Environmental Indicators for the Evaluation of Wood Products in Consideration of Site-Dependent Aspects: A Review and Integrated Approach

Nadine May 1, Edeltraud Guenther 1,*, and Peer Haller 2

1 Chair of Environmental Management and Accounting, Technische Universität Dresden, 01062 Dresden, Germany; ema@mailbox.tu-dresden.de
2 Institute of Steel and Timber Construction, Technische Universität Dresden, 01062 Dresden, Germany; holzbau@mailbox.tu-dresden.de
* Correspondence: ema@mailbox.tu-dresden.de; Tel.: +49-351-463-34313

Received: 31 August 2017; Accepted: 18 October 2017; Published: 21 October 2017

Abstract: On the way towards a more biobased economy, the sustainable use of global wood resources remains a challenge as several trade-offs arise, e.g., from an increased energetic use of wood, an increased use of innovative but probably less recyclable wood composites, or from the need to conserve other forest ecosystem services. The aim of this study is to identify existing environmental indicators and methods for an evaluation of the sustainability of wood products in consideration of all life cycle stages, site-dependent aspects and later use in corporate decision-making. We chose a systematic literature review to answer the research questions explicitly and comprehensively. Qualitative content analysis was used to code indicators and scientific methods according to the Pressure-State-Response (PSR) framework. The sample (N = 118) is characterized by a high number of life cycle assessment (LCA) case studies. In 51% of all studies, the study authors use a combination of different methods. A total of 78 indicators and 20 site-dependent aspects could be identified in the sample. The study findings represent a first step towards a holistic environmental assessment of wood products.

Keywords: environmental indicators; wood products; literature review; site-dependent aspects; life cycle assessment; Pressure-State-Response framework; decision-making

1. Introduction

Due to global challenges such as climate change, resource scarcity, and political uncertainties [1], many organizations are increasingly forced to take resource-related aspects into account in their decisions concerning the production or procurement of products and raw materials in order to gain a competitive advantage in the future [2]. Such decisions can include the diversification of supply sources, the increase of process and material efficiencies including recycling, or the substitution of scarce and non-renewable materials by alternatives with similar properties and higher availability [3,4]. An alternative, renewable resource which is highly versatile and widely utilized in the material-intensive sectors of construction, furniture, and packaging and that has shown increasing harvesting rates over the last decades is wood [5,6]. Its inherent material properties together with its ecological advantages, e.g., a low embodied energy and global warming potential, make it particularly competitive to state-of-the-art construction materials such as steel and concrete [7]. However, there are also some challenging aspects associated with the resistance and availability of wood.

Due to its nature, it often has to undergo chemical treatment when used for outdoor constructions with direct exposure to humidity, and consequently can bear a certain toxicity potential [8]. More resistant tropical wood species are rare and can hardly be used in a sustainable way due
to widespread illegal logging [9]. Origin and trading routes are often not completely and transparently documented, mainly as a result of poor governance of forests, high wood processing capacities, and inadequate tracking systems [10]. Even if labeling has become more common over the last years, it is still voluntary for most companies [11]. In addition, harvest statistics are often reported on the country level instead of regional or local level of ecosystems [5]. For the global wood resources, scarcity is already evidenced [5,12]. This scarcity can cause conflicts among different stakeholder groups since forests provide diverse ecosystem services such as being habitats for complex communities of species, producing wood for material and energetic utilization, providing space for recreation, and posing a regulatory force on the meso- and microclimate [13]. In addition, regional forest conversion measures in Central Europe have led to a spread of so far less profitable, but more biodiversity-supportive endemic broad-leaved tree species [7,14,15]. Strategies on the development towards a more biobased economy, such as the European Bioeconomy Strategy [16], are quite reasonable when considering the associated carbon dioxide (CO$_2$) mitigation, avoidance of critical waste and economic innovation, but can ultimately lead to a higher demand for wood resources.

Alongside reliable environmental assessment of wood products as well as strong legislation and monitoring systems in the respective wood-producing country, new, material-efficient technologies are needed in order to reduce the pressure on forest ecosystems. Being able to use even the short sections of the tree crown and to exploit less critical wood species from the region, molded wood has the potential to substitute conventional wood processing technologies in the construction and furniture sector in the future [7]. Moreover, new areas of application can be opened in the construction sector, which is nowadays mainly characterized by concrete and steel [17], by improving the wood-inherent properties in a way that they gain a high stability, diversity of forms, and resistance to environmental influences.

Strategies, either on the economic or the corporate level, that are based on an increased use of renewable resources such as wood are not environmentally beneficial when resource extraction exceeds the carrying capacity of forest ecosystems [18]. Therefore, an evaluation of the sustainability of wood products is needed, in which the entire product life cycle is considered including the likely affected ecosystems. Environmental indicators can contribute to evaluation of wood products in general and more specifically to an assessment of the site-dependent impacts of a more biobased economy.

In Section 2, theoretical considerations and definitions regarding the sustainable use of forest ecosystems, life cycle thinking, and site-dependent aspects are introduced before the applied scientific methods and materials are presented in Section 3 of this article. The results are shown in Section 4 and further discussed regarding the contained site-dependent aspects and their implementation in corporate decision-making in Section 5. Final remarks and an outlook for future research demand conclude this article.

2. Theoretical Considerations and Definitions

2.1. Existing Criteria and Indicators for the Sustainable Use of Forest Ecosystems

In connection with forest ecosystems, criteria and indicators are used to conceptualize and implement sustainable forest management (SFM) at the level of nations, regions, or forest management units (FMU), and to facilitate the monitoring of the effectiveness and quality of SFM [19,20]. Criteria should always reflect general principles of the sustainable use of forests, e.g., as they are laid out in the documents Agenda 21 and Forest Principles of the United Nations Conference on Environment and Development (UNCED) [20–22]. Furthermore, they should be quantified, qualified, or described by indicators that are measurable, of analytical soundness, and relevant to stakeholders [20,23]. Indicators can be defined as variables meant to describe both the actual state and the development of systems [24]. For instance, Forest Principle No. 15 [22] reads “Pollutants, particularly air-borne pollutants, including those responsible for acidic deposition, that are harmful to the health of forest ecosystems at the local, national, regional and global levels should be controlled.” and can be addressed with the criterion “soil acidification” and the indicator “soil pH” measured at different times. With the
help of indicators, environmental information about complex phenomena can be quantified and simplified to improve communication [25] and support strategic and operational decision-making. The selection of suitable environmental indicators is a process with different decision points and usually dependent on political objectives or scientific requirements and, therefore, requires a high level of transparency about the basis of the information [26].

Because of these requirements, the development of scientifically-sound and internationally agreed upon criteria and indicators has been a long stakeholder process which gathered pace particularly after the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro. Stimulated by the findings of UNCED [21,22] and convinced by their urgency, intergovernmental initiatives around the world have intensified their work on the definition of criteria and indicators for the implementation at regional, national and FMU levels [27]. The European initiative, which was led by the Ministerial Conference on the Protection of Forests in Europe (MCPFE: Helsinki 1993, Lisbon 1998, Vienna 2003), finally resulted in the development of the Improved Pan-European Indicators for Sustainable Forest Management, which were adopted in 2002 [28]. Another simultaneous initiative on boreal and temperate forests in North America was the Montreal Process. The International Tropical Timber Organization (ITTO) already started in 1992 to develop criteria for the monitoring of sustainability in tropical forests. As a result of the different geographical backgrounds of the initiatives, various concepts and an extensive set of criteria and indicators have been produced, which, though they are largely comparable, ask for harmonization [20].

Some international non-governmental organizations, such as Forest Stewardship Council (FSC) [29] and Program for the Endorsement of Forest Certification schemes (PEFC) [30], just to mention the two most prevalent ones [31], have developed different sets of criteria and indicators for the FMU level. Furthermore, they have initiated a voluntary labeling system that allows not only for the certification of forest resources but also the tracking of wood products emerging out of these resources (chain-of-custody certification) [32].

