, resulting in three SDG clusters and four SDG target clusters based on environmental, social and economic criteria, or a combination thereof. The investigation of key parameters in the analyzed studies demonstrated trends in SDG targets per year, region and machine category. Additionally, the relevance of SDG targets for forest operations was assessed, SDG targets were classified based on their impacts, and future trends were estimated. Despite the negative impact of forest operations on several SDGs, a positive trend toward more sustainable forest management was observed across all SDGs. This study offers insights into key aspects that warrant attention in future endeavors to enhance the sustainability of forest operations in Europe.

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Criteria & indicators; SDG; sustainability; timber logging; wood supply chain

Introduction

The forest sector has been at the forefront of sustainable development efforts for many years (von Carlowitz 2012), and it continues to play an important role in the transition to a sustainable society (Baumgartner 2019). Specifically, forests contribute substantially to global terrestrial biodiversity, serve as essential carbon sinks, and provide important contributions to climatic and hydrological regulation (Carr et al. 2021; Da Aguayo Lopes Silva et al. 2023). They offer a wide range of ecosystem services, such as energy and timber production, pollination support, and cultural enrichment through recreational activities (Alcamo et al. 2005; Brockerhoff et al. 2017; Da Aguayo Lopes Silva et al. 2023).

To support the aims of sustainable development, strategies for sustainable forest management (SFM) have been developed and applied (Schweier, Magagnotti et al. 2019). SFM is a well-established concept that has been intensively examined in the scientific literature over the last centuries (Ducey and Larson 1999; Wilkie et al. 2003; Hahn and Knoke 2010), with a strong increase in interest in the topic, in the past few decades (Marchi et al. 2018; Schweier, Magagnotti et al. 2019). However, society is placing new and complex demands on forests that are not necessarily compatible with each other, for example regarding mitigation of the effects of climate change, renewable energies, and biodiversity conservation (United Nations 2023a; Sotirov et al. 2024). Policy instruments addressing these societal demands and challenges lead to consequences for forest management. In view of these changes, the concept of SFM requires a thorough review (Prins et al. 2023), and its effective implementation depends on forest operations sustainability. According to Marchi et al. (2018), the five key performance areas required to ensure the sustainability of forest operations are environment, ergonomics, economics, quality optimization of products and production, and people and society. One of the challenges of forest operations is to consider the impacts of different management strategies and to assess the performance of different processes, products and services (Schweier, Magagnotti et al. 2019).

In September 2015, the United Nations adopted the 2030 Agenda for Sustainable Development and introduced the Sustainable Development Goals (SDGs) in response to environmental challenges and the need for inclusive growth. The SDGs consist of 17 globally recognized objectives, encompassing 169 targets and 232 indicators, to be achieved by 2030 (United Nations 2015). Primarily, the SDGs aim to address the basic needs of developing countries, including reducing hunger and providing access to education, water and sanitation services. By attempting to cover all that is good and desirable in society, the SDGs have been criticized as being vague, weak or meaningless (Holden et al. 2017). Prioritizing the SDGs could help mitigate these drawbacks and avoid the risk of meeting the secondary goals while failing to achieve the primary ones

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(Holden et al. 2017). The forest sector holds promise for advancing the SDGs, particularly in terms of sustainable land use and climate action. SFM is explicitly recognized in SDG15 (Le Blanc 2015; Gratzer and Keeton 2017), which aims to protect, restore and promote the sustainable use of terrestrial ecosystems, including forests. It also addresses issues such as desertification, land degradation, and biodiversity loss (United Nations 2023a).

Over the five years leading up to 2024, several studies have been conducted to analyze the connection between the forest sector and the SDGs. Three studies have identified a complex relationship between the forest sector and the SDGs in Austria (Baumgartner 2019; Hazarika and Jandl 2019; Ma et al. 2022). On a global level, Carr et al. (2021) identified 63 SDG targets associated with potentially beneficial, damaging or mixed impacts on forests. Da Aguayo Lopes Silva et al. (2023) and Katila et al. (2020) conducted a systematic review, also on a global level, to understand the methods used to assess the contribution of the forest sector to the SDGs. Ma et al. (2023) developed an assessment approach that integrates the contribution of different ecosystem services to the SDGs, and they evaluated the temporal and spatial dynamics of these services in China from 2000 to 2020. These studies provide strong evidence that there is a need for an in-depth review of the concept of SFM, probably because of radical changes in our society, e.g. in the fields of climate change, renewable energy and biodiversity conservation (Prins et al. 2023).

To truly embody sustainability, both forest management and forest operations are required to implement management strategies to address all three pillars of sustainability. In addition, there is a strong need to analyze forest operations from the SDG perspective. A framework to assess various levels of sustainability in forest operations is outlined in Grünberg et al. (2023). These authors analyzed 423 studies conducted between 2017 and 2022 to identify criteria for assessing the sustainability of timber harvesting operations. These criteria were required to address at least one pillar of sustainability in order to quantify the impact of sustainable forest operations (SFO). However, only 4 of these studies (Kühmaier et al. 2019; Schweier et al. 2018; Schweier, Blagojević et al. 2019; Tuomasjukka et al. 2018) covered all three pillars of sustainability. Grünberg et al. (2023) identified 33 criteria and 46 indicators as suitable for assessing SFO. The use of criteria & indicators (C&I) in forestry originates from the necessity to evaluate the benefits and sustainability of forest management systems (Prabhu et al. 1996; van Lammerts Bueren and Blom 1997). According to Prabhu et al. (1999), criteria are principles or standards by which issues are judged, while indicators are variables or components of the forest ecosystem used to assess specific criteria. The C&I approach is effective in measuring aspects of SFO at various levels, i.e. national, regional, local and forest management unit (Wolfslehner et al. 2005). To date, no study has been carried out to analyze the interaction between SFO and the SDGs, to specifically address how forest operations are linked to the SDGs and their targets and how they influence best management practices in wood supply chains.

In the present study, we help address this research gap by reviewing the interaction between the goals of SFO and the SDGs. The first objective of our study is to identify the SDGs and SDG targets that are suitable for describing the sustainability of forest operations. For this purpose, we compare the SDGs of the United Nations (2023b) and the C&I of SFO defined by Grünberg et al. (2023). The second objective is to review the literature from the period 2017–2022 that deals with the assessment of SFO and to analyze how often the SDGs or SDG targets identified in the first step are mentioned directly or indirectly in these articles. Additionally, we compare the extent to which the C&I defined by Grünberg et al. (2023) are reflected in the SDGs and SDG targets. The third objective is to analyze expert opinions on the relevance of the SDGs for SFO, describe their impacts, and forecast the future development of forest operations with respect to the SDG targets. The goal of our study is to raise awareness of the connection between SDGs and SFO and to identify starting points for integrating SDGs into forest operations.

Materials and methods

This study consists of four parts. First, the methodology used to select the studies related to SFO is outlined. Second, SDGs and targets are identified that, like the previously defined C&I, serve as assessment metrics for SFO. These selected SDGs and targets are then analyzed further. Third, cluster analysis (Hazarika and Jandl 2019; Carr et al. 2021) is employed to examine the interrelationships among the SDGs and targets, as well as the connections between the SDGs and the C&I identified by Grünberg et al. (2023). Further, a bibliometric analysis (Da Aguayo Lopes Silva et al. 2023; Ma et al. 2022) is conducted and descriptive statistics are calculated to evaluate these SDGs and targets based on predefined parameters. Finally, the relevance of SDG targets to forest operations is evaluated by categorizing the impact of forest operations on SDGs as positive or negative. An expert assessment is used to estimate future trends of these impacts.

