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A Systematic Review of Timber Tracking and Tracing in Forest and Timber Industry Supply Chain: An Analysis of Subject Areas, Objectives, and Characteristics

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Abstract

In the past decades, a considerable body of literature has emerged on timber tracking and tracing in the forest and timber industry supply chain. Therefore, a systematic literature review was conducted using an established method (»PRISMA«). To help define the relevance of timber tracking and tracing, this review addresses the subject areas, objectives and characteristics from scientific studies conducted over the past 25 years. In total 213 papers were included in the qualitative synthesis of the subject areas and objectives, with a 160 of those included in the characteristics synthesis to analyse comparable publication contents.

This study demonstrates the rationale behind the research efforts in the field of timber tracking and tracing. The results showed that the main key objectives were to combat illegal logging and trade, provide sustainable forest management, enable tracking and tracing, enhance efficiency, ensure legal compliance, determine the origin of timber and to identify species. The characteristics of the analysis methods used showed that genetic methods, physical chemistry methods, image methods, geomatics, certification, Radio-Frequency Identification (RFID) and smart technologies and software applications were most common. Most research activities were conducted in Asia and Europe. The majority of tracking and tracing methods were found to be highly practical. The application along supply chain dominated because of the high number of publications in genetic methods where a comprehensive application is possible. Furthermore, the forest, harvesting, and manufacturing were identified as core application areas. Most studies lacked an economic evaluation of the developed solutions, which is a crucial aspect to consider for future successful implementation. The number of tree/wood species involved was notably extensive with a considerable diversity observed across continents. It will be essential that future research incorporates new technologies such as artificial intelligence (AI) that is currently emerging in the field of timber traceability. This can help achieve the identified objectives and address existing and future challenges through the self-learning property of AI.

Keywords: timber tracking, timber tracing, forest supply chain, timber industry supply chain, combat illegal logging, combat illegal timber trade

1. Introduction

Timber tracking and tracing plays an important role in the forest and timber industry supply chain, and a considerable amount of research has been conducted on this topic in recent decades. It is worthwhile to consider the meaning of the terms »tracking« and »tracing« in this context. According to Jansen-Vullers et al. (2003), »tracking is a method of following an object through the supply chain and registering any data considered of any historic or monitoring relevance«. Van der Vorst (2006) defines traceability as »the ability to document and trace a product (lot) forward and backward and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales«. »Tracing«

is described by these elements and differs most from »tracking« in its forward and backward oriented approach. In this publication, the terms »tracking« and »tracing« were interpreted in a broad sense, and all publications containing data and information that could be relevant to ensure traceability were included.

Past studies on timber supply chains mainly focused on the methods and effects of timber tracking and tracing but have been varied and wide ranging. Côté (1999), for example, dealt with forest product certification and its influence on the worldwide forest environment. Chiorescu et al. (2003) developed a databased traceability system with a 2-axis log scanner for sawmills to close the critical information gap between log sorting station and saw intake. In the area of policy studies, Beeko and Arts (2010) analysed the EU-Ghana Voluntary Partnership Agreement (VPA), which is included in the Forest Law Enforcement Governance and Trade (FLEGT) action plan. Scabin et al. (2012) estimated the growth rate by dendrochronology of five illegally logged tree species in the Anavilhanas National Park in the Amazon. Biometric traceability of logs through digital log end images was tested by Schraml et al. (2015). Finch et al. (2020) researched DNA variation to predict the geographic origin of Spanish Cedar (*Cedrela odorata* L.). Flaig et al. (2023) used a new chemotaxonomic method to identify tropical wood species in paper.

Reviews in timber tracking and tracing frequently focus on the methods applied. Dykstra et al. (2003) provided an overview of technologies for log tracking, such as chemical and genetic fingerprinting, Radio-Frequency Identification (RFID) labels, and mechanised coding systems. Lowe and Cross (2011) reviewed timber tracking (species, origin and logs or wood products) by molecular marker methods. Dormontt et al. (2015) investigated forensic methods for timber identification (visual, chemical, and genetic). The implementation of RFID in wood supply chains was reviewed by Tsioras et al. (2022). Silva et al. (2022) reviewed computer vision-based technology for automated wood identification. He and Turner (2022) investigated blockchain applications in forestry by systematic literature review to identify benefits, opportunities, and challenges. 3D technologies and data in forestry for recording and visualisation were reviewed by Murtiyoso et al. (2023).

Studies and reviews that primarily focussed on the application of the traceability methods frequently attempted to ascertain their advantages and disadvantages as well as potential avenues for improvement to stimulate further research and to identify a viable path into practice. The most recent review also examined advantages and problems of various timber traceability methods for determining the effective ones for application in Africa (Tonouéwa et al. 2024). However, a central question remained unanswered by the available studies: What were the motives behind these research efforts? Many studies were conducted with the objective to combat illegal logging (Dykstra et al. 2003, Beeko and Arts 2010, Scabin et al. 2012, Dormontt et al. 2015, Finch et al. 2020, Silva et al. 2022, Flaig et al. 2023, Tonouéwa et al. 2024). It is reasonable to assume, that, while combating illegal logging is an important objective, it is not the sole objective of timber tracking and tracing.

To date, no study has derived the key objectives to determine what drives this research. In order to gain a deeper comprehension of the objectives of the studies, it is essential to identify study characteristics, including the type of research, the methods employed, their application area and practicality, and cost of implementation. The aim of this review was to identify subject areas and objectives of research in the field of timber tracking and tracing in the forest and timber industry supply chain.

2. Materials and Methods

This study was conducted in accordance with the PRISMA Statement of Moher et al. (2009). PRISMA stands for »Preferred Reporting Items for Systematic reviews and Meta-Analyses« and was developed for reviews in the health care sector. The review follows a 27-item checklist, and a four-phase process flow structured into:

⇒ Identification

⇒ Screening

⇒ Eligibility

⇒ Included.

This was supported by downloadable template documents for researchers to re-use (Moher et al. 2009).

The checklist was used as guidance as certain items proved challenging to apply in the context of the forest and timber industry sector. The process flow was adopted and adapted for use in the present study. The information sources for the review were the scientific databases Scopus and Web of Science (Core Collection & Science Citation Index Expanded). An electronic search strategy was developed for both databases by programming a similar query string for locating publications in the area of »timber tracking and tracing in the forest and timber industry supply chain«. The search was limited to articles, review articles, editorial material, proceeding papers, conference papers, letters, notes, and reviews summarised as papers in English. The query was conducted using all available fields (e.g. article titles, abstracts, key words, authors, affiliation, etc.) and encompassed the entire period from the past up to 31 December, 2023. The following terms were used for the electronic search: timber tracking, timber tracing, forestry, timber industry, wood tracking, wood tracing, supply chain, timber marking, wood marking, and tree marking. The query strings are available in Appendix A.

Duplicates were removed in accordance with the PRISMA process flow. In the screening phase, the title, keywords, and abstract were examined. If the records provided insights pertinent to the subject matter, they were selected for a full text assessment for eligibility. Records that did not match these criteria were excluded. In the eligibility phase, the full text of the remaining papers was reviewed. In this phase, the primary areas of focus and principal topics were identified, which formed the base for the qualitative and characteristics synthesis as part of the inclusion phase of the PRISMA Statement. Papers deemed unsuitable were excluded. The entire review was documented in the form of text files and Excel datasheets to provide a comprehensive record of its inception.

2.1 Qualitative Synthesis – Subject Areas and Objectives Analysis

In the qualitative synthesis, the subject areas and objectives were analysed. All papers were classified according to identified subject areas during the full-text assessment. The subject areas emerged based on the content of the papers. The main subject areas identified were: Timber tracking and tracing methods, analysis, tools, technologies and applications, devices, conformity assessment, reviews, policy studies and a preface. These are defined as follows:

⇒ Genetic methods – »Genetic methods are useful to infer species identity and are promising tools to control the geographic origin of logged timber. DNA barcoding and multilocus approaches using nuclear and chloroplast microsatellites as well as Single Nucleotide Polymorphism (SNPs) are the main methods in use to determine species identity« (Degen and Fladung 2008)

⇒ Physical chemistry methods – »Physical chemistry is the branch of chemistry concerned with the interpretation of the phenomena of chemistry in terms of the underlying principles of physics« (Encyclopedia.com 2019)

⇒ Image methods – »Image tracking is meant for detecting two-dimensional images of interest in a given input« (viso.ai 2024)

⇒ Blockchain methods – »Blockchain is a shared, immutable ledger for recording transactions, tracking assets and building trust« (IBM 2024)

⇒ Wood anatomy methods – »The wood macroscopic and microscopic structure is used to identify its genus (and species). […] The identification of wood via its anatomy is the oldest timber tracking method and can therefore build on decennia of experience« (Global Timber Tracking Network 2024)

⇒ Conventional marking methods:

- ✓ Paint – »Paint: to apply colour, pigment, or paint to« (Merriam-Webster, Incorporated 2024)
- ✓ Spray – »Spray can: a pressurized container from which aerosols are dispensed« (Merriam-Webster, Incorporated 2024)
- ✓ Ink print – »Print: to produce writing or images on paper or other material with a machine« (Cambridge University Press & Assessment 2014)
- ✓ Hammer branding – »In hammer branding, logs are manually marked with specific hammers, […]. This simple method involves verification using a huge number of symbols, usually identified locally. Hammering is easy and quick to impress, but the markings are often difficult to read. In Thailand logs are typically stamped with the log ID, year of harvesting, and the logo of the plantation« (Kaakkurivaara 2019)

⇒ Combination of methods – Combining different tracking and tracing methods (RFID-tags, geomatics, physical chemistry methods, scanner, paint, Quick Response (QR)-codes…) within the supply chain.