2.2. Existing Criteria and Indicators from a Life Cycle Perspective

For a holistic evaluation of wood products, we have to move the focus away from simply the resource to the whole product life cycle. Due to the wide range of possible uses of wood for material and energetic purposes, the generation of manifold by-products, and the possibility of repeated use (wood cascade), the forest wood chain (FWC) is often used as a comprehensive concept [33]. In a forest wood chain, the production and eventual consumption of different primary and secondary wood products is linked to the original forest resource; however, the single processes might be geographically separated due to global transport and trade [34]. Established evaluation techniques that are based on the quantification of material and energy flows along a product’s life cycle are life cycle assessment (LCA), material flow analysis (MFA), carbon footprint (CF), or life cycle sustainability assessment (LCSA). Life cycle inventory (LCI) databases such as ecoinvent [35], GaBi [36], or Probas [37] provide quantitative information for a process-based modeling of wood products. In 2007, the developers of the ecoinvent version 2 database [38] issued specific technical background information on how to calculate environmental impacts of the energetic and material use of wood [33]. A total of 100 wood products and wood utilizations have been inventoried in order to identify the most relevant influencing variables on the LCA results of wood. Furthermore, they derived eight criteria for a sustainable use of wood which should be considered in life cycle assessments, e.g., efficient processing and effective use of wood, avoidance of chemical preservatives and careful selection of coating materials, easier recycling, use of incineration residues as fertilizer, and production of durable wood products.

Since Werner et al. (2007) [33] primarily focus on aspects that are methodologically evaluable by life cycle assessments, the authors of this review complemented the list of criteria with principles found in the criteria and indicators schemes of intergovernmental initiatives such as MCPFE [28], non-governmental initiatives such as FSC [29] and PEFC [30], corporate associations such as the World Business Council for Sustainable Development (WBCSD) [39], and additional scientific literature [40].
All principles were then summarized to form the following key messages on a sustainable use of wood resources and products over the whole life cycle (see Table 1).

Table 1. Principles for the sustainable use of wood over the whole life cycle (based on [28–30,33,39,40]).

<table>
<thead>
<tr>
<th>Life Cycle Stage</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource</td>
<td>Maintaining the health, productivity, protective and recreational functions as well as the CO₂ retention of forests (ecosystem services)</td>
</tr>
</tbody>
</table>
| Upstream chain   | Careful logging  
                   | Priority use of low-value timber  
                   | Use of certified wood  
                   | Use of many wood species (biodiversity)  
                   | Use local wood resources (transport) |
| Production       | Production of smaller dimensions  
                   | Production of higher added value products (up-scaling)  
                   | Reduction of waste (material efficiency)  
                   | Use of minimally processed wood  
                   | Production of durable wood products  
                   | Ensuring the decomposition into preferably unmixed fractions (eco-design) |
| Use              | Low use of impregnating agents in dependence of the application situation  
                   | Priority use of natural or low toxic coatings  
                   | Higher service intensity of goods and services |
| End of life      | Wood utilization longer than growth cycle of timber of comparable size and quality (carbon storage)  
                   | Use of recycled wood (wood cascade)  
                   | Use of combustion residues as fertilizer (cradle-to-cradle) |

Some researchers have already established life cycle thinking in the evaluation of single wood products or complete forest wood chains and have selected indicator sets for each life cycle stage following more or less the principles shown in Table 1. Because there is no standard practice, the selection, prioritization, and grouping of indicators was determined by overall objectives and mindsets of the researchers, or causal relationships.

Geibler et al. (2010) [41] developed their indicator set by analyzing the concepts of different sustainability initiatives along the forest value chain, splitting the concepts into dimensions, categories, aspects, and indicators, and validating the selection outcome within a stakeholder process. Cobut et al. (2012) [42] investigated environmental indicators in a life cycle perspective by comparing different ISO (International Organization for Standardization) type I ecolabels in North America, Europe, and Japan. Lindner et al. (2010) [34] used similar existing indicator sets to develop a sustainability indicator framework for the whole FWC, which enables not only a balanced consideration of the three dimensions of sustainability, but also the use of qualitative indicators and whole-chain as well as chain segment related indicators. With the final assessment tool ToSIA (Tool for Sustainability Impact Assessments of forest-wood-chains), they were then able to compare different FWC technologies, political measures, or a changed consumer behavior [43].

None of these authors derived their indicator sets and methodological approaches from a systematic literature search or examined possibilities to consider site-dependent aspects in holistic sustainability analyses. For the practical demonstration of their conceptual frameworks, only a few indicators have been utilized. Which position an indicator holds in a cause-and-effect relationship is not explicitly mentioned, nor are indicators set in relation to existing causal chain concepts.

One common causal approach we applied in this study to classify indicators is the Pressure-State-Response (PSR) framework. It was originally developed by the Organization for Economic Co-operation and Development (OECD) and examines human activities in relation to impacts on the environment and eventual feedback from society [23,44]. It distinguishes three indicator categories: indicators of environmental conditions (state of natural resources), indicators of environmental pressures (pressure by human activities), and response indicators (societal response). Although this causal chain concept is recommended from a scientific point of view, it is rather used for the presentation of indicator results than for their selection [45]. The framework has already been
extended by the European Environment Agency to the Driving force-Pressure-State-Impact-Response (DPSIR) framework to better address the individual contributions of different economies to current and future environmental problems (driving forces) and to develop sector-specific measures (response) [46]. However, we chose the simplified PSR concept because, based on the given information in the sample, the collected indicators could not be unequivocally allocated to a particular driving force or response in the sense of the DPSIR concept. Moreover, we see advantages in the use of the PSR concept on the grounds of a better comprehensibility and our focus on the environmental dimension of sustainability [47]. As with the DPSIR structure, the PSR structure is also compatible with the cause-effect logic in corporate decision-making [48,49].

2.3. Site-Dependent Aspects

Forest ecosystems are affected by many stress factors. Fragmentation by infrastructure, invasive species, and climate change can have severe influences depending on the inherent vulnerability of forests [50]. The use of wood resources should therefore consider the current status of forest ecosystems and possible pre-existing defects.

On a local scale, assessments of the drivers of vulnerability of forests, e.g., climate change, forest land-use change, forest management, or the use of forests by the community, are, according to Sharma et al. (2013) [51], not available or adequate methods are missing in order to establish appropriate forest management schemes. The prevailing method for ecological wood product assessments from a life cycle perspective including the consideration of upstream chains is life cycle assessment, as is later shown within this review. However, most LCAs only focus on the production part of a product life cycle without taking the environmental impacts of biological production systems into account [52]. Moreover, forest ecosystems and wood industries are dynamic systems in the dimensions of time and space [52], a fact that cannot be addressed with static models representing an abstract environment only. Hofstetter (1998) [53] describes this drawback of LCAs in a triple-sphere concept (valuesphere, ecosphere, and technosphere) and calls for a differentiated assessment of site-specific aspects in order to better understand the interactions between a product system (technosphere) and its surrounding environment (ecosphere). Besides this, he explains the regional dependency of the valuesphere of human beings with the help of cultural theory. The valuesphere encompasses human beliefs, attitudes, and convictions and leads to subjective choices of LCA analysts and decision makers, e.g., while defining the goal and scope or selecting safeguard objects (health, resources, and nature) [53].

An analysis utilizing geographic information systems (GIS) poses an alternative streamlined approach to characterize the vulnerability of forest ecosystems instead of a cost-intensive on-site risk assessment [54]. The challenge is then to find georeferenced data at a good quality and appropriate spatial resolution that allow the deduction of sound environmental indicator values and the drawing of an accurate picture of the status of a forest ecosystem. Moreover, in corporate decision-making on products and raw materials, the use of georeferenced data is not yet the state of the art as it is in landscape, resource and infrastructure planning [55–57].