Study selection

To provide an overview of C&I for SFO, Grünberg et al. (2023) conducted a systematic literature review to identify relevant studies from 2017 to 2022. Three search queries were performed in Scopus: (a) “Timber harvesting” OR “timber harvest” OR “wood harvesting” OR “wood harvest” OR “forest harvesting” OR “forest harvest” OR “residual stand” OR “timber logging” OR “short rotation forestry” OR “tree harvesting”, (b) Forest AND (harvester OR forwarder OR cable OR bulldozer OR tractor OR trailer OR skidder OR excavator OR chainsaw OR “chain-saw” OR “motor manual” OR helicopter OR “feller buncher”), (c) Wood AND (harvester OR forwarder OR cable OR bulldozer OR tractor OR trailer OR skidder OR excavator OR chainsaw OR “chain-saw” OR “motor manual” OR helicopter OR “feller buncher”). More than 3,900 studies were returned by the Scopus literature database for this period. Grünberg et al. (2023) found 423 studies to be relevant for the evaluation of SFO. The 423 studies were classified according to numerous parameters and were stored in an Excel spreadsheet, which forms the literature database used in the present study.

Table 1. Selected Sustainable Development Goal (SDG) targets and indicators, as described by the United Nations (2023b), and the explanations for their selection as relevant to this study. In the first column, the number before the dot identifies the SDG and the number after the dot refers to the target.

SDG target	SDG indicator	Explanation of relevance
3.4	Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease	Effects on human health of machine operating (vibration, noise) or wood processing (dust), human–machine interactions, mental workload, and emissions from combustion processes affecting forest workers` health
3.9	Mortality rate attributed to unintentional poisoning	Release of substances (e.g. oil spillage, chemical management) and emissions from combustion affecting forest workers` health
4.2	Participation rate of youth and adults in formal and informal education and training in the previous 12 months	Training activities or work experience (seniority) influencing the work performance of forest operations
6.6	Change in the extent of water-related ecosystems over time	Investigating the effects of harvesting operations on the water regime (e.g. hydraulic soil conductivity or water erosion) or case studies in water catchment areas
7.3	Energy intensity measured in terms of primary energy and gross domestic product (GDP)	Energy consumption (J, Wh), direct or indirect (fuel) contributing to the energy intensity of a production process
8.2	Annual growth rate of real GDP per employed person	Economic valuation of harvesting activities in monetary units based on the use of methods that influence employability (e.g. fully mechanized vs. motor-manual operations)
8.4	Material footprint	Consumption of non-renewable resources in the form of e.g. machine usage (h), utilization rate (utilization), and fuel and oil consumption, demonstrating resource efficiency and promoting sustainable growth
8.5	Unemployment rate	Workload and labor demand by sex and age indicating the economic growth
8.8	Fatal and non-fatal occupational injuries per 100,000 workers	Work accidents, physical workload, musculoskeletal disorders, and hazards during forest operations, demonstrating the risk of having a fatal or a non-an occupational injury
9.4	CO_2 emissions per unit of value added	CO_2 emissions (in particular from combustion processes and harvest waste management) contributing to climate change
12.2	Material footprint	Use of natural resources (mostly wood) described on a quantitative scale (e.g. efficiency, productivity) to ensure sustainable consumption
12.4	(a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment	Quantification of negative emissions from combustion, residues and other waste, and pollutants over a longer period (life cycle approach), supporting waste reduction
13.2	Total greenhouse gas emissions	Greenhouse gas emissions derived from fuel combustion or soil disturbance (soil gases) contributing to climate change
15.1	Forest area as a proportion of total land area	Sustainable use of ecosystems (direct effects on the ecosystem, i.e. ecological criteria), treatment of a real case study, with no theoretical concepts or simulations, thereby contribution to reduction of land use
15.2	Progress toward sustainable forest management	Application of sustainable forest harvesting methods, supporting reforestation and restoration
15.4	Coverage by protected areas of important sites for mountain biodiversity	Sustainable use of mountain forests (slope ≥ 30% or altitude > 1000 m) and timber extraction with appropriate methods such as cable yarders in flat terrain moors to foster protection forests
15.5	Red List Index	Estimation of the impacts of forest operations on animal or plant species (or parts thereof, e.g. roots) or on special habitats, contributing to biodiversity conservation

Identification of relevant SDGs, SDG targets and indicators

A description of the SDG targets and indicators was published in the Tier Classification of SDG Indicators on 31 March 2023 (United Nations 2023b). A critical appraisal scoring system, explained in the following paragraphs, was developed by the authors of this study and was used to determine relevant SDG targets for SFO (Table 1). In this context, "relevant" indicates that the SFO mentioned in the paper under study has a positive or negative impact on the SDG targets.

In our study, forest operations refer to the partial wood supply chain from the forest stand to the landing at the roadside (Schweier, Magagnotti et al. 2019). All processes were considered, i.e. felling, delimbing, bucking, extracting and storing trees as assortments at the landing in preparation for transport to the mill (Figure 1). The system boundary was therefore considered wood supply processes at the forest site.

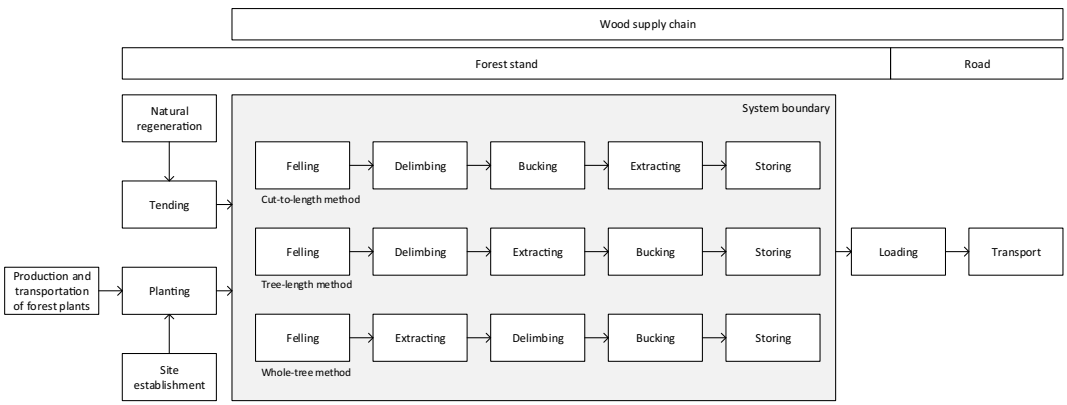

Figure 1. System boundary of wood supply processes considered.

For example, it was evaluated whether the emissions from forest operations have an impact on climate change, whereas the extent to which the products made from the harvested timber have an impact on climate change was not assessed.