⇒ Dendrochronological analysis – »Dendrochronology or tree-ring dating is the method by which timbers are precisely dated through measurement and analysis of the trees ring width. The variation in the tree-ring width, influenced by the annual climate variation during the trees growth, is the code used in dendrochronology« (Dendro.dk 2002)

⇒ Geomatics – »Geomatics is the discipline of gathering, storing, processing, and delivering spatially referenced information. It encompasses the fields of surveying, mapping, remote sensing (LiDAR [Light Detection and Ranging] or HDS [High-Definition Laser Scanning] Scanning), photogrammetry, hydrography, global positioning systems (GPS), and geographic information systems (GIS). It is often an umbrella term for every method and tool, from data acquisition to distribution, including math, computers, and Earth science« (Sebago Technics 2024)

⇒ Radio-Frequency Identification (RFID) – »Radio Frequency Identification (RFID) is a technology that uses radio waves to automatically identify and track objects. RFID systems typically consist of a reader device that emits radio waves, and an RFID tag attached to the object being tracked. The tag contains a small electronic circuit and antenna that responds to the radio waves emitted by the reader, allowing the reader to read the information stored on the tag« (Multi-Tech Systems Inc. 2024)

⇒ Smart technologies and software applications – »»Smart« technology refers to the integration of computing and telecommunication technology into other technologies that did not previously have such capabilities. What makes a technology »smart« is its ability to communicate and work with other networked technologies, and through this ability to allow automated or adaptive functionality as well as remote accessibility or operation from anywhere« (Williams College 2024)

»Application software is a type of computer program that performs a specific personal, educational, and business function. Each application is designed to assist end-users in accomplishing a variety of tasks, which may be related to productivity, creativity, or communication« (Quickbase 2024)

⇒ Sensors – »Sensor: a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control)« (Merriam-Webster, Incorporated 2024)

⇒ IDs & codes – »Identification: the act of recognising and naming someone or something« (Cambridge University Press & Assessment 2014)

»Code: a system of words, letters, or signs used to represent a message in secret form, or a system of numbers, letters, or signals used to represent something in a shorter or more convenient form« (Cambridge University Press & Assessment 2024)

⇒ Certification – »Certification is a confirmation by a »third party« that requirements of e.g., international standards, industry specifications or technical rules are met. Certification is based on a conformity assessment in which the fulfillment of the requirements is checked. The subject of such assessments can be, for example, products, projects, processes, or management systems« (DQS Holding GmbH – Headquarters 2024)

⇒ Reviews – »A review article can also be called a literature review, or a review of literature. It is a survey of previously published research on a topic. It should give an overview of current thinking on the topic. And, unlike an original research article, it will not present new experimental results« (Informa UK Limited 2024)

⇒ Policy studies – Studies that deal with regulations, conventions, and ordinances against illegal, unsustainable, and controversial timber use as well as political and economic contexts on national or international level

⇒ Preface – »Preface: the introductory remarks of a speaker or author« (Merriam-Webster, Incorporated 2024).

To ensure consistency and accuracy, a proportional allocation was applied for publications that were assigned to multiple subject areas, each publication totalling a count of one.

Based on the full-text assessment, the objective of each paper was determined. In most studies, the objective was clearly formulated in the introduction or in other sections. Overarching key objectives were formed from the identified single objectives. Afterwards each paper was allocated to a key objective. Enabling tracking & tracing itself has also been mentioned as an objective in many publications and therefore an own key objective category was established.

2.2 Characteristics Synthesis – Analysis of Comparable Publication Contents

In the characteristics synthesis, an analysis was conducted encompassing the following main aspects: year of publication, geographical distribution, type of research, method, application area, practicality, and cost. Year of publication is the year when the paper was published.

The following continental division was chosen for the geographical distribution: Asia, Africa, North America, South America, Europe, Oceania, and

Antarctica. The border between Europe and Asia was drawn at the Urals. North America and South America were divided at the boarder of Panama and Colombia. Oceania includes Australia, Polynesia, Melanesia, and Micronesia. For the geographical distribution, a distinction was drawn between the »research continent« and the »authors research continent«. Research continent means that the investigations (e.g. samples, observations, field analysis, laboratory analysis, etc.) were made on the respective continent. Authors research continent indicates where the authors of the publications with their affiliated research institutions were located.

The type of research was determined in the materials and methods section of each assessed publication. The classic subdivision into field and laboratory research was useful. Beyond that, further types were formed to enable categorisation, such as system proposal, model, simulation, and impact analysis. There were also combinations of research types like field survey and model. Further categories were interview, review, questionnaire, and field survey combined with other different types subsumed as others. Those that could not be assigned were summarised as others. The method classification was adopted from the subject areas.

For the definition of the derived application areas, timber supply chain stages were mainly used, such as harvesting, processing, transport, and manufacturing. While processing tree into logs is part of harvesting, it was mentioned separately because some papers referred to it. As the application possibilities were very heterogeneous, application locations have also been included in the definition of the application areas, such as forest, plantation, and log yard as well as business processes like trade. Different combinations were possible under these aspects.

An attempt was made to derive the practicality of the methods and application areas from the information of individual papers. Practicality means suitable for practical use and was divided into derivable, semi-derivable, not derivable, and not determinable. The factors experimental setup, results, suitability, and effort were used for the evaluation. Derivable means that most factors could be evaluated positively, semi-derivable means that there are some weaknesses, not derivable that a practical implementation is rather unsuitable, and not determinable that no statement can be made based on the information.

The cost criterion was categorised, whereby »determined« means that the costs of the implemented tracking and tracing methods were part of the publication, »quoted« that costs from other comparable publications were cited in the respective publication. »Not determined« means that no cost calculation was carried out for the mentioned method within the framework of the publication.

Reviews, policy studies and one preface were excluded from the characteristics synthesis. This primarily served to create comparability of the characteristics of the single studies. If publications had to be assigned to multiple characteristics, a proportional allocation was made, each publication totalling a count of one.

3. Results

3.1 Flow Diagram – Timber Tracking and Tracing Review

A total of 967 records were identified by database search utilising the specified query strings up to the final date 31 December, 2023 (Fig. 1). Of these, 419 records were sourced from Scopus and 548 from Web of Science. Following the removal of duplicates, the total number of records decreased to 890. In the subsequent screening, 656 records were identified as unsuitable and excluded from further consideration. The remaining 234 full-text papers were subjected to a further assessment to determine their eligibility. Of these, 21 were excluded with reasons (either unsuitable or not accessible). In total, 213 papers were included in the qualitative synthesis of subject areas and objectives. The characteristics synthesis comprised 160 papers, where reviews, policy studies and one preface were excluded.

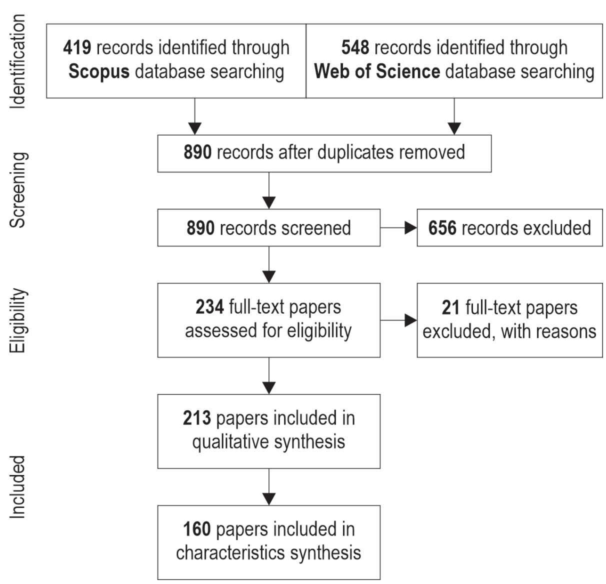

Fig. 1 Flow diagram of systematic literature review in accordance with PRISMA statement

3.2 Qualitative Synthesis – Subject Areas and Objectives Analysis

3.2.1 Subject Areas

Genetic methods constituted the most frequent subject area (65.0 publications; Fig. 2). This number is notably higher than that of any other subject area. The second and third most frequent subject areas were reviews (23.6) and policy studies (21.0), followed by physical chemistry (16.7) and image methods (16.5), which were ranked second and third from a methodological perspective, closely followed by geomatics (15.2). 10.5 publications dealt with certification, 9.1 with Radio-Frequency Identification (RFID) and 7.7 with smart technologies and software applications. The latter subject areas subsumed publications dealing with a range of topics, including the Internet of Things (IoT), Near Field Communication (NFC), flow analysis, virtual planning tools and applications. A total of 5.7 publications combined different tracking and tracing methods along the supply chain and were therefore summarised as a combination of methods. Further publications addressed blockchain methods (5.0), sensors (4.8) and dendrochronological analysis (4.5). A limited number of publications dealt with IDs & codes (2.9), wood anatomy methods (2.7) and conventional marking methods (1.3), which included hammer branding, ink print, paint, and spray. Ultimately, the query also identified a preface (1.0).