2.4. Overall Objectives of the Review

The present study is motivated by a holistic perspective on the environmental impacts of wood products. Therefore, criteria and indicators to evaluate their sustainability should be systematically identified in the scientific literature. This search should start without any methodological restrictions in the beginning to find approaches beyond LCA. The study focuses on the environmental dimension of sustainability only and thus takes a closer look at the processes at the boundary between the technosphere and ecosphere, following the concept of Hofstetter (1998) [53]. Nevertheless, technical and social aspects are likewise considered when they are closely related to environmental aspects, as the distinction between them can be fuzzy. Moreover, the life cycle of wood products in a classical sense of LCA should be considered as well as possible site-dependent aspects. The study does not
distinguish between wood resources from natural systems (natural forests) and wood resources from human-made systems (silviculture) [58].

Based on the deliberations above, two main questions were of particular interest to the authors when conducting the study:

- Which environmental indicators and scientific methods exist in the literature for a life cycle oriented, ecosystem-based assessment of wood products?
- Which site-dependent aspects are involved in the environmental assessment of wood products?

The following section describes the step-by-step procedure of the systematic literature review and the materials we chose to answer the research questions.

3. Materials and Methods

A systematic literature review can deliver a reliable and evidence-based knowledge basis for a specific phenomenon or question and, therefore, supports well-informed and context-sensitive decisions of practitioners and policy-makers [59]. As a transparent and reproducible method, it also raises the methodological rigor of academic research [59]. Based on the advantages for all stakeholder groups, we chose a systematic literature review for this study to answer the research questions on sustainable wood products explicitly and comprehensively [60]. For the search and screening process of the literature and the selection of appropriate exclusion and inclusion criteria, respectively, we followed the recommendations of Fink (2014) [60], Littell et al. (2008) [61], and Zumsteg et al. (2012) [62].

In a first step, we used our research questions derived in the second section of this article to obtain appropriate search terms. Furthermore, we identified suitable literature databases and websites and discussed all choices within a group of researchers specialized in environmental evaluations and systematic literature reviews. The final literature search was conducted in February 2016 by means of two bibliographic databases (EBSCOhost—Academic Search Complete and Business Source Complete, Web of Science) and the online search engines of four major publishers (ScienceDirect, Emerald, SpringerLink, and Wiley). For unpublished work and conference proceedings, we used Google Scholar and SSRN (Social Science Research Network). In all search cases, Boolean operators were used, allowing for the connection of four search terms and the consideration of synonyms for “wood”, “environmental”, “indicator”, and “life cycle”, so that not only comprehensive but also specific search results could be obtained (see Table 2 and Table S1). By including the term “forest”, the search is extended to the forest ecosystem in order to respect the linkage between the product system and the natural resource. As the study put emphasis on the ecological dimension of sustainability, the economic and social dimensions were not directly sought with the selected search terms, which should not diminish their principal importance. Nevertheless, the terms “sustainab*” and “green” have been included in order to not exclude information from studies focusing on the broader concept of sustainability.

<table>
<thead>
<tr>
<th>Term 1</th>
<th>Term 2</th>
<th>Term 3</th>
<th>Term 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>wood</td>
<td>AND environmental</td>
<td>AND indicator</td>
<td>AND life cycle</td>
</tr>
<tr>
<td>timber</td>
<td>AND ecological</td>
<td>AND criteria</td>
<td></td>
</tr>
<tr>
<td>forest</td>
<td>AND sustainab*</td>
<td>AND index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AND green</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The asterisk serves as wildcard to find all terms sharing the same word root.

The respective search algorithm was primarily applied to title, abstract, and keywords, whereas the SpringerLink search engine only delivered results within a full text search. A total of 1717 hits, of which 1280 hits were without duplicates, could be obtained with this search routine including peer-reviewed articles, books, research reports, and conference proceedings (see Figure 1).
In a second step, practical screening criteria have been applied to the search results by reading the title, abstract, and keywords of the publications. No restrictions were specified with regard to the time frame the publication was issued. All publications written in English language were considered independently from their cultural and geographic background. Literature with no direct access to the original source was excluded. Based on our research questions and the overall objective of the review, which is primarily the assessment of wood products, literature on bioplastics, bioenergy, pulp and paper, as well as short rotation coppice was ignored. The scope was further narrowed to literature that use indicators or specific criteria to evaluate the wood product’s sustainability, as we were specifically interested in the use of the indicators for decision-making purposes, and to literature that considers at least one phase of a wood product’s life cycle. The review should focus on diverse indicator-based methods applied similarly in research and practice; however, the authors were aware that the literature search might lead to a sample that is biased in a way that it is dominated by quantitative studies [61] such as life cycle assessments and underrepresented by unpublished studies [64], e.g., studies from practice. Qualitative studies investigating and developing scientific concepts around the topic were fully considered by the review and only serious quality deficiencies in the eyes of the authors of this review should lead to the exclusion of a study. Consequently, 1022 non-relevant publications were excluded from further study.

It was decided that a second practical screening should be run on the full text of the remaining 258 publications in order to assure a consistent input sample for the methodological screening, as this should be conducted as part of the final content analysis. In this way, 112 publications could be excluded due to their content irrelevance and 20 due to their non-availability, a rejection rate that is considered tolerable with respect to the remaining sample size of 126 publications. A further eight publications were later recognized as being irrelevant for the research questions during the methodological screening of the full text.

Figure 1. Stepwise process chart for the systematic literature review (based on [63]).
In a fourth step, the textual content of 118 publications (see Table S2 for a detailed list of reviewed publications) was analyzed with the support of the MAXQDA coding software [65], among them being 114 peer-reviewed studies, one report, and three book chapters. Qualitative content analysis was the method of choice for the synthesis of the search results as it helps to structure large datasets in a systematic and verifiable way [66,67]. The development of the coding scheme and the reading of the publications was guided by the overarching research questions embedded in the PSR framework. This approach avoids abstract categorizations, facilitates and accelerates the sampling of relevant text, and helps to draw correct inferences from the written text to answer the research questions [66]. Furthermore, it makes clear which context in terms of the assumed network of correlations the authors chose for the content analysis [66].

The coding scheme should not only reflect the research questions appropriately, its category codes should also be exhaustive, explicit, and independent from each other [68]. Meeting these requirements, seven independent category codes (bibliography, study details, research approach, indicators, origin of indicators, region-specific aspects, and other) were defined by the authors prior to the actual coding process. Furthermore, first subcodes were determined based on common classifications in life cycle assessments [69], decision-making principles, and stakeholder theory [70] (see Table 3). During the reading of the selected literature, the coding scheme was complemented with additional subcodes inductively derived from texts so that the final coding scheme encompassed 291 subcodes (see Table S3 for the complete coding scheme).

Table 3. Coding scheme: Category codes and 1st level subcodes.

<table>
<thead>
<tr>
<th>Bibliography</th>
<th>Study Details</th>
<th>Research Approach</th>
<th>Indicators</th>
<th>Origin of Indicators</th>
<th>Region-Specific Aspects</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title Author Year</td>
<td>Main topic</td>
<td>Region</td>
<td>Continent</td>
<td>Study design</td>
<td>Methods</td>
<td>Pressure</td>
</tr>
<tr>
<td>Funding</td>
<td></td>
<td>Sector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first author completed the first round of coding, and then reviewed the codings a second time (intra-coder reliability) to increase their objectivity and reliability [66,67]. The material-oriented validity was met by a systematic sampling procedure and a joint verification of the coding scheme and categories in conjunction with the co-authors [66,68]. Further measures ensuring a high quality of the review include a comprehensive documentation (see Tables S1 and S4) and a fully computer-aided analysis. For the interpretation of the results, there is a distinction between the number of documents (N_{doc}) and the number of codings (N_{cod}), which can differ from each other due to multiple coded attributes.