The focus was on direct and indirect effects of forest operations (McEachran et al. 2021) within the system boundaries. A direct impact is defined as one having quantifiable variables available to determine its effects. One example is measured vibration values for a chainsaw. Indirect effects have no measured values, but the actions presented in the corresponding paper indicate that they affect the performance of the indicator values. An example of this is the implementation of technical measures to improve the vibrations of a chainsaw without having measured them.

The methodology was designed to identify, quantify and assess relevant SDGs and SDG targets in the area of SFM. To achieve this, a combination of expert assessment and comparison with existing literature was deemed the most appropriate. The experts identified included the lead authors of the baseline study (Grünberg et al. 2023), individuals who have published several times on SFO, and the moderators of the panel discussion "Sustainable Forest Operations (SFO): Challenges and Opportunities Towards a Resilient Wood Supply Chain" at the IUFRO World Congress 2024 in Stockholm. These experts were also invited to contribute to this publication as coauthors. While assessing the relevance of SDGs and SDG targets and assigning C&I is inherently subjective, standardization was achieved by establishing rules and defining system boundaries, as agreed by the experts.

Interaction of SDGs and SDG targets and C&I for assessing SFO

In addition to the literature database and the identification of relevant goals, targets and indicators of sustainable development, a comparison was made to show how often the C&I defined by Grünberg et al. (2023) are reflected in the SDGs and SDG targets. Additionally, a cluster analysis was performed to illustrate the frequency of use and interrelationships among the SDGs and their targets in scientific studies. This analysis was carried out using VOSviewer (version 1.6.19), a freely available software, originally developed for analyzing scientific publications (van Eck and Waltman 2010). It has a user-friendly interface that makes it accessible to researchers with varying levels of programming or statistical expertise. Cluster analysis results are easy to interpret, facilitating the identification of patterns or relationships within the data. It is important to note that the interpretation of clusters may be somewhat subjective and dependent on the researcher's judgment. In addition, while the export options were somewhat limited, they adequately met our needs (van Eck and Waltman 2014).

As outlined in the "study selection" section, key parameters were established by Grünberg et al. (2023) to categorize the selected studies based on comparable attributes. For each parameter, available correlations with the SDGs were analyzed. For the "harvesting machines" parameter, the relevance of the SDGs that had been analyzed in at least 30 scientific publications concerning SFO in the past 6 years was evaluated. The assessment was conducted separately for each machine category.

Quantification of impacts of forest operations on SDGs and prediction of future trends

A general measure of relevance was determined by dividing the number of SDG targets relevant to SFO by the total number of available targets within each SDG according to the United Nations (2023b). It was further assessed whether forest operations have a positive, neutral or negative impact on the achievement of the SDGs, and an explanation for their valuation was generated. Subjective expert assessments of the impacts of timber harvesting and its future implications were conducted. These assessments were discussed among the coauthors and synthesized to arrive at a collective result. Additionally, future trends regarding the contribution of forest operations to the SDGs were predicted by the authors, supported by references from the literature.

Results

SDGs and SDG targets

In total, 9 of 17 SDGs and 17 of 169 SDG targets (United Nations 2023b) were identified as relevant to the assessment of SFO. Table 1 shows the SDG targets, the associated indicators, and the explanations for why these targets were selected.

We checked whether the forest operations referred to in the 423 studies (Grünberg et al. 2023) affect the SDGs or SDG targets mentioned in Table 1. A study could be assigned to several SDGs or SDG targets. The most pertinent SDGs were those that aim to protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, halt and reverse land degradation, and halt biodiversity loss (SDG15). The outcome that all of the 423 considered studies have a link to SDG15 (100% of the analyzed studies) can be explained by the fact that Grünberg et al. (2023) only concentrated on the topic of SFM. There was also a strong focus on: promoting long-term, inclusive and sustainable economic growth and achieving full and productive employment and decent work for all (SDG8, 55%); ensuring sustainable consumption and production patterns (SDG12, 43%); ensuring access to affordable, reliable, sustainable and modern energy for all (SDG7, 21%); and ensuring healthy lives and promoting well-being for all at all ages (SDG3, 19%). All studies focused on promoting the implementation of SFM practices, including measures to halt deforestation, restore degraded forests, and increase afforestation and reforestation efforts globally (SDG target [T] 15.2, 100% of all studies analysed). Other key SDG targets that were addressed included achieving sustainable management and efficient use of natural resources (T12.2, 41%) and ensuring the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, particularly forests, wetlands, mountains and drylands, in alignment with international agreements (T15.1, 41%). Additionally, studies also prioritized urgent and substantial action to reduce the degradation of natural habitats, halt biodiversity loss, and protect threatened species from

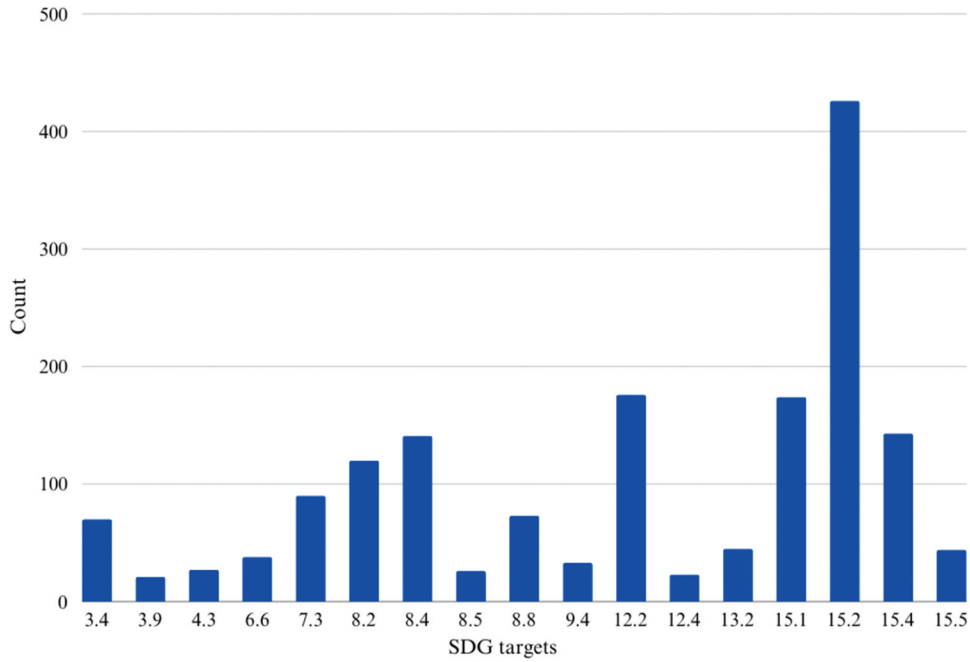

Figure 2. Relevance of Sustainable Development Goal (SDG) targets for sustainable forest operations: number of studies linked to each SDG target considered, out of the 423 studies in total.

extinction (T15.4, 34%) and to improve global resource efficiency in consumption and production (T8.4; 33%) (Figure 2).