3.2.2 Objectives

Combat illegal logging & trade was the most frequent key objective (92.0), followed by sustainable forest management (36.0) and tracking & tracing (26.0 publications; Fig. 3). As publications also generally stated tracking & tracing as objective, this category was established. Efficiency and legal compliance were of equal frequency, representing the key objective of 20.0 publications. The least frequent key objectives were origin determination (10.0) and species identification (9.0).

3.2.3 Connection Between Subject Areas and Objectives

Fig. 4 presents the key objectives broken down by subject area in percentage of papers.

The most frequent main objectives in the subject area of conventional marking methods were combating illegal logging & trade, tracking & tracing, and

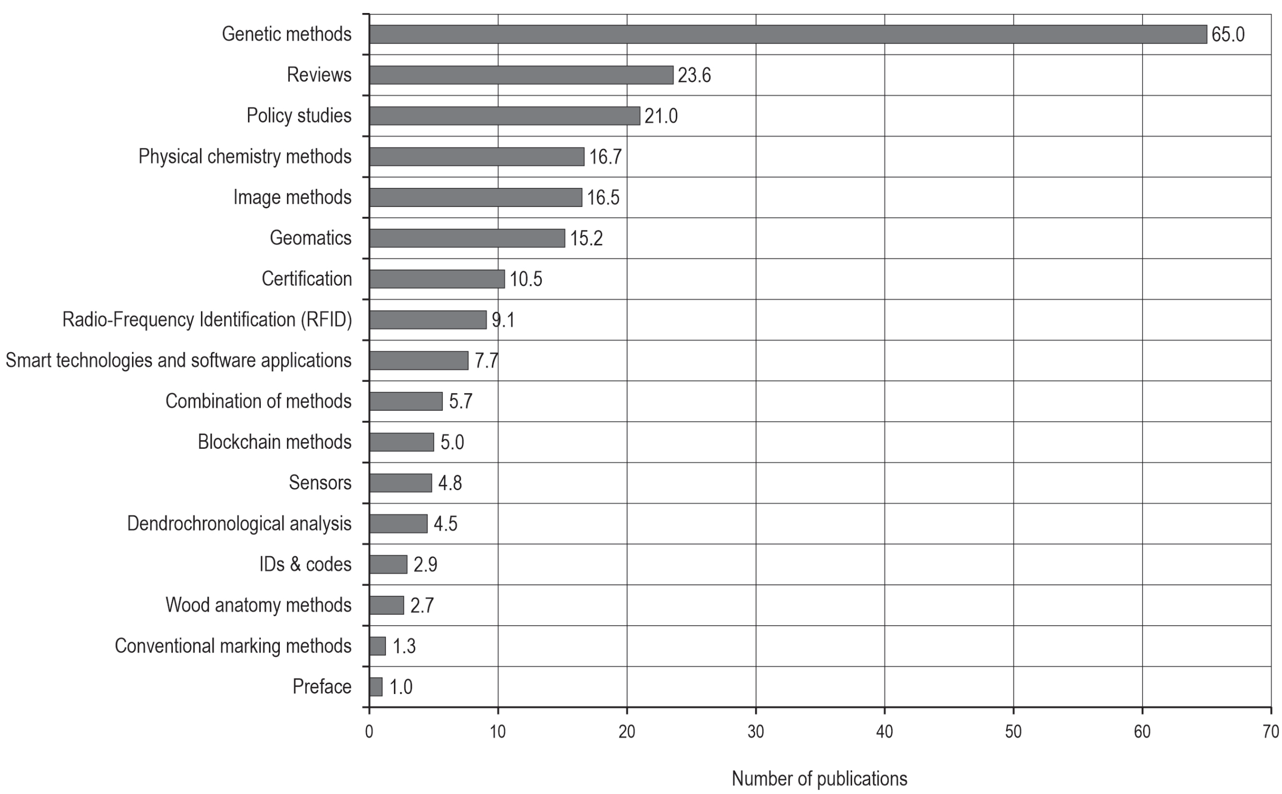

Fig. 2 Number of publications per identified subject area (note: publications that identified multiple subject areas were assigned proportionally so that each paper accounts for a single entry)

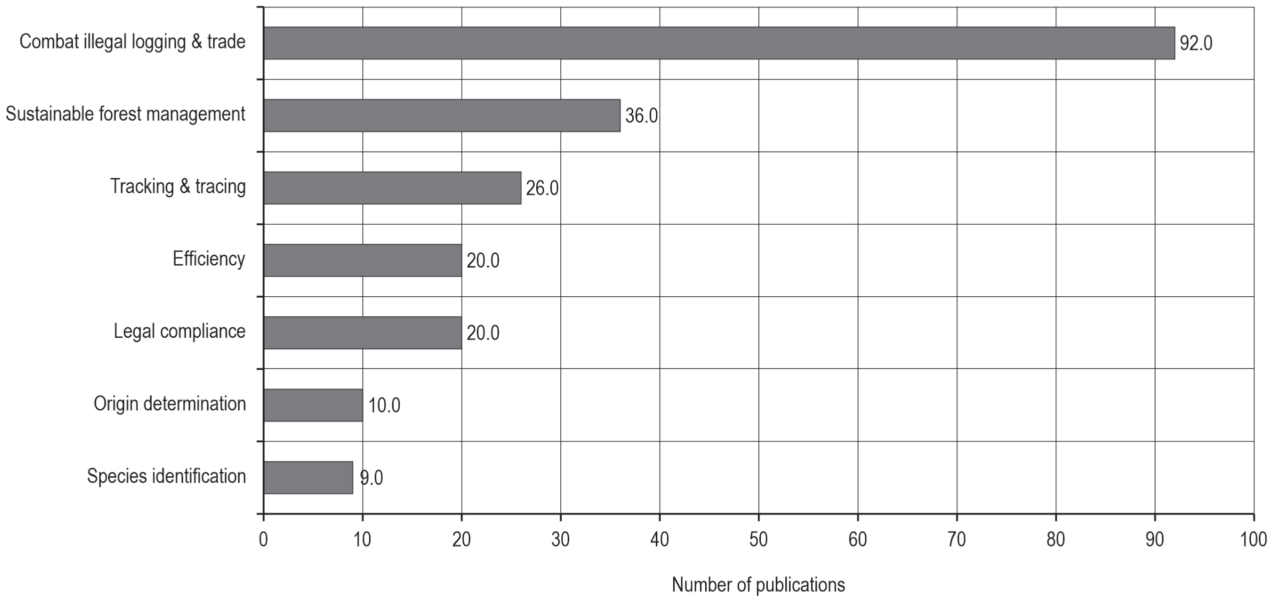

Fig. 3 Number of publications according to derived key objectives

legal compliance, with respective frequencies of 26.7%. Efficiency was present in 20.0% of the papers.

In the subject area of wood anatomy methods, the most frequent objective was combating illegal logging & trade (50.0%), followed by legal compliance (37.5%) and origin determination (12.5%).

Objectives in blockchain methods focused on combating illegal logging & trade (40.0%) and tracking & tracing (30.0%). Further objectives were legal compliance (20.0%) and efficiency (10.0%).

Combating illegal logging & trade (32.4%) and efficiency (29.4%) were the predominant objectives in combination of methods. These were followed by legal compliance (17.6%), tracking & tracing (14.7%) and origin determination (5.9%).

Tracking & tracing (56.9%) was identified as the main objective in publications focusing on Radio-Frequency Identification (RFID). A further 18.3% of the publications in this subject area focused on combating illegal logging & trade. Origin determination (11.0%), efficiency (10.1%) and legal compliance (3.7%) were less frequently named objectives.

A total of 36.4% of the publications in the subject area of image methods aimed at combating illegal logging & trade, followed by species identification (18.2%), efficiency (18.2%), tracking & tracing (15.2%), origin determination (6.1%) and sustainable forest management (6.1%).

Physical chemistry methods were primarily employed with the objective of combating illegal logging & trade (77.0%). A smaller proportion of papers had either origin determination (11.0%), efficiency (6.0%) or tracking & tracing (6.0%) as their objective.

The majority of publications on genetic methods were aimed at combating illegal logging & trade (60.0%). The remaining proportion of publications could be allocated to the objectives of tracking & tracing (11.5%), legal compliance (11.5%), sustainable forest management (7.7%), species identification (7.7%) and origin determination (1.5%).

The key objective of the preface was to combat illegal logging & trade (100%). Given that there was only one publication in this area, a graphical representation was not provided in Fig. 4.

3.3 Characteristics Synthesis – Analysis of Comparable Publication Contents

3.3.1 Year of Publication

The first identified study by the present review on timber tracking and tracing was published in 1999 (Fig. 5). Following a period of inactivity, a number of studies were published between 2003 and 2006. From 2008 on, the number of publications per year increased constantly from 1 to 11 in 2015. Subsequently, it was more volatile, reaching its highest point in 2020 (26) and maintaining a high level as of 2023 (14). The average number of publications was 6.4 for the entire period under review and 13.1 in the last 10 years.