4. Results

4.1. Characterization of the Sample

The sample (N_{doc} = 118) is characterized by a high number of case studies (70%). Conceptual work can be found only in one third of the studies (see Figure 2). Most of the authors focus on Europe as their area of investigation, which correlates with the high number of main authors (72%) reporting European backgrounds. In total, only 33 countries are represented by the sample. The oldest publication in the sample is an article from Davidson (1985) [71] concerning the consequences of exploiting the resources of tropical forests published in *The Environmentalist*. The most frequently used journal for publication is the *International Journal of Life Cycle Assessment* since LCA and footprints are the most relevant methods applied in the studies. Other common journals are the *European Journal of Forest Research* and the *Journal of Cleaner Production*.
To discover possible external influences on the study execution and research results, all funding sources mentioned in the acknowledgements of the studies have been coded. It turned out that the prevailing form of funding was national funding (39%). Funding from the European Union (EU) (10%) or from the United Nations (UN) (1%) are rather underrepresented in the sample. Furthermore, it can be shown that some studies from universities (19%) were financed by their own resources that are not further specified or were a result of a doctoral dissertation. At least 19% of the studies obtained support from industry either by direct financing or by provision of data and expertise, and 12% of the studies from non-governmental organizations.

The majority of studies deal with environmental issues within the construction (N_{doc} = 47) and forestry sector (N_{doc} = 45). A few studies address the furniture (N_{doc} = 6) and packaging sector (N_{doc} = 6). Fourteen studies tackle more general, superordinate aspects such as wood transport, forest wood chains (partly or as a whole), total organic carbon flows including carbon sequestration and the cascading use of wood.

Because the sample was overrepresented by European studies, softwood species such as pine (N_{doc} = 29) and spruce (N_{doc} = 15) were the most investigated tree species followed by endemic hardwood species such as beech (N_{doc} = 13) and oak (N_{doc} = 7).

The prevailing methodology among all studies is LCA. Taking also LCI, LCSA, and footprints into account, it appeared 78 times (66%) in the sample. Due to the selected research questions and search terms, this result is not surprising. Rather interesting is the fact that in 51% of all studies the study authors combined at least two methodologies to broaden their investigation. With the help of the functions Configuration Table and Code-Co-Occurrence Model within MAXQDA (see Figure 3), the most common combination pairs could be identified: LCA + numerical modeling [72–82], LCA + eco-design concept [75,76,83–91], LCA + Multi Criteria Decision Analysis (MCDA) [79,92–95], and MCDA + Criteria and Indicators [41,44,50,96,97]. Although statistical analyses such as regression analysis, correlation analysis, and cluster analysis are strong tools for the evaluation of empirical data, they were not frequently used throughout the sample.

All investigated wood objects mentioned in the studies were grouped according to the associated sector and then juxtaposed with their particular reference objects. Reference objects are alternative investigation objects (e.g., different scenarios) the wooden investigation object is directly compared with. They were grouped according to the life cycle stages addressed in the studies or assigned to methodological aspects. By counting the occurrence of the different combinations, the main research fields of the sample of this review could be identified (see Figure 4 and Table S2).
Figure 3. Usage of scientific methods in the sample. The frequency of occurrence is shown in brackets after the indicated method and for the most common combinations of methods along the connection lines. Methods shown in orange color do not contribute to the methodological extension of methods shown in blue color, but were kept in the figure for the sake of completeness.

Figure 4. Main research fields of the sample determined by the frequency of different combinations of wooden investigation objects ($N_{\text{cod}} = 233$, $N_{\text{doc}} = 118$) and their reference objects ($N_{\text{cod}} = 233$, $N_{\text{doc}} = 141$). Multiple options are possible and thus lead to a higher number of codings than studies.

Forestry-related studies have set their focus in most cases on a comparison of different forest management strategies [98–105] or specific ecolabels and certification schemes such as FSC and
PEFC [11,106–109] in different geographical regions. FWCs are sometimes only partly covered by studies comprising the processes from harvest to the sawmill gate [110], or from harvest to intermediate wood products leaving the sawmill gate (e.g., sawn wood and by-products) [111], or further on to the end consumer wood product leaving the factory gate as an engineered wood product (e.g., plywood, particle boards, fiber boards, laminates, or veneers). In those cases, the impacts of different wood types, end-of-life strategies, or effects of different allocation strategies were usually explored [83,112,113].

FWCs are considered as a whole in order to define and test holistic sustainability indicators or to investigate the influence of changed forest management regimes [34,41,96]. For the investigation of the influence of the wood products industry on the global carbon balance and the potential of carbon sequestration through an increased use of wood products, dynamic optimization models have been applied by some authors [114–117]. Different transport modes for wood were addressed by only two studies [118,119].

In particular, some LCA studies investigate the effectiveness of advanced methodological approaches, for instance the integration of biodiversity or land use assessment methods into LCA [120,121], or different allocation schemes in case of multi-output processes [43,74,122]. Furthermore, the sensitivity of results has been tested by a variation of LCIA methods [78], background processes such as energy supply systems [119], the time horizon [123], or the geographical reference system [124,125].

Construction-related studies primarily examine the whole building or single building components and compare the wood case with other construction materials such as concrete, brick, stone, steel, aluminum, and synthetic polymers [126–133]. The comparison of different wood treatments, e.g., by means of copper, zinc, boron, or chromium [95,134,135], or different designs [85,92,136] represents a central research approach in some studies. Only a few studies address furniture or packaging items. For the sake of simplicity, one study [137] was allocated to furniture though the object under investigation rather belongs to household devices. A total of 14 studies do not follow a comparative approach [50,52,82,138–148].

4.2. Collected Indicators

The main objective of the presented study was a collection of indicators for wood products that allow for the evaluation of their environmental dimension of sustainability over the entire life cycle. In order to provide a first structured overview of the identified indicators, general headings were assigned to them according to Pressure-State-Response framework (see Figure 5). Altogether, 700 codings were set in the documents, more than half of them belonging to the large canon of impact category-indicators of classical LCIA. As these indicators are used to describe the environmental burden of industrial products, they are categorized as anthropogenic Pressure exerted during the wood product life cycle on the natural environment. Most of the studies apply midpoint indicators to their investigated object [75,112,149]. If applied, category endpoints are mainly used to evaluate the damage to the natural environment [92,107] or the loss of natural resources [81,113]. In some comparative studies [83,121,138], the application of single score indicators such as Eco-indicator 95/99 [150], ReCiPe [151], or IMPACT 2002+ [152] was the method of choice to facilitate the assessment of alternatives. Another common group of indicators we have allocated to Pressure are LCI indicators representing the elementary input and output flows of material or energy entering and leaving the system without human transformation [69]. Those could be collected from, e.g., [8,121,153].
Concerning the State of the ecosystem that is impacted by the pressures, we found several indicators describing the wood resource itself, e.g., as area covered by forest [98,103,105,108], as standing volume [100,136] and carbon stock [80,145], as proportion of dead wood [120], tree height [105], or tree age [120]. To meet the complex nature of biodiversity, some authors helped themselves by quantifying the genetic diversity or the invasive species in a particular area [50,72,107] or by using the size of areas under protection as a proxy indicator [44,154]. The matter of soil protection was addressed by some studies with the determination of the soil fertility [96], the soil erosion potential [139], pedomorphological parameters such as cation exchange capacity [71,72], or the pH value [120]; however, the actual procedure for the determination of the indicators often remained vague in the studies. The regional water balance was investigated by some studies by measuring the precipitation [155], evapotranspiration or surface runoff in a certain area [72], or by modeling the whole water flow in the water catchment area [52,100]. The frequency and spatial extent of hazards such as fire incidents [50] can have a severe impact on the State of a forest ecosystem and was therefore included in the list of codings.