Interlinkages of SDGs, SDG targets and C&I for assessing sustainable forest operations

Of the 33 possible C&I defined by Grünberg et al. (2023), productivity, costs, energy consumption, emissions and soil nutrients were analyzed in numerous studies addressing various SDGs (Figure 3). Productivity serves as a crucial metric for assessing system efficiency and is therefore often used as an input parameter, together with other criteria. One question could be, for example, whether the damage to the remaining stand will increase with higher productivity. Social C&I, representing SDG3 (which aims to ensure healthy lives and promote well-being) and SDG4 (which focuses on training and lifelong learning opportunities), primarily deal with measures to minimize human exposure and physical workloads and to improve working conditions through training activities. Ecological criteria, especially soil moisture content, water erosion, and hydraulic conductivity, serve as indicators of SDG6's objective to protect and restore water-related ecosystems. Similarly, energy efficiency (SDG7), economic productivity (SDG8), productive and safe employment, and resource efficiency (SDG12) have commonalities with the C&I of productivity, costs, energy consumption, and emissions found in SDG9, which focuses on increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes. Additionally, SDG13, targeting actions against climate change, is well represented by the C&I quantifying emissions and energy consumption. SDG15, pertaining to the protection, restoration and sustainable use of terrestrial ecosystems, particularly forests, is related to several important C&I, including productivity, costs and machine – soil interactions.

Strong connections were observed between SDGs 7, 8 and 12, as energy consumption, economic valuation, and material footprint (both nonrenewable and renewable resources) were often examined within the same studies (Figure 4). Another notable cluster was observed between SDGs 3, 4 and 8, indicating joint investigations of human health impacts, occupational accidents and hazards, and the impact of training and work experience. Further, water-related aspects (SDG6) were consistently addressed separately, with weaker connections to other SDGs.

As illustrated in Figure 5, C&I can contribute to the achievement of various SDG targets. For instance, reducing premature mortality from non-communicable diseases and promoting mental health and well-being (T3.4), as well as promoting safe and secure working environments (T8.8), can be facilitated by incorporating and enhancing social C&I in SFO practices. Additionally, reducing deaths and illnesses from hazardous chemical exposure and from air, water and soil pollution and contamination (T3.9), as well as achieving environmentally sound management of chemicals and all wastes throughout their life cycle (T12.4), can be promoted through strategies such as reducing fuel consumption, minimizing lubricant loss, and mitigating emissions from combustion processes. Improving the efficiency of economic C&I can contribute to higher levels of economic productivity (T8.2) and to increased resource efficiency in production (T8.4). Further, ensuring full and productive employment and promoting decent work (T8.5) can be achieved by introducing more efficient

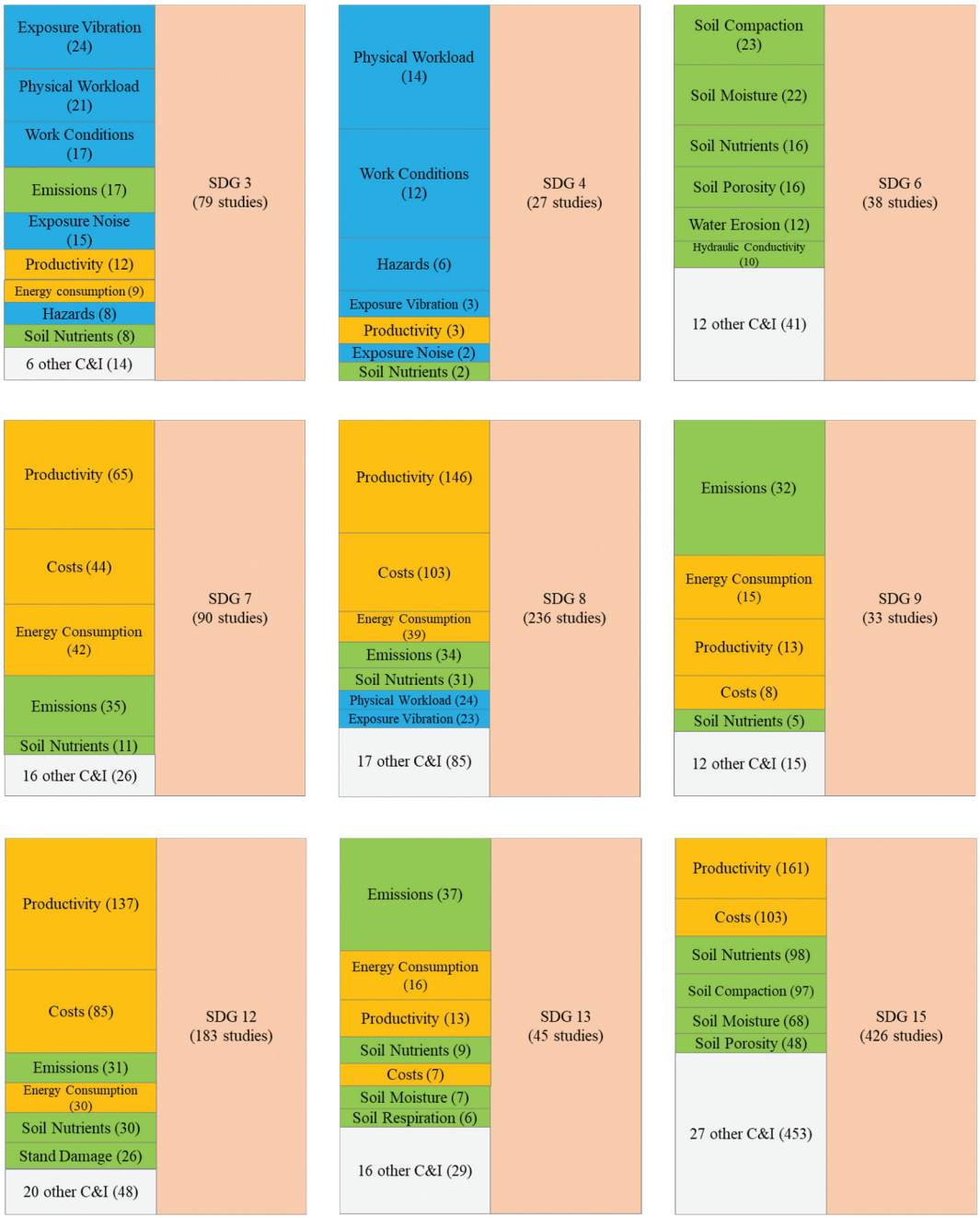

Figure 3. Interlinkages between criteria & indicators (C&I) for sustainable forest operations and Sustainable Development Goals (SDGs). The size of a rectangle corresponds to the frequency of occurrence. The colors represent economic (orange), ecological (green) and social (blue) C&I. C&I with a share of < 5% are aggregated under "other C&I" (gray). The total number of criteria in the left column can be higher than the number of studies in the right column, because there are studies where several criteria were examined together.

harvesting systems and enhancements in working conditions, safety and workload management. SFM and efficient use of natural resources, including wood products (T12.2), can be evaluated using productivity metrics. In terms of the conservation, restoration and sustainable use of forests, it is relevant to consider ecological and soil physical C&I, especially indicators related to machine – soil interactions and stand damage. SFM (T15.2), including management of mountain ecosystems (T15.4), encompasses nearly all C&I identified by Grünberg et al. (2023), with a focus on economic factors and machine – soil interactions. To address the reduction of habitat degradation, biodiversity loss, and the protection of threatened species, it is beneficial to focus on C&I representing biodiversity and soil indicators. C&I related to targets 4.3, 6.6, 7.3, 9.4 and 13.2 were not included in Figure 5, as they have a distribution similar to that of SDGs 4, 6, 7, 9 and 13, as shown in Figure 3.