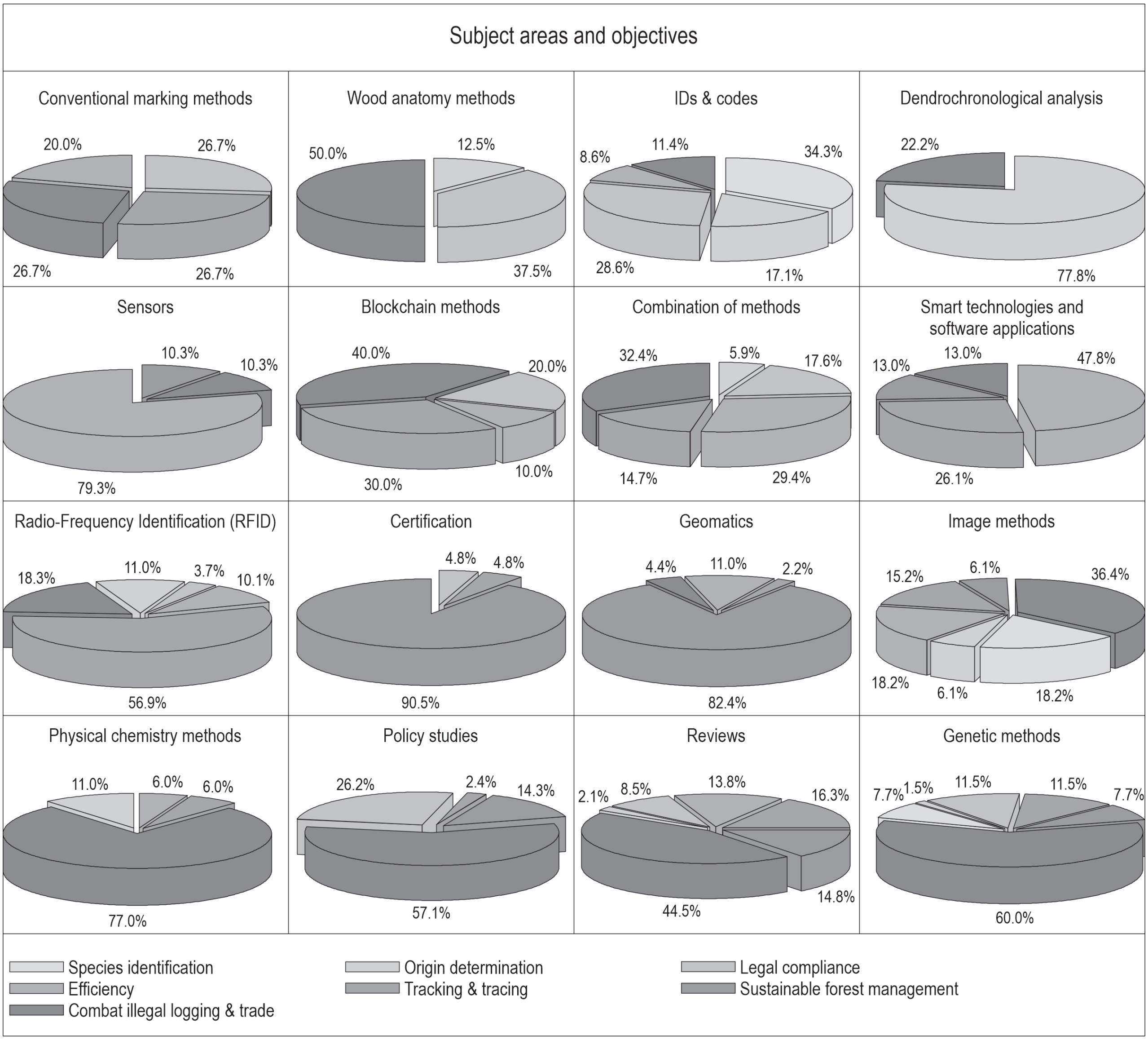

Fig. 4 Relative number of publications by subject areas and key objectives

3.3.2 Geographical Distribution

Most of the investigations were conducted in Asia (46.0) and Europe (45.8), followed by North America (26.3), Africa (21.5) and South America (16.5 publications; Fig. 6). Four publications reported research activities in Oceania.

The majority of the publications were authored by individuals based with their affiliated research institutions in Europe (65.2), followed by Asia (42.7) and North America (28.3 publications; Fig. 7). A total of 13.2 publications had their authors based in South America, while in 6.7 were located in Africa. The lowest number of publications related to the authorship was observed for Oceania (4.0).

3.3.3 Type of Research

The combination of field & laboratory (80.0) research was the most common type of research in timber tracking and tracing. Next were standalone field (23.0) and laboratory research (21.0). Less frequent types were system proposals (7.0) and models (5.0). The research type interview & other (5.0) combined interviews with either information, observation, or questionnaire. Review & other (4.0) combined reviews with either questionnaire, interview, laboratory, or case study. Others (4.0) summed up the types workshop, tutorial, SWOT (Strengths – Weaknesses – Opportunities – Threats) analysis and software development. In 3.0 papers field research was combined with

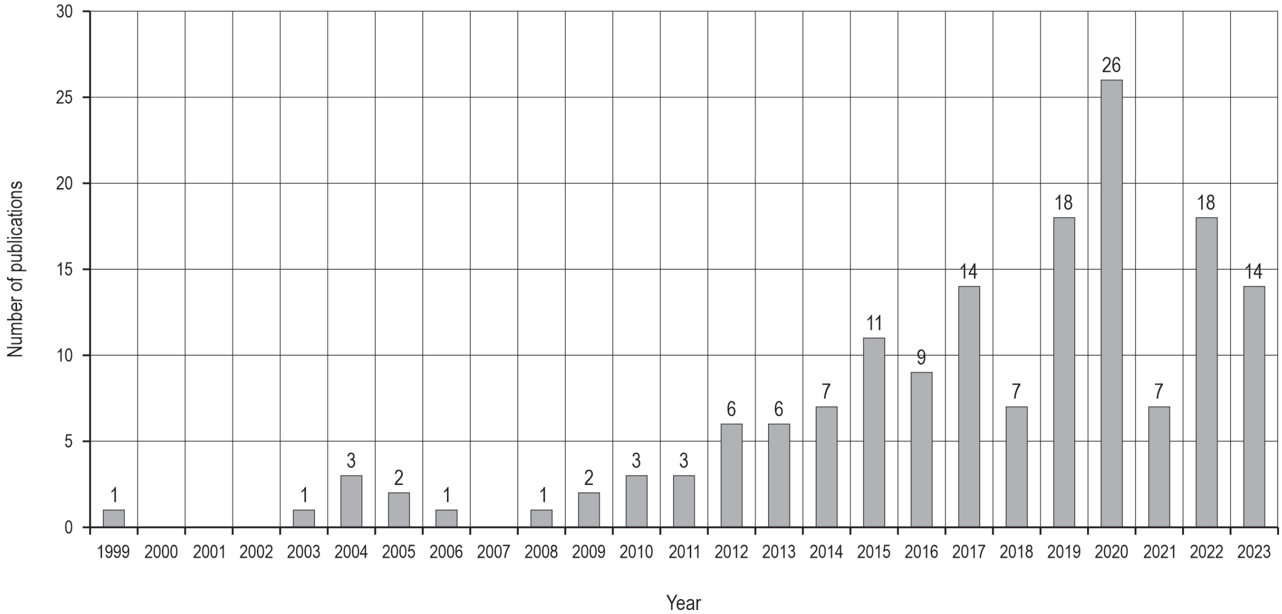

Fig. 5 Number of publications in timber tracking and tracing sector by year

Fig. 6 Number of publications on respective research continent

the development of a model. The type questionnaire & other (2.0) included in one paper field and laboratory research as its second part. Impact analysis, field & other (field research combined with either an expert survey & model or a simulation) and simulation research each accounted for 2.0 publications.

3.3.4 Methods

By far the largest number of publications were in the field of genetic methods (64.0). This was followed by physical chemistry methods (16.7) and image methods (16.5). Further publications involved the methods geomatics (13.3), certification (10.0), Radio-Frequency Identification (8.3) and smart technologies and software applications (7.2). In 5.7 publications, a combination of at least two different methods was investigated. A total of 4.5 publications dealt with blockchain methods. Dendrochronological analysis (4.0), the use of sensors (3.3) as well as IDs & codes (3.0) also stood out

Fig. 7 Number of publications on respective authors research continent

as methods. Wood anatomy methods (2.2) and conventional marking methods (1.3) had the lowest number of publications.

3.3.5 Methods by Year

From 1999 to 2003, only a few methods were investigated (Fig. 8). This changed in 2004 and 2012, when the number of methods researched multiplied. The sharp increase in genetic methods started in 2010, and there were no other methods with such intensive research activity. Most of the methods were featured in less than 10 publications over the last 25 years. Certification had the most consistent growth in publications over the period investigated. Publications on Radio-Frequency Identification have also been very constant from 2003 onwards. On the other hand, physical chemistry methods, image methods, and geomatics were very intensively researched in the last decade and have therefore shown a stronger increase in a shorter period of time than the other methods. Smart technologies and software applications had a robust increase, especially between 2018 and 2020. All other methods had a very slow growth in the number of publications by year.