Indicators describing the forest management practice in terms of legality, logging, and reforestation [104,111,141,156] represent decision-making both on a strategic and operational level. They are assigned to the category Response as the introduction of forest management rules is considered a consequence of former mismanagement. Regional wood production has advantages in terms of short transport distances and local added value. It is determined by some studies as production within a specific radius [76] or as a ratio of regionally produced wood to the total wood used [41]. Since the decision on the use of a regional resource should be made depending on the state of the resource itself, this indicator is interpreted as a Response. Value chain communication refers to the active involvement of actors along the steps of the value chain such as suppliers and results from a learning process about the optimization of wood products [41]. Similarly, eco-design principles such as the use of recycled wood or certified wood, the application of modular concepts, or the avoidance of critical materials emerge from critical mindsets of humans and thus are allocated to the category Response [85,89].

We further characterized the indicators regarding their origin by differentiating between three stakeholder groups (policy, science, and industry) [70]. In total, we found 57 indicator sources in the studies. The background information about the authorship was either directly extracted from the studies or determined by follow-up research. In 54% of all cases, the policy was either involved together with other stakeholders in the development of the respective indicator or the sole driver. Science and industry were involved in 54% and 40% of all cases, respectively. This can be considered an almost balanced ratio among all stakeholders, which also reflects their principle interests in this issue. A full list of the origins of indicators is provided in Table A1.
5. Discussion

5.1. Identified Indicators from a Life Cycle Perspective

The arrangement of all collected indicators along the life cycle of a wood product exhibits obvious gaps especially for the ecosphere (see Table 4). This is owed to the fact that the coded indicators have been used in the studies only to describe the State of the wood resource, i.e., the forest ecosystem. They were not used to evaluate other affected ecosystems along the life cycle of a wood product. As the value chain of a wood product is a global issue nowadays, the integration of the spatial dimension of environmental impacts (Pressure) in environmental assessments is necessary to obtain a more realistic picture. This can be accomplished with the support of GIS tools. A special position is taken by category indicators from life cycle assessments as they cumulate all environmental impacts over the life cycle or only parts of it depending on the chosen system boundaries. The category Response includes principles seen in performance measurement systems, e.g., eco-design principles. By applying those principles, all life cycle stages of a wood product can be addressed.

The allocation of indicators and their level of abstraction, i.e., the specification of an indicator as measureable parameter or as superordinate term without a unit, are not consistent throughout the whole sample of the review. Moreover, we see many blank fields. This is due to the different mindsets and objectives of the respective researchers. Precise indicators and metrics are not always available for each aspect and a clear differentiation between aspects and indicators is often missing, which is why we decided not to follow the aspect/indicator differentiating approach of Geibler et al. [41] and to consider 78 indicators in general that could be collected from the given sample.

Table 4. Coded indicators according to the PSR framework and along the wood product’s life cycle (N_{cod} = 700, N_{doc} = 118).

<table>
<thead>
<tr>
<th>Categories</th>
<th>N_{cod}</th>
<th>Wood Resource</th>
<th>Upstream Chains</th>
<th>Production</th>
<th>Use</th>
<th>End-of-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCI</td>
<td>175</td>
<td>Land use</td>
<td>Resource depletion</td>
<td>Resource efficiency</td>
<td>Energy use</td>
<td>Water use</td>
</tr>
<tr>
<td>LCIA Midpoint</td>
<td>315</td>
<td>Global warming potential →</td>
<td>Ozone depletion →</td>
<td>Eutrophication →</td>
<td>Acidification →</td>
<td>Ecotoxicity →</td>
</tr>
<tr>
<td>LCIA Endpoint</td>
<td>41</td>
<td>Damage to natural environment →</td>
<td>Damage to human health →</td>
<td>Loss of natural resources →</td>
<td>Climate change →</td>
<td></td>
</tr>
<tr>
<td>LCIA Single score</td>
<td>10</td>
<td>Eco-indicator 95/99</td>
<td>ReCiPe</td>
<td>IMPACT 2002+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>9</td>
<td>Road density</td>
<td>Transport intensity/distance</td>
<td>Transport vehicles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>5</td>
<td>Noise</td>
<td>Indoor air quality</td>
<td>Toxicy in case of fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical aspects</td>
<td>2</td>
<td></td>
<td>Durability/corrosion</td>
<td>Resistance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Cont.

<table>
<thead>
<tr>
<th>Categories</th>
<th>N_{cod}</th>
<th>Wood Resource</th>
<th>Upstream Chains</th>
<th>Production</th>
<th>Use</th>
<th>End-of-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood resource</td>
<td>40</td>
<td>Forest cover</td>
<td>Standing volume</td>
<td>Carbon stock</td>
<td>Tree age</td>
<td>Tree height</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>27</td>
<td>Areas under protection</td>
<td>Number of animals/plants</td>
<td>Genetic diversity</td>
<td>Rarity of species</td>
<td>Invasive species</td>
</tr>
<tr>
<td>State</td>
<td></td>
<td>General soil protection</td>
<td>N flux</td>
<td>Soil fertility</td>
<td>Soil erosion</td>
<td>Soil compaction</td>
</tr>
<tr>
<td>Soil protection/conservation</td>
<td>22</td>
<td>General water protection</td>
<td>Water quality</td>
<td>Stream flow/water flux/water balance</td>
<td>Precipitation</td>
<td>Surface runoff</td>
</tr>
<tr>
<td>Regional water balance</td>
<td>9</td>
<td>General water protection</td>
<td>Water quality</td>
<td>Stream flow/water flux/water balance</td>
<td>Precipitation</td>
<td>Surface runoff</td>
</tr>
<tr>
<td>Hazards</td>
<td>1</td>
<td>Occurrence of fire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco design principles</td>
<td>29</td>
<td>Certified wood</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response</td>
<td></td>
<td>Modular concept</td>
<td>User-specific design</td>
<td>Use of renewable energy</td>
<td>Avoidance of critical materials</td>
<td>Minimal number of components</td>
</tr>
<tr>
<td>Forest management practice</td>
<td>11</td>
<td>Legality</td>
<td>Logging</td>
<td>Reforestation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional procurement/production</td>
<td>3</td>
<td>Regional wood production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value chain communication</td>
<td>1</td>
<td>Sustainability requirements for suppliers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

→ The arrow indicates environmental impacts that can be determined for single life cycle phases or cumulated for the whole life cycle.

5.2. Site-Dependent Aspects

The second research question of this study refers to site-dependent aspects and how they are addressed by the different scientific approaches which we collated with the help of this literature review. Site-dependent aspects are first of all strongly associated with the characteristics of ecosystems at small or medium scales depending on the uniformity of their extent. Spatial changes of the characteristics of ecosystems such as land use, water balance, carbon stock, or biodiversity are decisive and measurable parameters for the evaluation of ecosystem functions and vulnerability potentials. However, based on the content of all codings, we distinguish between three categories: site-dependent aspects connected
with the social perspective of sustainability (1–3); with the environmental perspective of sustainability, specifically the ecosystem (4–9); and with the scientific methodology (10–20) (see Table 5).

Table 5. Inductively derived classification of site-dependent aspects according to the social perspective, characteristics of ecosystems and methodological issues.

<table>
<thead>
<tr>
<th>No</th>
<th>Site-Dependent Aspect</th>
<th>Social Perspective</th>
<th>Ecosystem</th>
<th>Methodology</th>
<th>Codings ($N_{doc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acceptance</td>
<td>x</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>National legislation</td>
<td>x</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Country-specific certification schemes</td>
<td>x</td>
<td>(x)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Regional forest inventory data</td>
<td>x</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Wood characteristics</td>
<td>x</td>
<td>(x)</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Land use</td>
<td>x</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Biodiversity</td>
<td>x</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>x</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Climate</td>
<td>x</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Sample selection</td>
<td>x</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>Combined methods</td>
<td>x</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>Country-specific tools</td>
<td>x</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Global value chains</td>
<td>x</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>Country-specific databases</td>
<td>x</td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>15</td>
<td>Regional damage characterization factors</td>
<td>(x)</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>16</td>
<td>Scale</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>17</td>
<td>Spatiotemporal dynamics</td>
<td>(x)</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>Transport</td>
<td>x</td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>19</td>
<td>Expert knowledge</td>
<td>(x)</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>Normalization</td>
<td>(x)</td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

x: fully addressed site-dependent aspect; (x): partly addressed site-dependent aspect.