Target 15.2 emerged as the most frequently occurring SDG target in the documents, with strong linkages to all other targets (Figure 6). This cohesion within SDG15 arises from its collective focus on the protection, restoration and

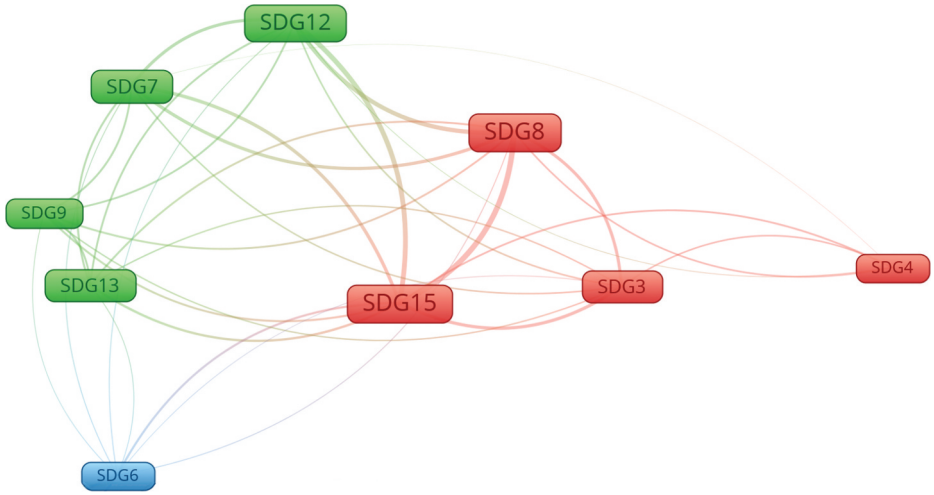

Figure 4. Sustainable Development Goal (SDG) co-occurrence network, where the size of each SDG (node) represents the frequency of occurrence in the analyzed documents, while different colors indicate distinct clusters.

Figure 5. Interlinkages between criteria & indicators (C&I) for sustainable forest operations and Sustainable Development Goal (SDG) targets. The size of a rectangle corresponds to the frequency of occurrence. The colors represent economic (orange), ecological (green) and social (blue) C&I. C&I with a share of < 5% are aggregated under "other C&I" (gray).

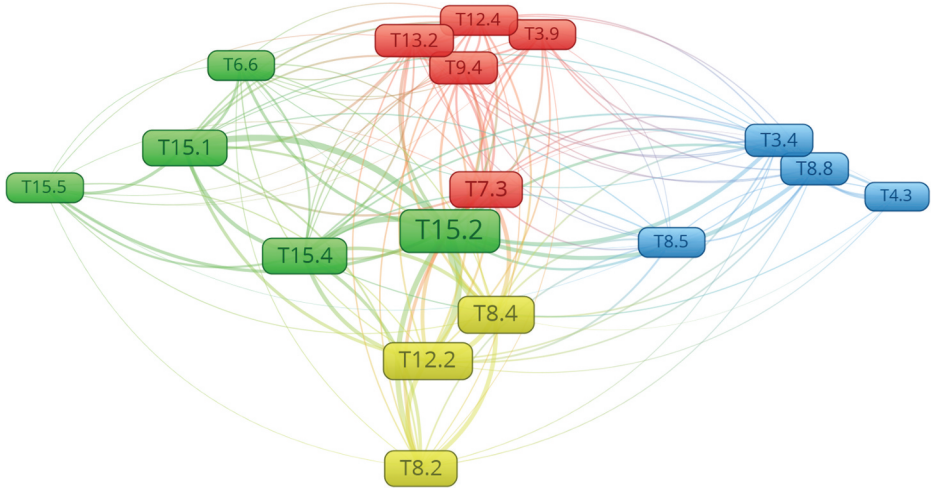

Figure 6. Co-occurrence network of Sustainable Development Goal (SDG) targets. Node size indicates the frequency of occurrence in the analyzed documents and different colors signify distinct clusters.

Table 2. Relative number of investigated Sustainable Development Goal (SDG) targets per year. The numbers refer to the proportion of studies per SDG target out of the total number of studies within one year, expressed as a percentage. Numbers in bold indicate SDG targets that were strongly represented in the years 2017–2019, while numbers in parentheses indicate those for the years 2020–2022.

	SDG target																
Year	3.4	3.9	4.3	6.6	7.3	8.2	8.4	8.5	8.8	9.4	12.2	12.4	13.2	15.1	15.2	15.4	15.5
2017	8	**12**	2	**16**	16	31	41	**12**	8	12	29	**10**	14	57	100	**53**	18
2018	13	**6**	4	**13**	19	42	33	**12**	16	9	45	**7**	10	57	100	**34**	9
2019	13	2	5	**11**	21	23	25	2	13	5	39	4	14	55	100	**52**	14
2020	(20)	3	3	8	16	25	36	5	(18)	5	45	3	5	29	100	22	4
2021	(19)	3	(7)	5	(27)	29	33	5	(21)	7	41	5	11	33	100	32	10
2022	(20)	6	(14)	5	(25)	22	31	2	(23)	9	43	5	11	30	100	24	11

sustainable use of terrestrial ecosystems. Additionally, the examination of water-related ecosystems in T6.6 establishes further connections to terrestrial ecosystems. Economic productivity (T8.2) and resource efficiency (T8.4) are closely connected to the sustainable management and efficient use of natural resources (T12.2), which reflects the productivity of the harvesting system. Another interconnected cluster encompasses targets related to hazardous chemicals and air, water and soil pollution and contamination (T3.9), energy efficiency (especially in terms of fuel consumption, T7.3), increased resource-use efficiency (T9.4), environmentally sound management of chemicals and all wastes throughout their life cycle (T12.4), and climate change aspects (specifically CO_2 emissions, T13.2). Finally, a social cluster encompasses mental health and well-being (T3.4), education (4.3), employment (T8.5) and the provision of a safe and secure working environment (T8.8).

Parameter analysis

Although a six-year period may seem relatively short for a trend analysis, it was evident that the number of studies examining T3.9, 6.6, 8.5, 12.4 and 15.4 has decreased over the years. Conversely, there has been a greater emphasis on T3.4, 4.3, 7.3 and 8.8 (Table 2).

When scientific studies across different regions are compared, research in East and Southeast Asia has predominantly focused on education (T4.3), energy efficiency (T7.3), economic productivity (T8.2), efficient use of natural resources (T12.2), and climate change aspects (T13.2)

Table 3. Relative number of investigated Sustainable Development Goal (SDG) targets per region. The numbers refer to the proportion of studies per target out of the total number of studies in the respective region, expressed as a percentage. Numbers in bold indicate SDG targets that have often been examined in the regions, while numbers in parentheses indicate those that have been examined less frequently.