3.3.6 Methods and Practicality

Practicality was fully derivable for image methods, dendrochronological analysis, and wood anatomy methods (Fig. 9). Genetic methods, physical chemistry methods, geomatics, Radio-Frequency Identification, smart technologies and software applications, combination of methods, IDs & codes as well as conventional marking methods demonstrated a high proportion of derivable practicality. In most cases, the share of publications with derivable practicality was higher than that of the publications in which practicality was semi-derivable, not derivable, or not determinable. In the case of physical chemistry methods and IDs & codes, there were also publications with methods whose practicality could not be determined. Regarding blockchain methods and sensors, semi-derivable and not derivable practicality predominated. In the case of certification, the semi-derivable practicality was derived most frequently.

3.3.7 Application Areas

Genetic methods can cover all supply chain stages. In this field, 87.0 publications were identified. Forest refers to the application in a forest stand. A total of 28.0 publications researched potential applications in the forest, with particular emphasis on geomatics and physical chemistry methods. Eleven publications investigated methods applied in a manufacturing context, where image methods and sensors were frequently utilised. Harvesting & log yard were the possible application areas in 6.0 publications, which featured image methods in many cases. The rest of the publications were classified into a multitude of potential application areas where different methods were applied and no predominant method could be derived.

3.3.8 Application Areas and Practicality

In Fig. 10, the application areas were expanded to include practicality. The application of genetic methods across all supply chain stages was deemed practical for many publications. The same applied to

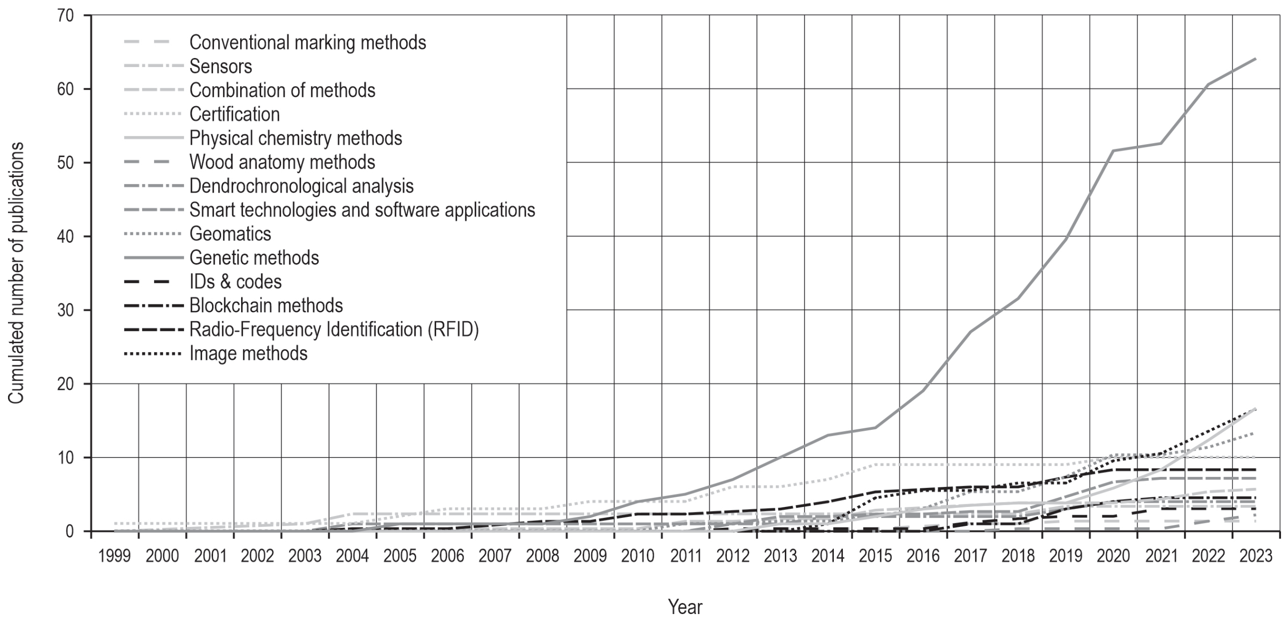

Fig. 8 Cumulated number of publications by methods and year

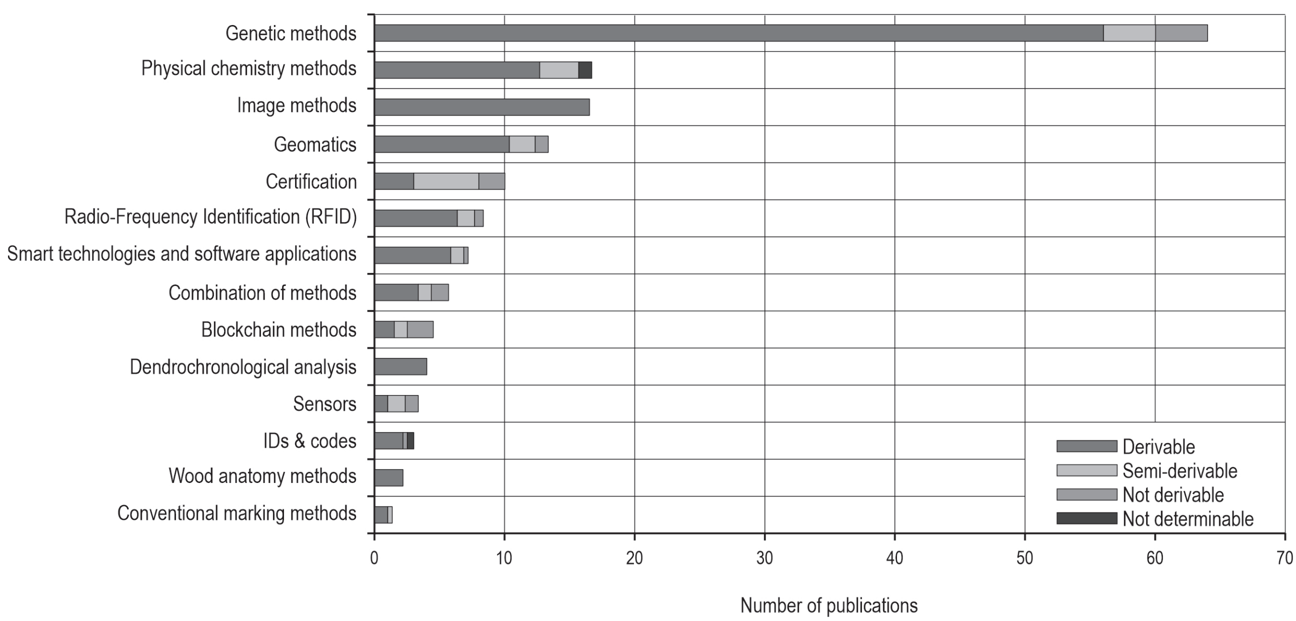

Fig. 9 Methods and practicality

forest with geomatics and physical chemistry methods. A high proportion of practicality was also derived for manufacturing, where image methods and sensors are the predominant technologies. Application in harvesting & log yard involving image methods was regarded highly practical. The other categories were too diverse to permit the formulation of general statements.

3.3.9 Practicality and Costs

In 79% of the publications, the suitability of the researched tracking and tracing methods for practical use was derivable, while in 12% of cases, this was at least semi-derivable. In 8% of the publications, the practicality of the methods was not derivable, and in 1% it was not determinable. In 93% of the publications, the costs associated with tracking and tracing methods

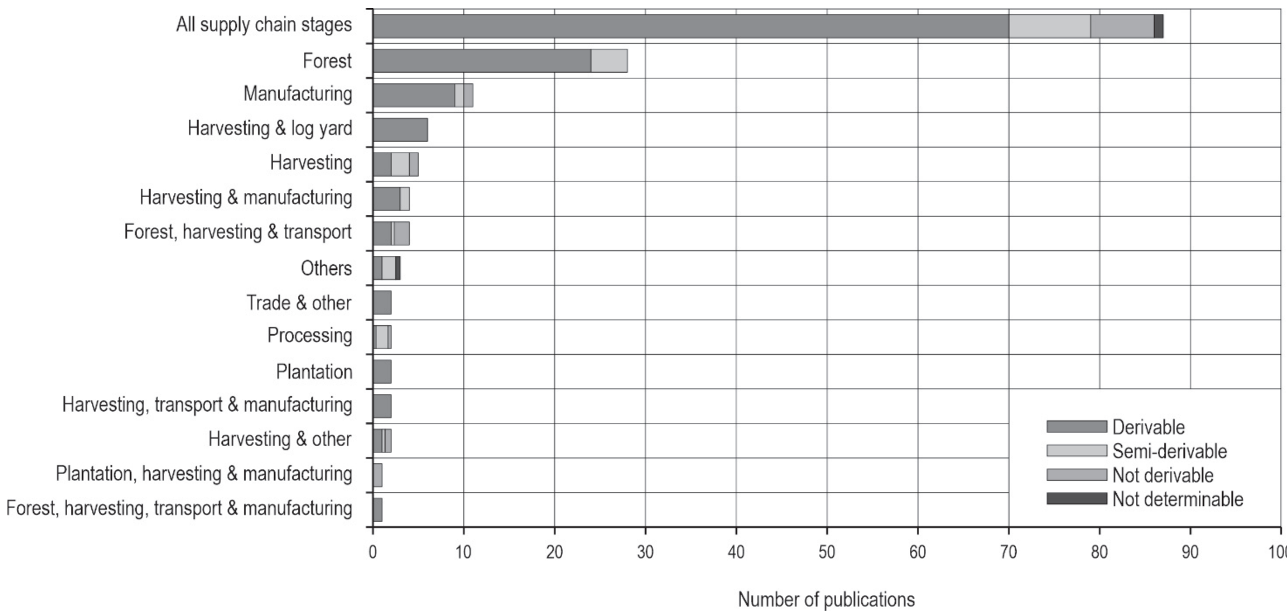

Fig. 10 Application areas and their practicality

were not determined. Only 6% of the publications provide a determination of costs, while 1% offered a quote.