1. Acceptance: The analysis of the studies in the review revealed that site-dependent aspects can have an influence on the valuesphere of people and, therefore, have to be taken into account when assessing the sustainability of wood products. The actual beliefs and values of people are reflected in the acceptance and interests of various stakeholders in the region. Zuo et al. (2009) [156] describes this issue for the regional procurement of building materials for the purpose of reconstruction in Banda Aceh (Indonesia) after the tsunami hit the coast in 2004. Werner and Richter (2007) [157] see the different mental models and values of people as a result of the historical circumstances in the respective country and recommend the involvement of concerned stakeholders when preparing an LCA. Slocombe and van Bers (1992) [154] perceive an increased acceptance of ecological design-criteria if one is focused on a smaller area and denote this influencing factor as bio-regionalism.

2. National legislation: The institutional dimension of sustainability [158], i.e., the power of steering by national legislation or national action plans, plays a decisive role not only in the sustainable development of the European forest-based sector [159], but also in a public procurement that is increasingly guided by ecological criteria [148]. As opposed to green ideas manifested in laws and funding programs, voluntary certification schemes could not have successfully disseminated without the support and acceptance of the industry.

3. Country-specific certification schemes: For historical reasons, there are several country-specific certification schemes because they often started as national initiatives [42,107]. All certification schemes have certain requirements in common, but will keep their regional particularities until there is an overall global scheme implemented which substitutes them.

4. Regional forest inventory data: The whole carbon stock of a forest is dependent on the prevailing forest management regime [124]. To verify the stability of a forest’s carbon stock, regional forest inventory data are required. For instance, boreal forests usually grow slower and, therefore, assimilate less carbon than forests in more temperate areas [160]. In contrast, the soil in the boreal zone is the most important carbon stock due to a slow decomposition at lower temperatures [161] and, nowadays, more and more threatened by global warming. Wolfslehner et al. (2013) [162] calculated the hardwood volume very precisely by means of a fixed radius sample plot and...
5. Wood characteristics: Gustavsson and Sathre (2010) [165] as well as Nebel et al. (2006) [166] indicate in their studies that the forest biomass has to be distinguished in wood types and wood species if the forest production is part of an LCA. Not only do the different types of forest biomass differ in their range of material applications in the construction, furniture, or packaging sector due to their specific inherent properties, they also exhibit different biomass production rates and thus different carbon balances. Vogtländer et al. (2013) [116] mention in their study on carbon sequestration in wood products that data on specific wood types are not readily available for LCA practitioners, making even tier 2 calculations [167] of country-specific greenhouse gas inventories less accurate.

6. Land use: Another factor with a strong spatial dependence is land use. Changes in land use can have significant effects on the carbon balance within a wood cascade [153,168]. Furthermore, authors report on correlations with the climate at the habitat level of tropical forests [71], water balances due to changed evapotranspiration and outflows [52], and biodiversity through loss of habitats [120]. In the latter case, the authors see a rising awareness, but also difficulties in evaluating such correlations. García-Quijano et al. (2007) [72] recommend the establishment of a standardized global approach to assess the impact of land use effects, especially under the consideration of local management options. Allacker et al. (2014) [121] prefer the combination of two land use methods, soil organic matter [169] and Eco-indicator 99, for building LCAs. Fehrenbach et al. (2015) [140] use the hemeroby concept to consider land use in LCA by defining seven ordinal classes to appropriately characterize the naturalness of forest ecosystems. Slocombe and van Bers (1992) [154] suggest that timber production should be implemented only on suitable forestry land. However, one has to bear in mind that the use of wood-based materials in comparison to non-wood materials may show a poorer material efficiency resulting in a need of more land area or an intensified forest management [165,170].

7. Biodiversity: In LCA, the use of indicators properly describing the loss of biodiversity is still under development. Land use as a proxy indicator for biodiversity is a popular approach [125,171], but mainly focusing on species richness only. However, the number of species in an ecosystem is not the only determinant to measure changes in biodiversity [120,172,173]. Functional diversity can be the more reliable metric, as it connects species loss with ecosystem functions [174].

8. Water: Launiainen et al. (2013) [175] point out that local conditions also have to be considered when applying a water footprint methodology. They emphasize that the correct mapping of the spatial variability along the entire production chain of wood products is a crucial point for the calculation of their water use impacts.

9. Climate: The energy demand for heating and cooling of buildings may be, depending on the thermal mass of the building, more or less influenced by fluctuating climatic conditions [165]. Stazi et al. (2014) [81] reveal in their study that this region-specific parameter has a significant effect on the environmental burden of the chosen building envelope. Ultimately, they recommend a wooden lightweight envelope even if passive cooling techniques should be additionally applied in hot and dry climates.

10. Sample selection: Site-dependent aspects within the technosphere are primarily seen as attempts by researchers to methodically manage spatial variability. In comparative LCA, variability of products is usually addressed by contrasting a base case (default case, state-of-the-art) with one or more alternative cases (scenarios). In the case of wood products, spatial variability can be considered by the type of sample selection, e.g., by choosing different wood species from different vegetation zones. This was done by Feifel et al. (2015) [135] as well as Pommier et al. (2015) [90], who compared regional European pine wood with tropical wood from Africa. A prerequisite is that adequate local data exist to discover the differences in the biomass production and
pre-processing of the timber. To get a representative picture of the environmental pressures caused by the timber industry in Ghana, Eshun et al. (2010) [125] paid attention to an appropriate regional distribution within their selected company sample. Furthermore, they calculated the local emissions based on the respective production volume. In the case of very large investigation areas, a subdivision can be useful to respect spatial variability. The fact that this subdivision does not have to be exclusively based on ecological criteria is shown in the study by Glazyrina et al. (2015) [176] who also used economic criteria such as tax revenues to cluster Russia into six not necessarily adjacent zones.

11. Combined methods: Another possibility to increase the site-dependent specificity of environmental product analyses is the combination of different scientific methodologies in the sense of a more interdisciplinary approach. Some authors make use of GIS in their investigations, for instance, to consider different speed limits in the analysis of transports [118] or to identify areas with a high inherent vulnerability [50]. Heuvelmans et al. (2005) [52] argue that showing the spatial variability of indicator scores with GIS layers delivers too much detail on a scenario where rather the total effect is of interest for decision-making. Apart from that, georeferenced analyses can be helpful for the identification of concrete areas where management actions primarily have to be implemented. Stazi et al. (2014) [81] used dynamic simulations to predict the energy consumption of a building and thereby increased the accuracy of the LCA results for the use phase. According to Tsang et al. (2014) [177], site-specific exposure pathways can be described more accurately by combining LCA with risk assessments. Wolfslehner and Vacik (2008) [44] brought up the idea of combining the Analytic Network Process (ANP) with the PSR framework in order to evaluate forest management strategies since PSR causally links human activities with changes in the state of ecosystems. Werner and Richter (2007) [157] recommend the combination of LCA with other sophisticated methods that are able to describe the manifold ecosystem services and functions of forests, thus indicating the true environmental value of wood products.

12. Country-specific tools: In some cases, it might be recommendable to use country-specific tools, i.e., exclusively tailored to national conditions, such as the TRACI model (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) from US EPA (United States Environmental Protection Agency) to consider site-specific aspects in environmental modeling [8,134,177,178].

13. Global value chains: Global value chains are characterized by an international dispersion of the different stages of a production process [179]. The Tool for Sustainability Impact Assessments of forest-wood-chains (ToSIA) supports the consideration of different locations along the value chain of a wood product by using indicator values that relate to the spatial boundary of the respective production stage [34,43].