	SDG target																
Region	3.4	3.9	4.3	6.6	7.3	8.2	8.4	8.5	8.8	9.4	12.2	12.4	13.2	15.1	15.2	15.4	15.5
East & Southeast Asia	11	3	**11**	11	**22**	**36**	31	6	14	(3)	**53**	3	**14**	44	100	47	(3)
Europe	**20**	**9**	6	(7)	**27**	28	**41**	**9**	**21**	**9**	**46**	**7**	**12**	(36)	100	(30)	8
Latin America	**24**	(1)	(4)	(7)	(13)	27	27	(3)	**24**	**9**	35	4	**12**	(35)	100	(19)	(5)
Middle East	(9)	(0)	9	**17**	(7)	(17)	(17)	(4)	(7)	(4)	(20)	(0)	(4)	**57**	100	**65**	**20**
North America	(4)	(0)	(4)	13	**27**	**38**	**36**	(4)	(7)	**9**	**44**	**9**	**11**	**51**	100	40	**20**

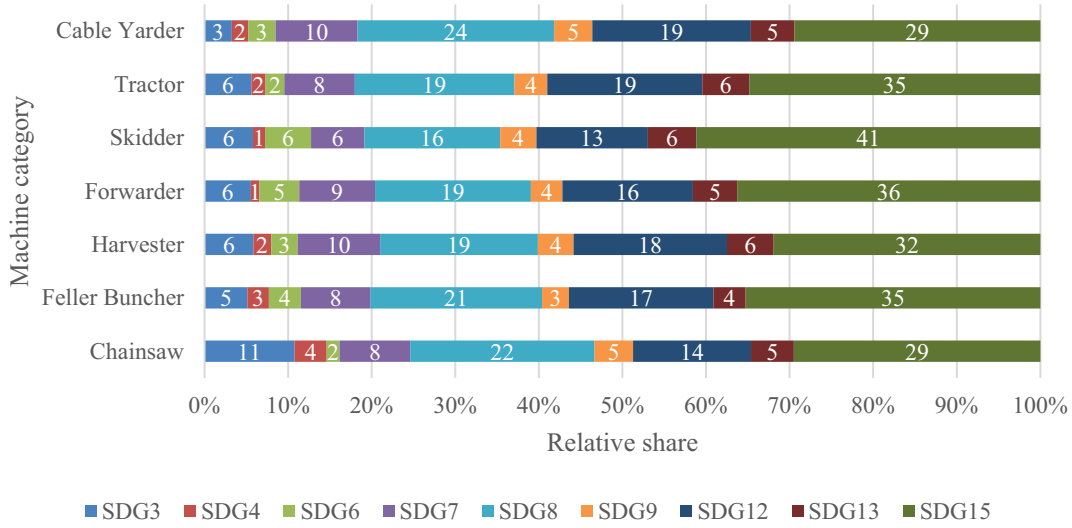

Figure 7. Relevance of the Sustainable Development Goals (SDGs) for various harvesting machines.

(Table 3). Europe has a strong focus on ensuring healthy lives and well-being (SDG3), sustainable and modern energy (SDG7), sustainable economic growth (SDG8), resilient infrastructure and sustainable industry (SDG9), sustainable consumption and production (SDG12), and climate action (SDG13). Latin America stands out as having the most studies focused on promoting mental health and well-being (T3.4) and creating safe and secure working environments (T8.8). In the Middle East, research efforts have been concentrated on water-related issues (T6.6) and terrestrial ecosystems (SDG15). North America leads in research related to energy efficiency (T7.3), economic productivity (T8.2), and the sound management of chemicals and waste (T12.4).

Felling and processing with a chainsaw has been considered in numerous studies aimed at improving worker health conditions (SDG3) and educating workers (SDG4) to recognize and avoid dangerous working conditions (Figure 7). Harvesters and forwarders have been the subject of a disproportionately large number of studies focused on enhancing energy efficiency (e.g. reducing fuel consumption, SDG7) and minimizing climate change impacts (e.g. reducing CO_2 emissions, SDG13). Research on machine – soil interactions, particularly with skidders, has concentrated on water-related concerns (SDG6) and terrestrial ecosystems (SDG15). Ground-based harvesting systems have been more extensively studied for their impact on terrestrial ecosystems (SDG15) compared with chainsaws and cable-based systems.

Impacts of SFO on SDGs and future trends

An analysis of the experts' evaluation revealed that SDG8 and SDG15 are influenced the most by forest operations (Table 4). Six of the 17 SDGs were not directly impacted by forest operations. Among the SDG targets, 11 are negatively affected, 4 are neutral, and 4 are positively influenced by forest operations. The trajectory of forest operations indicates a positive trend toward fostering SFM across all SDGs.

Discussion

In this study, we explored the current state and evolving trends of research on SDGs in the field of SFO. We identified relevant SDGs and their associated targets, and then mapped SFO criteria and indicators to them. In addition, we outlined the expected impacts of forest operations on the achievement of SDG targets and presented future trajectories. To illustrate these assertions, we provided examples showcasing various impacts. Our findings can have implications for researchers, development agencies, and policymakers.

Interpretation of results

Over half of the SDGs, and approximately 10% of the SDG targets, are influenced by forest operations. Notably, our assessment focused on the effects of timber harvesting within the boundaries of the forest system (from the forest site to the landing). If we were to expand these boundaries to include upstream and downstream processes and to consider the indirect effects of forest operations, we would expect a larger number of relevant SDGs and targets. Previous studies (Baumgartner 2019; Hazarika and Jandl 2019; Katila et al. 2019; Ma et al. 2022) have highlighted a substantial interaction between SFO and protecting, restoring and promoting the sustainable use of terrestrial ecosystems, sustainably managing forests, combating desertification, and halting and reversing land degradation and halting biodiversity loss (SDG15). However, SFO also serves as a driver for promoting sustainable economic growth, achieving full and productive employment (SDG8), and ensuring sustainable consumption and production patterns (SDG12).

In our review of literature from 2017 to 2022, we did not identify direct impacts of forest operations on SDG1 (end poverty), SDG2 (end hunger), SDG5 (gender equality), SDG10 (reduce inequality), SDG11 (make cities inclusive, safe, resilient and sustainable), SDG14 (conserve marine resources), SDG16 (promote peaceful and inclusive societies), or SDG17 (strengthen the partnership for sustainable

Table 4. Impacts of sustainable forest operations on Sustainable Development Goals (SDGs) and future trends.