3.3.10 Tree/Wood Species

The number of tree/wood species involved in the experiments was highly variable, ranging from a few to several thousand, with specimens across all continents. As a result, meaningful recording was not feasible. In 31 publications, out of 160, species in question was not specified.

4. Discussion

4.1 Objectives and Subject Areas

The seven key objectives identified are an accurate reflection of the motives behind research in timber tracking and tracing over the last 25 years.

It is evident that combating illegal logging & trade represents a primary objective. This objective was dominant in the application of physical chemistry methods, genetic methods, image methods, combination of methods, blockchain methods, wood anatomy methods, policy studies, and reviews. The following examples serve to illustrate this point. Chemical fingerprinting was employed by Deklerck et al. (2020) to prevent illegal logging and timber trade. Preventing overexploitation and illegal trade in the African timber species *Nauclea diderrichii* by SNP markers was attempted by Blanc-Jolivet et al. (2020) to realise this on a genetic level. Wimmer et al. (2023) showed that tracing wood logs with image data of log ends between different stages of the supply chain is possible under certain conditions (good annual ring pattern visibility or same wood cut pattern), which could be a useful tool for Industry 4.0 and to combat illegal logging. Controlling illegal timber logging and trade by combining tree marking paint with a microtaggant additive and applying it in the form of large QR codes on the cross-sectional surface of logs was another innovative approach (Knowles et al. 2017). The applicability of blockchain in Russian-Chinese timber trade was investigated by Vilkov and Tian (2019) via SWOT analysis. Certification schemes and governmental strategies were not able to prevent illegal timber trade between Russia and China. Blockchain could be the solution to this problem (Vilkov and Tian 2019). Gasson (2011) analysed the challenges of wood anatomical identification of CITES (Convention on International Trade in Endangered Species of wild fauna and flora) listed species, such as ramin (*Gonystylus* spp.), Brazilian Rosewood (*Dalbergia nigra*) and Agarwood (*Aquilaria* and *Gyrinops* species) to support legal timber trade. Analysing policy instruments with a focus on EU FLEGT and other instruments (e.g. EU Timber Regulation, US Lacey Act, etc.), which aimed to combat illegal logging and trade played also an important role (Overdevest and Zeitlin 2014). Low et al. (2022) reviewed species and origin identification technologies for the top 322 global priority timber taxa, which are important tools to combat illegal logging and illegal timber trade. All these publications show how important the objective of combating illegal logging & trade has been for researchers in the past decades. South America, Africa and Asia seem to suffer greatly from this problem and research is therefore being carried out to combat illegal logging and trade. Parallel to this, attempts are also being made to counteract this at a political level, as the implemented policy instruments show.

Sustainable forest management emerged as the second most important objective. Geomatics and certification were frequently used to achieve this objective. Significant advancements in the field of geomatics allows to manage forests more sustainably. Airborne LiDAR (light detection and ranging) data can be instrumental in supporting tree marking in harvesting for sustainable forest management and climate change mitigation (Georgopoulos et al. 2023). Another example is the detection of trees in coniferous forests by airborne LiDAR in Oregon to investigate the spatial distributions of trees, which can be used for forest restoration monitoring (Olszewski et al. 2022). Pinagé et al. (2016) investigated the potential of RapidEye imagery and field data for the detection of selective logging and the prevention of forest degradation in the Brazilian Amazon. Frey et al. (2019) compared the determination of forest structural richness between expert ratings and tracing by a LiDAR-based index, which is highly relevant for biodiversity conservation. This outline clearly shows the innovative strength of research to support sustainable forest management. Certification also focused on sustainable forest management. The oldest publication of this review comes from the field of certification. Côté (1999) conducted an analysis of the potential impact of forest product certification on the global forest environment, as well as the identification of potential limitations to enhance its effectiveness. The state and trends of forest certification in Bolivia, the roles and perspectives of stakeholders, and the main benefits and challenges were investigated by Espinoza and Dockry (2014). Rahim and Shahwahid (2009) analysed how the west Malaysian log supply was influenced by sustainable forest management practice with a special focus on certification. It is therefore evident that certification has always played an important role in the research of sustainable forest management. However, the views of the studies on this topic are often divergent and will be discussed in more detail in the practicality section of the characteristics chapter.

Tracking & tracing as objective was frequently referenced in research on RFID technology. An early study by Korten and Kaul (2008) examined the use of RFID tags in harvesting operations to find out applicability in the timber supply chain. Mtibaa and Chaabane (2014) proposed a real-time wood tracking architecture using RFID technology to gain added value through facilitating tracking of various aspects of the wood's journey, including origin, utilisation, transformation, production, transportation, and process stage. The survival rate of UHF RFID tags in timber harvesting operations was determined by Picchi et al. (2015). These were just a view examples of many studies, but they show the research commitment in this area. The assumed reason that tracking & tracing has emerged as an own key objective is that many studies remain very general in the objective area to keep the application possibilities broad.

Efficiency constituted another key objective, as evidenced by publications on sensors as well as smart technologies and software applications. In the field of sensors, Chiorescu and Grönlund (2004a) developed a traceability system, utilising a fingerprint approach, between log sorting station and saw intake on debarked logs. This was achieved by 3D log scanner data and recognition algorithms, which enabled to close a critical information gap between log sorting station and saw intake. Sandak et al. (2019) developed a sensorised timber processor head to gather data for grading logs. The development of an interactive web 3D planning tool for sustainable forest production, where the forest environment is virtually reconstructed for several applications (e.g. marking, simulation, planning, etc.) in mountain areas, was published by Panizzoni et al. (2015). This constitutes an excellent example of scientific work in the field of smart technologies and software applications. Another intriguing example in this domain was the deployment of a Near Field Communication (NFC) traceability system for three different forest nurseries in Italy, coupled with a blockchain-based web application to gather information on the individual plant, which can be used for management, monitoring, digitisation, transparency, and traceability (Figorilli et al. 2021). The aim of all these publications is to increase efficiency in the timber value chain, and some of these applications are already finding their way into practice.

The objective of ensuring legal compliance emerged as a further objective in timber tracking and tracing. Nevertheless, while it was a prominent feature in some subject areas, it was not the dominant objective in any subject area. It played a significant role in genetic methods and policy studies. Supporting the enforcement of laws on timber trade by genetic timber tracking using nuclear SNP markers to prevent from exploitation (Blanc-Jolivet et al. 2018b) is an example of a study where legal compliance was the main objective. Identifying the contribution of scientific research on deforestation-free products, which is the goal of the new European Union Deforestation Regulation (EUDR) to combat the major threats to the global forests, was analysed by Corona et al. (2023) and plays an important role in legal compliance as well.

Determination of origin was the primary objective within dendrochronological analysis. An illustrative example is dendroprovenancing of pine wood in Spain based on local and regional climate scales which influences tree-ring width and can be traced for origin identification of timber (Akhmetzyanov et al. 2020). Boswijk and Fowler (2019) used tree-ring data for the purpose of dendroprovenancing an important New Zealand construction timber species, thereby gaining insights into the geographical origin of this timber used in buildings in the 19th and early 20th century. It is concluded that dendrochronological analysis is a solid method for timber tracking and tracing and therefore provides reliable results for origin determination.

Species identification represents the final objective in timber tracking and tracing. It is dominant in IDs & codes. This category, however, consists of only one publication. Compiling of a geo-referenced wood reference collection called WorldForestID is an example of wood authentication in trade (Gasson et al. 2021). Higher numbers of papers were identified in image methods (3.0) and genetic methods (5.0). Abdul Hamid et al. (2018) developed a method for denoising wood images to improve image quality, which is crucial for an effective automatic wood species identification. An example of application in the field of genetic methods is the precise species identification of East Indian sandalwood by DNA barcoding to prevent adulteration with other species on the market (Dev et al. 2014). In some countries it seems to be extremely difficult to distinguish the native wood species with the naked eye, so that the objective of species identification is of great importance there.