14. Country-specific databases: Single datasets in LCA databases such as ecoinvent are often developed in a European context. In order to allow a worldwide application without losing significance, they are often adapted to different geographical reference systems or used as a template for more generic, global datasets. For the same reason, life cycle impact assessment methods, such as Eco-indicator 95/99, need to be adapted to the respective geographical background [149]. In our sample, we found several studies making use of national databases or adapted datasets [84,94,142,149,180–182] in order to get a more realistic picture of the prevailing electricity mix, technologies, or end-of-life scenarios in a respective country. Nevertheless, freely available or purchasable datasets often do not reflect the most recent state of technological developments.

15. Regional damage characterization factors: The magnitude of damages are highly dependent on the sensitivity of the respective ecosystem [183]. Therefore, several researchers criticize the fact that there are not enough regional characterization factors for damage assessments available in LCA, and that those that exist are often only valid for a European or North American
background [89,121,171,173]. Nevertheless, the use of site-generic characterization factors can be acceptable if applied as a worst case scenario [171].

16. **Scale:** As indicators for SFM often emerge from a long-term political process of negotiation such as MCPFE with the intention of meeting worldwide interests, they may lose their relevance or validity on local scales [145], where “... SFM is embedded in a network of external and internal relationships” [97] (p. 167). To implement MCPFE in the national context of Austria, Wolfslehner and Vacik (2008) [44] therefore derived a smaller set of indicators that fit better to small-scale forestry. Another remedy to this problem can be the collection of input data at the process level [34]. The depletion of resources such as water and soil is often done on a global scale. However, the global perspective ignores the idea that site-dependent and more or less immobile resources cannot compensate each other or only at a great expense [184]. Therefore, Heuvelmans et al. (2005) [52] recommend a resource depletion assessment for water resources on a regional or local scale as well as a dynamic reserve life. Even if wood products are intended for indoor use only, they could have undergone chemical treatments that may later result in harmful emissions of volatile organic compounds. In favor of a better estimation of the human toxicity potential of treated wood products, a downsampling of environmental assessments to the indoor level is recommended by Jönsson (1999) [185] and Tarantini et al. (2011) [148]. According to Sharma et al. (2013) [50], assessments on a local scale are required for selecting appropriate resilience enhancement measures for a particular forest. On the contrary, Ianni and Geneletti (2010) [155] recommend forest restoration measures on the landscape level to include larger ecosystems as a whole.

17. **Spatiotemporal dynamics:** Similar to many scientific methodologies that are popular in practice, LCA is affected by the dilemma that an increase in accuracy requires a rise in complexity at the expense of practicability. However, some authors criticize the static character of the LCA concept that ignores the spatially and temporally dynamic interactions at the shared boundary of ecosphere and technosphere [123,157,185–187]. Heuvelmans et al. (2005) [52] introduced a new impact category (regional water balance) in their study to overstep classical system boundaries and enable better risk assessments for droughts and floods based on seasonal water quantities in agri- and silvicultural production systems.

18. **Transport:** In a globalized world, an important element of a wood product’s life cycle is the transport whose environmental impact depends on the transport distances, transport weights, and transport means [113,122,188]. As the modeling of a transport process can be very complex and usually requires the application of a separate tool [118], authors in the sample of the review either used mean values as a rough approximation of the true transport distance [125] or run different transport scenarios (local to global) to evaluate the sensitivity of the overall outcome [119].

19. **Expert knowledge:** Lipušček et al. (2010) [183] recommend the involvement of local expert knowledge under the assumption that they can provide more reliable information on the sensitivity of a local or regional ecosystem than other external sources such as aggregated databases or national statistics. Expert opinion can also be valuable for the derivation of scenarios [95] and the weighting of life cycle inventory results [183].

20. **Normalization:** In case of life cycle assessments, the normalization of category indicator results constitutes an optional step to better assess their relevance in relation to a selected reference value [69]. In the sample, some authors used normalization with the intention to obtain a more representative product unit (e.g., size of deck surface per year of use) to allow product comparisons, where one product is set to 1.0, or to allow comparisons with the national average impacts for US families or the population of Europe [121,134].
5.3. Support of Corporate Decision-Making

With regard to the Triple Helix of state, science, and industry [70], the life cycle and site-dependent perspective of analysis as described above provide valuable insights for governmental agencies and researchers, whereas implications for the industry require deeper examination of the observed results. In exploring the results from the industry perspective we take the role of a decision-maker in an FMU and refer to contemporary performance measurement frameworks [48,49]. They distinguish between different levels for strategic and operational performance measurement: The collection of both financial and non-financial indicators constitutes the basic level of the system; their intended use is to inform decision-making and to evaluate organizational performance, in our context specifically the product life cycle of wood. The analysis of cause-and-effect relationships uses these indicators to derive a strategy. An advanced use of these indicators comprises the implementation of the strategy by defining objectives, action plans and results and connecting incentives with the indicators. Beyond the use for information and evaluation on an organizational level, the managerial performance is evaluated based on these indicators. A further differentiation includes monetary rewards. Only if our study’s findings in terms of the identified environmental indicators are connected with the complex organizational processes will the results provide an added value to decision-making processes in industry.

Concerning the indicators as structured for the life cycle perspective, the state level and the pressure level are focused more on informational purposes, whereas the response level indicators can be directly used for corporate decision-making, e.g., the request for certified wood by customers leads to changes towards eco-design [76,89,106]. From none of the publications could we derive the use for cause-effect analysis along the whole life cycle of a wood product or even for performance evaluation.

Concerning the region-specific analysis, the social perspective is highly relevant for decision-making: Only if eco-design criteria are accepted and supported by national legislation and/or certification schemes do decision-makers feel encouraged to promote them. Ecosystem indicators are only partially relevant for industry-specific use: wood characteristics might be relevant for customization of products, water availability might drive the selection of production processes, and climate change might gain importance for a wide range of stakeholders. Methodological aspects might appear relevant for science only. However, a closer look reveals their indirect importance for several criteria: Country specific adaptation might be appropriate whenever the criteria or their values differ between countries, such as for acceptance or legislation, but also for ecosystem characteristics such as water availability. Global value chains involve an explicit decision regarding which parts shall be included in the corporate strategy.

Of course, not all of the mentioned indicators may be applicable for every practitioner as they are often subject to unbundled responsibilities in an organization and embedded in various corporate guidance such as material safety data sheets (MSDS) or fire safety regulations.

6. Conclusions

The review of 118 publications provides a comprehensive overview of indicators and methods that have been used by researchers and practitioners to evaluate the environmental dimension of sustainability of wood products. Key principles and indicators for the sustainable use of wood resources and wood products have been identified in the literature originating from different stakeholder groups and covering different stages of the wood product’s life cycle. It emerged from the analysis that LCA is the prevailing method to determine the environmental impacts of wood products. In order to overcome the shortcomings of LCA in terms of linear process modeling, temporal and spatial uncertainties, and inconsistently chosen system boundaries [189], many researchers combine LCA with other common methods such as eco-design principles, MCDA, and numeric, ecosystem-based modeling to address the complex characteristics of wood products. Site-dependent aspects could be identified for the forest ecosystem itself, the applied scientific methodology, and the respective valuesphere of researchers or other stakeholders, which demonstrates their relevance.
for the environmental assessment of wood products. The involvement of local expert knowledge, the collection of additional environmental information of affected ecosystems as well as the application of flexible and extendable models can help to better address such site-dependent aspects. Finally, the indicators can be used for decision-making towards eco-design, but also for resource considerate purchasing and processing.