SDGs and targets	Relevance (%)	Impact	Explanation for impact assessment	Future trend	Explanation for prediction of future trend
Goal 1. End poverty in all its forms everywhere	**0**	**no direct impacts**			
Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	**0**	**no direct impacts**			
Goal 3. Ensure healthy lives and promote well-being for all at all ages	**15**				
3.4. By 2030, reduce by one-third premature mortality from non-communicable diseases, through prevention and treatment, and promote mental health and well-being		negative	Forest operations might have negative effects on human health (e.g. dust, vibration, noise).	positive	Innovations in terms of ergonomics and working conditions, as well as higher safety standards. Future forests are climate adaptive and resilient, and society can use them for recreation and well-being.
3.9. By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and from air, water and soil pollution and contamination		negative	Substances or emissions can affect the health conditions of people (in particular emissions from combustion processes).	positive	Innovations in terms of machine technology and configuration, with more efficient combustion processes.
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	**10**				
4.3. By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university		positive	People learn during their training as machine operators and on the job.	positive	Further and more customized training offers, including training with digital tools and virtual environments for an immersive experience.
Goal 5. Achieve gender equality and empower all women and girls	**11**				
5.5. Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life		negative	Traditionally, the forest operation sector is male-dominated.	positive	Further mechanization and development of machines and equipment that also attracts women; forestry 5.0 supports heavy work but requires human decisions.
Goal 6. Ensure availability and sustainable management of water and sanitation for all	**13**				
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes		negative	Forest operations might reduce the quality of water-related ecosystems by impacting the soil during driving and generating emissions to soil and water.	positive	Less impact on the soil due to improved machine design with higher contact surface and less slippage; better planning of skid trails through digitalization and thus less impact on the soil; higher standards in machine design and configuration and thus fewer emissions into the soil and water; increasing awareness of forest planners leading to carefully planned operations with use of the best suitable harvesting methods.
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	**20**				
7.3. By 2030, double the global rate of improvement in energy efficiency		negative	Harvesting machines need energy to move and to process the trees.	positive	Energy efficiency is constantly being improved through the further development of machinery and increased efficiency of forest operations, recently also through electrification of machines or their parts.
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all	**33**				
8.2. Achieve higher levels of economic productivity through diversification, technological upgrading, and innovation, including through a focus on high-value-added and labor-intensive sectors		positive	Forest operations have a positive economic impact.	positive	Economic productivity can be increased by more efficient systems, development of innovations, automation and digitization.
8.4. Improve (progressively, through 2030) global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead		negative	Forest operations need non-renewable resources in the form of e.g. machine usage and fuel consumption.	positive	Resource efficiency can be increased by more durable systems, improvements in machine design, more efficient combustion processes, development of innovations, automation and digitization.

(*Continued*)

Table 4. (Continued).

SDGs and targets	Relevance (%)	Impact	Explanation for impact assessment	Future trend	Explanation for prediction of future trend
8.5. By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value		positive	Forest operations create jobs.	neutral	More efficient systems and a higher degree of automation and digitization could cause a loss of jobs in forest operations. On the other hand, new staff is needed for the development and operation of the automation and digitization processes.
8.8. Protect labor rights and promote safe and secure working environments for all workers, including migrant workers – in particular women migrants, and those in precarious employment		negative	Work accidents and hazards occur during forest operations.	positive	Innovations in term of ergonomics and working conditions, as well as higher safety standards.
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	**13**				
9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities		negative	Forest operations need resources and emit CO_2.	positive	Resource efficiency can be increased through more durable systems, improvements in machine design, more efficient combustion processes, development of innovations, automation, and digitization. Development of Payment for Ecosystem Services schemes fostering SFO.
Goal 10. Reduce inequality within and among countries	**0**	**no direct impacts**			
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	**0**	**no direct impacts**			
Goal 12. Ensure sustainable consumption and production patterns	**18**				
12.2. By 2030, achieve the sustainable management and efficient use of natural resources		neutral	Forest operations use wood as a natural resource (but in a sustainable manner).	positive	Sustainable management and efficient use of natural resources can be increased through improvements in machine designs and operational processes. More criteria for SFO can be used to increase sustainable management.
12.4. By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment		negative	Substances or emissions can affect human health and the environment.	positive	Sound management of chemicals and waste can be increased by improvements of manufacturing processes, machine designs and operational processes. Increase in the machine recycling rate at end-of-life.
Goal 13. Take urgent action to combat climate change and its impacts	**20**				
13.2. Integrate climate change measures into national policies, strategies and planning		negative	Forest operations emit greenhouse gases because of fuel combustion and soil disturbance (soil gases).	positive	Less impact on the soil, due to improved machine design, better planning of skid trails, and higher standards in machine design and configuration, and thus fewer emissions. Further development of better decision support tools supporting pre-estimation of potential impacts related to operations.
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	**11**				
14.1. By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution		neutral	Forestry operations can have an impact on marine ecosystems, but it is difficult to quantify their exact extent.	negative	Consistent application of SFO, which prohibits e.g. fuels from entering the forest soil.
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	**33**				
15.1. By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements		neutral	Forest operations have impacts on ecosystems but are able to positively influence relevant ecosystem services.	positive	Sustainable use of ecosystems can be improved through the consistent use of more efficient machines and improved planning processes.

(*Continued*)

Table 4. (Continued).

SDGs and targets	Relevance (%)	Impact	Explanation for impact assessment	Future trend	Explanation for prediction of future trend
15.2. By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests, and substantially increase afforestation and reforestation globally		positive	The main objective of SFO is the sustainable management of forests.	positive	SFM can be improved by more efficient machines, better planning, and the consideration of more criteria for SFO.
15.4. By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, to enhance their capacity to provide benefits that are essential for sustainable development		neutral	Forest operations can affect mountain ecosystems, but it is difficult to quantify positive and negative effects.	positive	Conservation of mountain ecosystems can be improved by more efficient machines, better planning, and greater consideration of criteria for SFO.
15.5. Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species		negative	Forest operations can disturb animal or plant species or parts thereof (e.g. roots) or special habitats.	positive	Degradation of natural habitats can be minimized by more efficient machines, better planning, and greater consideration of criteria for SFO.
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable and inclusive institutions at all levels	**0**	**no direct impacts**			
Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	**0**	**no direct impacts**			

Bold text is used for SDG goals and non-bold text represents the SDG targets.

development). However, forest operations are likely to have indirect impacts on these goals. For instance, creating new jobs for female forest workers in developing countries could contribute to reducing poverty (SDG1) and hunger (SDG2) (Baumgartner 2019), as well as promoting gender equality (SDG5) and lessening inequality within and between countries (SDG10). Various studies have been conducted to explore the linkages between SFM from the Ministerial Conference on the Protection of Forests in Europe (Forest Europe) (Wolfslehner et al. 2005) and the SDGs 3, 9, 13 and 15 (Hazarika and Jandl (2019). Further, synergies have been identified between the European forestry-based sector (Vision 2040 (FTP 2018); and SDGs 3, 7, 8, 9, 12, 13 and 15 (Hazarika and Jandl 2019). Ma et al. (2022) identified all SDGs as relevant to forests and forestry, with the exception of SDGs 4, 9, 10, 14, 16 and 17. Additionally, they observed that ecosystem services contribute to the achievement of all SDGs except for SDGs 4, 5, 10, 16 and 17 (Ma et al. 2023). Core SDGs, such as SDG 6, 7, 8, 12, 13 and 15, were highlighted as key areas where the forest industry and its value chain can have a significant impact, create long-term value, and drive sector transformation. In addition, supporting SDGs were identified, including SDG 1, 4, 5, 9 and 11, where the forest industry can make a meaningful contribution by promoting inclusive and sustainable economic growth through innovation, transparency and operational integrity (WBCSD 2019).