4.2 Characteristics

An initial publication of timber tracking and tracing research was a work about the possible impact of forest product certification on the worldwide forest environment by Côté (1999). Between 2003 and 2006, a notable increase in the number of publications in this research area was observed, with a first peak in 2004. During this period, significant research was conducted across a range of disciplines. Log scanners were tested to develop a traceability system for sawmills and to fill information gaps (Chiorescu et al. 2003, Chiorescu and Grönlund 2004a, 2004b). The management of timber in terms of production and consumption was investigated by dynamic material and energy flow analysis (Müller et al. 2004). Vidal et al. (2005) assessed the North American solid wood sector regarding the chain of custody certification for status determination because of the growing influence in the market place of forest products. Asif and Cannon (2005) employed DNA sequencing technology for the identification of an endangered species by extracting DNA from processed wood. Karsenty and Gourlet-Fleury (2006) investigated forest management in the Congo Basin regarding the sustainability of logging operations and shed light on certification. A second, considerably larger cluster occurred between 2008 and 2023. A notable surge in publications was observed in the years 2012, 2015, 2017, 2019 and 2020. It can be assumed that the increase in the number of publications is probably due to the increased global awareness of sustainability as a result of climate change. Forests counteract climate change, and sustainable forest management and legal timber utilisation are therefore of increasing importance, which is fuelling research activity. Murphy et al. (2012) studied current and potential tagging and tracking systems with a focus on efficiency and profitability. Template matching, which is an image processing technique to track boards of Scots pine for process optimisation, was researched by Johansson et al. (2015). Düdder and Ross (2017) proposed to track timber by a tamper proof system based on blockchain technology to avoid manipulation. Combating illegal logging by using DNA barcoding in combination with machine learning approaches for species and provenance identification was the aim of the study of He et al. (2019). Employing a mobile robot equipped with a 3D lidar (light detection and ranging) for three-dimensional mapping in forests to measure tree diameters was investigated by Tremblay et al. (2020). The publications mentioned are a few highlights that clearly illustrate the diversity of topics during this period.

From a geographical distribution perspective, the most active areas in terms of research work were Asia and Europe. Genetic methods were intensively investigated in Asia, as combating illegal logging & trade plays an important role on this continent. The reason for this could be that, especially in developing countries in Asia, sustainability is probably of secondary importance and economic interests prevail in the utilisation of the often very valuable timber, which probably encourages illegal logging and trade. An example is the protection of illegal felling in Taiwan using genetic markers as a potential crime-fighting tool (Huang et al. 2022). The development of SNP markers to trace the geographic origin in subtropical China, to combat illegal activities regarding logging and trade (Sun et al. 2023) is another. The region of Oceania was least active, ranking last. Nevertheless, it is home to a number of significant publications, especially on dendrochronological analysis. Dendrochronological dating of kauri timber in New Zealand's building constructions to investigate time-span from felling to construction dates is an example of scientific work in this area (Boswijk et al. 2014).

From the perspective of research type, most publications were combined field & laboratory studies. Karlinasari et al. (2021) sampled trees in field from different sites on Celebes Island to determine the origin of wood by near-infrared (NIR) spectroscopy in laboratory. The second most important area was field studies, where, for example, Picchi (2020) evaluated the operability of UHF RFID tags in marking standing trees over a period of two years with the aim of determining the long-term influence of environmental conditions in forests. Laboratory studies ranked third. Uetimane Jr. et al. (2018) used wood anatomy and chemistry to distinguish between two wood species from Mozambique in the laboratory.

Genetic methods were the most researched topics. It is assumed that reasons for the extensive research into genetic methods are probably advantages in timber tracking and tracing, such as no need for external tags, information cannot get lost, they are tamper-proof and applicable to all supply chain stages, and large quantities can be analysed with high accuracy. However, it is important though to highlight the contribution of less popular tracking and tracing methods, as they provide valuable scientific insights. Ruffinatto et al. (2019) developed a wood atlas and accompanying software, designated SIR-Legno (Supporto Informatico al Riconoscimento macroscopico del Legno, i.e. Informatic Support to Wood Macroscopic Identification) for the macroscopic wood identification of 48 Italian timber species. Such tools are of critical importance to combat illegal timber trade. Gallersdörfer and Matthes (2019) put forth a proposal for a transparent timber supply chain with sources validated through a smart contract system based on blockchain technology using the Ethereum platform. This system ensures that goods can only be created by an authorised party, that no duplicates are issued, and that the total volume of goods remains the same throughout the supply chain (Gallersdörfer and Matthes 2019). Kaakkurivaara (2019) investigated the potential of hammer branding, barcoding, and RFID as log identification technologies in the Thai timber industry to find a traceability system that helps in fulfilling export commitments, such as those set out in EU FLEGT and EUTR, with regard to the legality and sustainability of timber.

Methods which have been subject to sustained research are of particular interest. Examples of these are certification and RFID. The level of awareness of forest certification and green building systems among U.S. hardwood lumber producers was evaluated by Espinoza et al. (2012). Häkli et al. (2010) presented a prototype for log marking and tracking system which uses Ultra High Frequency RFID tags and facilitates data acquisition to optimize production efficiency and prevent illegal logging. The primary motivators for this sustained research activity appear to be sustainable forest management for certification and tracking & tracing for RFID.

Practicality of methods is an asset that promotes their implementation. The evaluation of practicality certainly involves a degree of subjectivity and it is therefore possible that others may have reached different conclusions. The field of image methods demonstrated the highest level of practicality. An illustrative example in this field is the XyloPhone, an attachment for smartphones designed for macroscopic wood imaging, with the potential for computer vision wood identification in the field, which could be a useful tool to combat illegal logging (Wiedenhoeft 2020). Practicality is important because it also implies user-friendliness and probably leads to increased user acceptance and dissemination of the solution. Genetic methods also demonstrated a high level of practicality. An example of a very pragmatic approach is the work of El Sheikha et al. (2013). Its objective was to develop a traceability tool based on the fungal flora of the tropical timber species teak and limbali. Molecular fingerprinting was employed to ascertain a statistical correlation between the fungal communities of the wood and their geographical origin, thereby enabling the traceability of the wood (El Sheikha et al. 2013).

The publications offered different views on the practicality of certification. In Peninsular Malaysia, forest certification has ensured compliance with environmental standards, rules, and regulations, which is perceived favourably (Armir et al. 2020). The implementation of certification in Ghana is hindered by a number of factors, including compliance costs, uncertain business environment, norms such as the fight against western imperialism, regulatory interference, and a lack of responsibility by timber companies (Carlsen et al. 2012). The internalisation of sustainable practices through sustainable forest management certification in the Dutch wood trade and timber industry was considerable (Chappin et al. 2015). Improving forest management, market access and marketing for certified wood products were common arguments for certification (Côté 1999). In his publication, Côté (1999) concluded and predicted benefits for developed countries but no improvement of forest management for developing countries through forest product certification. Furthermore, he states that, even if an impact certainly occurs in some countries, it will be small worldwide. A re-evaluation of these conclusions based on today's information and findings would certainly be of interest. In Bolivia, the implementation of forest certification was highly successful between 1996 to 2008 with a strong increase in certified forest area. Following this period of success, there was a marked decline, which was attributed to legal uncertainties, lack of government support, and discouraging market forces related to certification (Espinoza and Dockry 2014). Espinoza et al. (2012) published a survey on the awareness and perceptions of forest certification and green building systems among U.S. hardwood lumber producers. The authors summarised the challenges, such as low public awareness and lack of price premiums, as well as opportunities, such as positive image and market access. Even third-party certification does not provide complete certainty regarding the sustainability of expanded forest management plans in the Congo Basin (Karsenty and Gourlet-Fleury 2006). Sustainable forest management certification has been identified as a potential means of influencing the supply of logs and other timber products, thereby enhancing the international competitiveness in West Malaysian forestry, with a reducing effect on log supply being investigated through long-run analyses (Rahim and Shahwahid 2009). Certification schemes, have been viewed as innovative means of establishing environmental standards and governance. However, they have also been subject to scepticism regarding their ability to minimise deforestation pressure (Tzoulis et al. 2015). The expectation of direct benefits from chain of custody certification plays an important role in the North American solid wood sector and leads to an increasing number of certificate holders, but in reality, benefits were mainly indirect (Vidal et al. 2005). Despite these different results regarding certification, it is and remains an important tool to guarantee the sustainable origin of timber.

To ensure complete traceability of timber from the forest to the final timber product for the end consumer, it is extremely important to cover all supply chain stages with timber tracking and tracing methods. This ensures that there are no illegal activities in the supply chain and that the sustainable origin of the timber product can be guaranteed, which is crucial for many companies to generate market access. The application area dominated all supply chain stages, largely due to the prevalence of publications on genetic methods that could be integrated into all supply chain stages. In this context, the capacity to obtain intact DNA is crucial for subsequent species and origin determination. Asif and Cannon (2005) demonstrated that the extraction of relatively intact DNA from dry processed wood was possible. The age of the wood seemed to be a limiting factor, resulting in not useful DNA in one of their tests when it was extracted from a 50 years old wooden desk. Jaio et al. (2014) showed that DNA extraction was possible from 39 years old dry wood. Furthermore, DNA barcoding enabled species identification. Tnah et al. (2012) evaluated the extraction of DNA from dry wood and provided recommendations regarding the time after which intact DNA for forensic DNA profiling and timber tracking could still be extracted, which was six weeks after felling for logs and six months after felling for stumps. Geomatics have been subject of extensive research in recent years, which is why the application area forest emerged prominently alongside physical chemistry methods, where sampling was mainly carried out in the field. Wing et al. (2019) traced stems with airborne lidar to generate a map in a heuristic environment for group-selection treatments in the Blacks Mountain Experimental Forest in northeastern California. Watkinson et al. (2022b) classified timber origin through stable isotope ratio analyses of timber samples from two forest concessions in Gabon.