Further research demands mentioned in more recent studies mainly refer to the improvement of LCA, e.g., through the accounting of biotic resources [121], the consideration of the technical performance of building materials [180], the quantification of ecosystem services [139,157,164], the attributional allocation of long-lived products [190], the assessment of forest carbon dynamics including carbon tracking and soil carbon [143,145,165], the provision of interfaces to other modeling tools [191], the development of regional characterization factors for land use change [121], water balance [52,72] and biodiversity [72,171], and, finally, the increased application of such new approaches in case studies [123,138,154]. Moreover, the investigation of the influence of design decisions on the product quality and environmental performance of products is encouraged [82,192].

Besides a better availability of industrial data and user-friendly assessment tools [77,140,193], a more interdisciplinary sustainability research in principle is recommended [41,194]. Furthermore, stakeholders should be more often integrated in the analysis, e.g., for the development of weighting factors, to ensure a higher acceptance of the LCA results [19,34,41,187]. As the use of long-lived products, especially in furnishing, conflict with the short period of trends, we see additional socio-economic research demands concerning the acceptance and preferences of consumers. Saravia-Cortez et al. (2013) [195] also point to a possible impairment of the wood products’ quality through the higher usage of recycled ingredients.

In recent studies from Bach et al. (2017) [196] and Crenna et al. (2017) [18], both devoted to the conceptual development of LCA, indicator-based frameworks are presented that allow the integration of diverse biotic resources into LCA. In respecting cause-and-effect relationships, different origins of biotic resources (natural and man-made resources), and constraints for the availability of biotic resources, such conceptual developments can be promising for the future evaluation of wood products.

Having collected a variety of indicators within this review, we recommend a combination of indicators from all three aspects of the PSR framework for a holistic environmental assessment of wood products. We cannot finally say what the best combination of indicators and methods is because this would first require an investigation on the maturity of indicators with respect to criteria such as practicability and ecological effectiveness. Nevertheless, we consider our overview as a first step towards closing this research gap. Concerning the proliferation of resource-efficient and environmentally beneficial wood products, a subsequent step could be a comparative, extended life cycle assessment of wood products within a common scope but differing in their origin of the forest resource, tree species, production technology, end-of-life, and technical aspects such as weather resistance.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/10/1897/s1. Table S1: Search protocol; Table S2: Overview of 118 studies included in the review; Table S3: Overview of MAXQDA categories, main codes and subcodes; Table S4: PRISMA Checklist.

Acknowledgments: This work is financially supported by the Federal Ministry of Education and Research (BMBF) in the scope of the leading-edge Cluster BioEconomy (grant number 031A068A/PtJ, project 1.4 Faserverstärkte Formholzprodukte aus Buche; grant number 031A441A/PtJ, project Masten aus Form- und Furnierholz in Buche, VPI.12 BEECHPOLE). We further acknowledge support by the German Research Foundation and the Open Access Publication Funds of the TU Dresden.

Author Contributions: Nadine May conducted the systematic literature review and wrote the paper. Edeltraud Guenther supported the conception of the review, revised the review results, supported the interpretation of the results, and wrote the discussion on corporate decision-making. Peer Haller supported the conception of the review and revised the review results and drawn conclusions.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results.
## Appendix A

### Table A1. Origin of indicators ($N_{cod} = 147, N_{doc} = 118$).

<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Initiative</th>
<th>Codings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy</td>
<td>Classification-Based Forest Management (CFM) China</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>German National Forest Program/Nationales Waldprogramm (NWP)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sustainable Impact Assessment Guidelines (SIA) (EC)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Kreislaufwirtschaftsgesetz/Altholzverordnung (Germany)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Municipal Solid Waste Decision Support Tool (US EPA)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Forest Law Enforcement, Governance and Trade (FLEGT) (EU)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Nordic Ecolabel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>EU Ecolabel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Kyoto Protocol (UN)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Montreal Process</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>The Ecosystem Approach (UNCED)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pressure-State-Response framework (OECD)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Sustainable Development Indicators (SDI) (Eurostat)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>SDI (UN Commission on Sustainable Development)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pan-European Indicators (MCPFE)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>TRACI (US EPA)</td>
<td>8</td>
</tr>
<tr>
<td>Policy-Science</td>
<td>EcoMark Japan (Japan Environment Association, NPO)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>European Union Rural Indicators (PAIS-Project, Eurostat)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Forest Landscape Restoration (FLR) (IUCN 4-WWF)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>USEtox® (UNEP 6-SETAC)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Intergovernmental Panel on Climate Change (IPCC, UN)</td>
<td>3</td>
</tr>
<tr>
<td>Science</td>
<td>Biodiversity damage potential-land use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Life Support Function (LSF)-land use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Soil Organic Carbon (SOC)-land use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hemeroby-land use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ecological footprint</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lipasto emission calculation (VTT)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Water Footprint Network (NPO)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Literature</td>
<td>7</td>
</tr>
<tr>
<td>Science-Industry</td>
<td>Environmental Priority Strategies (EPS 2000)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LANCA® land use</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>natureplus label (construction)</td>
<td>1</td>
</tr>
<tr>
<td>Industry</td>
<td>BIFMA 12 Level Scorecared (furniture) (NPO) US</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cradle2Cradle (NPO) (US)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>EcoLogo environmental choice (Underwriters Laboratories) Canada</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>FloorScore (Scientific Certification Systems) US</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Greenguard (Underwriters Laboratories) US</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Indoor advantage gold (Scientific Certification Systems) US</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Indoor advantage (Scientific Certification Systems) US</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>DIN EN 15979 (2012)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>INIES 11 (EPD 12/FDES 13)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SmART 14 (MTS 15) (NPO) US</td>
<td>1</td>
</tr>
<tr>
<td>Policy-Science-Industry</td>
<td>Blue Angel</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Canadian Standards Association (CSA) (NPO)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Sustainable Green Ecosystem Council Japan (SGEC) (NPO)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Eco-Indicator 95/99</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>ReCiPe</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>LEED 16 points (USGBC 17)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>NF Environment furniture (AFNOR 18) France</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SFI 19 (NPO)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PEFC (NPO)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>FSC (NPO)</td>
<td>8</td>
</tr>
</tbody>
</table>

---

References


6. Schweinle, J. Wood & other renewable resources: A challenge for LCA. *Int. J. Life Cycle Assess.* 2007, 12, 141. [CrossRef]


32. Wingate, K.G.; McFarlane, P.N. Chain of custody and eco-labelling of forest products: A review of the requirements of the major forest certification schemes. Int. For. Rev. 2005, 7, 342–347. [CrossRef]


71. Davidson, J. Economic use of tropical moist forests while maintaining biological, physical and social values. *Environmentalist* 1985, 5, 3–28. [CrossRef]


76. Jrade, A.; Jalaei, F. Integrating building information modelling with sustainability to design building projects at the conceptual stage. *Build. Simul.* 2013, 6, 429–444. [CrossRef]


94. Rieradevall i Pons, O.; Aguado, A. Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain. Build. Environ. 2012, 53, 49–58. [CrossRef]


108. He, M.; Wu, Z.; Li, W.; Zeng, Y. Forest Certification in Collectively Owned Forest Areas and Sustainable Forest Management: A Case of Cooperative-Based Forest Certification in China. Small-Scale For. 2015, 14, 245–254. [CrossRef]


116. Vogtländer, J.G.; Van Der Velden, N.M.; Van Der Lugt, P. Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. Int. J. Life Cycle Assess. 2013, 19, 13–23. [CrossRef]

117. Somarriba, E. Sustainable timber production from uneven-aged shade stands of Cordia alliodora in small coffee farms. Agrofor. Syst. 1990, 10, 253–263. [CrossRef]


Sustainability 2017, 9, 1897


174. Jönsson, A. Including the use phase in LCA of floor coverings. *Int. J. Life Cycle Assess.* 2013, 18, 1345–1355. [CrossRef]


180. Ximenes, F.A.; Grant, T. Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. *Int. J. Life Cycle Assess.* 2013, 18, 891–908. [CrossRef]