We observed that certain SDGs and SDG targets serve to represent social (SDG3, SDG4, T3.4, T4.3, T8.8), environmental (SDG6, T6.6, T15.1, T15.5) or economic (SDG7, SDG12, T7.3, T8.2, T8.4, T12.2) C&I, while some have the capacity to be applied in a multi-criteria approach, taking into account at least two or all three pillars of sustainability (SDG8, SDG9, SDG13, SDG15, T3.9, T8.5, T9.4, T12.4, T13.2, T15.2, T15.4). T8.5, which aims to ensure full and productive employment and promote decent work, is an exemplary target covering all three pillars of sustainability. This target is expected to introduce more efficient harvesting systems characterized by higher productivity and lower costs, potentially leading to lower emissions and supporting improvements in working conditions, safety and workload management. By clarifying the interconnections between SDGs, targets and C&I for assessing SFOs, we can better prioritize which SDGs and SDG targets to focus on and determine the appropriate C&I to employ in the implementation of SFOs.

In 2020–2022, there was a greater emphasis on SDG targets T3.4, 4.3, 7.3 and 8.8 compared with in 2017–2019. This emphasis primarily relates to SDG targets with social criteria, indicating a greater focus in recent years on research to promote mental health and well-being, training and lifelong learning, and the creation of safe working environments. Some of these trends were also documented in the Forest Sector Outlook Study presented by FAO (2021).

SFM practices vary across East and Southeast Asia (Rametsteiner and Simula 2003). The framework commonly used in this region is known as reduced-impact logging (RIL), which is considered a step toward SFM. It promotes selective cutting to minimize the negative environmental impacts of forest operations (FAO 2004) while still meeting

the economic needs of the forest industry (Sist 2000). The strong focus on SDG15 in Latin America can be attributed to the need to adapt silvicultural treatments to prevent soil compaction in future forest conversions or forest stand reforms (Rodrigues et al. 2022). The Sixth Five-Year Development Plan (FYDP) in the Middle East, which emphasizes expanding the contribution of environmental criteria in the evaluation of forest activities (Goushehgir et al. 2022) shows also a strong connection to SDG15. Europe and North America are leaders in terms of innovative technology use and mechanization levels (Visser and Stampfer 2015; Visser and Harrill 2017), suggesting less need for catch-up and more research activity in these regions. A systematic review identified the USA, China, the UK, Australia, Indonesia, Austria, Germany and Italy as the countries publishing the most articles aimed at understanding the contributions of the forest sector to the SDGs (Da Aguayo Lopes Silva et al. 2023; Ma et al. 2022).

Chainsaw harvesting and processing are known to be strenuous and hazardous tasks (Laschi et al. 2016), which has led to numerous studies aimed at improving worker health conditions. Fully mechanized harvesting systems prioritize high levels of work safety (Bacescu et al. 2022; Sullman and Kirk 2001) and focus primarily on increasing efficiency while reducing costs and fuel consumption. Ground-based harvesting systems typically have a greater impact on soil than cable-based systems (Picchio et al. 2020) and are therefore often analyzed with ecological C&I. We did not observe significant differences in the distribution of SDGs and targets between different silvicultural systems or slope categories. However, there was a larger proportion of studies conducted in flat terrain related to ensuring the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (T15.1), as well as the sustainable management of forests in general (T15.2).

Improved SFM can have multiple synergies with the SDGs. These include enhancing sustainable productivity and resilience, providing additional biomass for human use, and addressing land degradation. Maximizing synergies and managing trade-offs will depend on the specific practices applied, the scale of implementation, governance structures, capacity building efforts, the degree of integration with existing land uses, and the involvement of local communities through benefit-sharing mechanisms, supported by frameworks such as the Land Degradation Neutrality under the UNCCD (IPCC 2022). The use of carbon sequestration to offset difficult-to-abate residual emissions is considered essential to achieving net-zero CO_2 or total greenhouse gas emissions. Improved forest management is one of the currently practiced methods of carbon sequestration. It can also enhance biodiversity and ecosystem functions, and contribute to employment and local livelihoods (IPCC 2022). According to IPCC (2022), improved SFM has synergies with SDGs 1, 9 and 15 with high confidence, SDGs 6, 8 and 14 with medium confidence, and SDG3 with low confidence. Synergies and trade-offs have been identified with SDG7 with high confidence, SDG11 with medium confidence, and SDGs 2 and 10 with low confidence. There are no identified synergies and trade-offs with SDGs 4, 5, 12, 16 and 17. While this is broadly consistent with our findings, we additionally classified SDGs 1, 2, 10 and 11 as less relevant to timber harvesting. However, these SDGs may indeed be relevant if the system boundaries are expanded.

Critical review of the data and method

We used the literature compiled by Grünberg et al. (2023) as our primary data source because it comprehensively covers the literature on SFO for the period 2017–2022, and it includes all relevant C&I for assessing SFO. Our goal was to identify and quantify the connections between SFO represented by the C&I outlined by Grünberg et al. (2023) and the SDGs. For a more in-depth trend analysis, it would be beneficial to extend the study period beyond six years. However, due to the considerable effort required to expand the data search or modify the existing data structure, we chose to use the available database, which adequately addressed our research objectives.

The literature database and the results of our study might be influenced by a combination of research needs in the forest operations sector and strategic decisions taken by the funding agencies. The latter can be political and often consider not only the research needs in an area but also aspects such as international agreements and societal trends. All studies in the literature database involved direct or indirect analyses of the effects of forest operations on sustainability or the improvement of SFM. The sustainable management of forests is one of the main objectives of SDG15 and therefore all studies in our database can be assigned to this SDG. The scope of our study was kept relatively narrow, with the intention to assess how typical forest operations (i.e. timber harvesting processes) are linked to the SDGs. We expected that this would allow us to focus more on forest operations and subsequently derive recommendations for better integrating the SDGs into sustainable forest management. However, this narrower scope meant that we could only map the indirect effects of forest operations (upstream and downstream processes) to a limited extent. Our study is therefore only suitable for providing a holistic view to a certain level, but it shows interfaces that are useful as starting points for future studies.

Analyzing the impacts of SFO on the SDGs and predicting future trends was a major challenge in our study. It is crucial to reiterate that our study focused exclusively on the impacts of timber harvesting on the SDGs within defined system boundaries. The assessment of impacts relied primarily on the database provided by Grünberg et al. (2023). However, experts identified additional SDGs and SDG targets as relevant that were not addressed in Grünberg et al. (2023), possibly due to a different focus or lack of studies during that period. This is reflected in the differences between Tables 1 and 4. While SDG5 and SDG14 were not addressed in Grünberg et al. (2023), they were considered relevant by the experts.

Conclusions

This paper highlights the linkages between SFO and the SDGs. By closely integrating the SDGs into the planning and execution of timber harvesting operations, sustainable development can be achieved while minimizing forest damage and maximizing mutual benefits. The 17 goals identified as relevant to the

assessment of SFO represent potential trade-offs or synergies that may either be overlooked by policymakers and development agencies or are the results of their previous decisions. It is important to recognize that the forest sector's connection to the SDGs varies with the context, and that SFM practices play a crucial role in maximizing positive contributions while mitigating negative impacts. Our study provides an overview of which SDGs can be considered for more sustainable planning and execution of forest operations. Our findings can be used as a check list or starting point for future research into the integration of sustainability concepts in SFM. Further, many of our results may be applicable to natural systems beyond forests, and there are likely numerous other important interactions that remain to be explored.

Disclosure statement

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