In the presentation of the application areas, harvesting and manufacturing are frequently mentioned. Häkli et al. (2010) developed a disposable wedge-shaped UHF RFID transponder which was applied into the butt end of the log. The biodegradable transponder is made of wood composite material and contains a metal antenna. It can be sawn, chipped and is pulpable as well, which is important to cause no processing problems, but of course than is destroyed. The transponder can be used for timber tracking from harvesting to transport to the sawmill and subsequently from log sorting to the saw intake (Häkli et al. 2010). Pahlberg et al. (2015) investigated the fusion of two feature detection methods, which increased the recognition rate for tracing floorboards made of Scots pine (*Pinus sylvestris* L.). The research was based on images of scanned boards produced in a sawmill in Sweden. This so-called wood fingerprint can be used for downstream tracing to identify the source of problems, e.g., an unsatisfactory quality of the final product (Pahlberg et al. 2015).

The practicality was high in the application area in all supply chain stages, but specifically also in the forest, in manufacturing, and harvesting & log yard. Especially genetic methods had a high practicality because of their possibility of application in all supply chain stages and were very innovative. One such innovative approach is the development of a DNA barcode database and an artificial intelligence (AI) analytical platform for the authentication of traded timber species in India. This species identification is intended to help preventing illegal exploitation of forests (Dev et al. 2023). AI is currently finding its way into many areas of application and should also be increasingly researched in timber tracking and tracing. AI could be combined with various tracking and tracing methods, and in addition to species identification, also support origin identification or other applications.

Given the limited number of publications in the remaining application areas, it is not possible to make any meaningful observations regarding the practicality of the approach. In conclusion, it can be stated that the proportion of publications with derivable practicality was notably high, reflecting the application-orientated nature of the research.

It is unfortunate, however, that the situation is not the same with regard to cost determination, which is of crucial importance for the implementation of tracking and tracing methods. No costs were calculated in almost all publications. There are a few exceptions such as Vidal et al. (2005), who determined average costs for chain of custody assessment (US$ 2.728–5.094), annual audits (US$ 938–1630) and certification renewal every five years (US$ 1.350–2.260) in their survey on chain of custody certification in the North American solid wood sector. In her cost analysis, Kaakkurivaara (2019) calculated equipment costs of 506,500 baht (US$ 15,079) and labour costs of 22,000 baht (US$ 655) for the use of RFID technology for log marking, assuming an annual log volume of 3000 m^3/year.

The number of tree/wood species included in the studies was highly variable. Charwat-Pessler et al. (2016) tracked logs of a single species with RGB (Red-Green-Blue) images within the wood supply chain. A species DNA barcoding library comprising 1550 taxonomically diverse timber species was compiled by Hu et al. (2022). In some instances, the tree species was not specified due to the universal applicability of the presented solutions. An illustrative example is the work of Sandak et al. (2019), in which a processor head prototype was developed, equipped with sensors to measure the timber quality of the processed tree species.

The combination of different tracking and tracing methods appears to be a reasonable approach for leveraging the unique advantages of each method at the most suitable supply chain stage. However, ensuring compatibility is crucial. Appelhanz et al. (2016) proposed a traceability information system to increase product trust and purchase intentions for wood products. This system employs a range of traceability methods (e.g. RFID, ink-printing, QR-code, etc.) for respective traceable units (e.g. high grade timber log, industrial wood log, lumber, particleboard, veneer sheet, etc.) within the wood furniture supply chain.

4.3 Practical Suggestions and Future Research Needs

Tracking and tracing methods can usually be applied independently of the tree species. Complete traceability of timber from the forest to the final timber product should ensure all supply chain stages are covered. To cover all supply chain stages, a genetic method is recommended, whereby a detailed method for each supply chain stage might be best suited but requires combining different methods along the supply chain. Regarding fully derivable practicality image methods, dendrochronological analysis and wood anatomy methods can be recommended. Genetic methods, physical chemistry methods, geomatics, Radio--Frequency Identification, smart technologies and software applications, combination of methods, IDs & codes as well as conventional marking methods can also be seen as highly practical. This does not apply to blockchain methods and sensors where semi-derivable and not derivable practicality predominated. Regarding certification, practicality can be seen as semi-derivable. Smart technologies and software applications are currently finding their way into practice for efficiency enhancement and therefore participants in the whole timber supply chain should be open minded to pave the way and profit from these developments. Blockchain based systems would have a high level of security but have not yet entered the timber supply chain. While RFID is often reported in studies as an opportunity, in timber supply chain practice it has not succeeded. Certification has established itself very well on the timber market and will probably continue to do so in the future, although scientific opinions differ. This leads to the assumption that a method is only successful if the market accepts it. However, there are exceptions, especially when it comes to legal regulations. Timber market participants could take advantage of the named methods to fulfil emerging policy instruments e.g. EUDR and meet legal compliance.

There is a research potential for tracking and tracing from the geographical distribution point of view in South America, Africa, and Oceania. In South America and Africa illegal logging and trade could be counteracted even better by intensifying research. More research should be done on investigating costs of tracking and tracing methods. In practice, the cost of a method has high relevance on its uptake. A total of 26 studies stated tracking & tracing in general as key objective. It would be good if future research could be more specific. Combined field & laboratory studies should be maintained because this approach has contributed to the high degree of practicality of the investigated methods. As AI is currently entering into this research field, the benefits of combining it with different tracking and tracing methods should be part of future research needs. Sustainable forest management and legal timber utilisation are important goals in times of climate change, where forests make an important contribution to store carbon dioxide in timber and the use of this raw material in long-lasting timber products can counteract global warming. Tracking and tracing research can therefore provide tools to ensure this and should be strengthened.

5. Conclusions

The research in timber tracking and tracing has been driven over the last decades mainly by the imperative to combat illegal logging and trade. Additionally, the objective of sustainable forest management, along with enabling tracking and tracing, enhancing efficiency, ensuring legal compliance, the determination of origin, and the identification of species stimulated the research in this field. The majority of publications were dedicated to genetic methods. Furthermore, the science community has investigated a multitude of alternative approaches, such as physical chemistry methods, image methods, geomatics, certification, RFID, smart technologies and software applications, blockchain methods, and sensors, among others. It should be noted that not all methods can be employed without consideration of the specific stage of the supply chain. Therefore, it may be advisable to consider a combined methods approach in future applications along the timber supply chain. The majority of the research in this field was conducted in Asia and Europe, followed by North America, with most of the authors with their affiliated research institutions coming from Europe, followed by Asia and North America. Thus, the scope is to expand research activities in this field on the other continents. A significant proportion of research in this field can be classified as practical research, a designation that is reflected in the high degree of practical applicability of various tracking and tracing solutions. Furthermore, the study demonstrated that, in addition to the potential application of genetic methods across all supply chain stages, application focused on the forest, harvesting, and manufacturing. This is a logic outcome when viewed from the perspective of timber supply chains, as these represent crucial core areas. With regards to practical application, it is regrettable that science in this field of research has not addressed costs so far, which would be crucial for facilitating a faster transfer of the developed solutions into practice. In order to achieve the identified and desirable objectives, it is essential that future research incorporates new technologies such as artificial intelligence (AI), which is currently emerging in the field of timber traceability, to address the current and future challenges. The self-learning property of AI can probably help in this regard.

Appendix A

Database: Scopus

Query string: (ALL(»timber tracking« OR »timber tracing« AND forestry OR »timber industry«) OR ALL(»wood tracking« OR »wood tracing« AND forestry OR »timber industry«) OR ALL(»timber tracking« OR »timber tracing« AND »supply chain«) OR ALL(»wood tracking« OR »wood tracing« AND »supply chain«) OR ALL(»timber marking« OR »wood marking« OR »tree marking« AND »supply chain«) OR ALL(»tree marking« AND forestry) OR ALL (»tree marking« AND »timber industry«)) AND (LIMIT-TO (DOCTYPE,»ar«) OR LIMIT-TO (DOCTYPE, »cp«) OR LIMIT-TO (DOCTYPE, »le«) OR LIMIT-TO (DOCTYPE, »no«) OR LIMIT-TO (DOCTYPE, »re«)) AND (LIMIT-TO (LANGUAGE, »English«))

Database: Web of Science (Core Collection & Science Citation Index Expanded)

Query string: (ALL=(»timber tracking« OR »timber tracing« AND forestry OR »timber industry«) OR ALL=(»wood tracking« OR »wood tracing« AND forestry OR »timber industry«) OR ALL=(»timber tracking« OR »timber tracing« AND »supply chain«) OR ALL=(»wood tracking« OR »wood tracing« AND »supply chain«) OR ALL=(»timber marking« OR »wood marking« OR »tree marking« AND »supply chain«) OR ALL=(»tree marking« AND forestry) OR ALL=(»tree marking« AND »timber industry«)) AND (DT==(»ARTICLE« OR »REVIEW« OR »EDITORIAL MATERIAL« OR »LETTER« OR »PROCEEDINGS PAPER«) AND LA==(»ENGLISH«)).

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