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REVIEW

Diversification of the forest industries: role of new wood-based products

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Abstract: This study identifies new wood-based products with considerable potential and attractive markets, including textiles, liquid biofuels, platform chemicals, plastics, and packaging. We apply a mixed-methods review to examine how the position of the forest industry in a given value chain determines the respective production value. An assessment is provided as to the degree to which these emerging wood-based products could compensate for the foreseen decline of graphic paper markets in four major forest industry countries: USA, Canada, Sweden, and Finland. A 1%–2% market share in selected global markets implies a potential increase in revenues of 18–75 billion euros per annum in the four selected countries by 2030. This corresponds to 10%–43% of the production value of forest industries in 2016 and compares with a projected decline of graphic paper industry revenue of 5.5 billion euros by 2030. The respective impacts on wood use are manifold, as many of the new products utilize by-products as feedstock. The increase in primary wood use, which is almost entirely attributed to construction and to some extent textiles markets, would be in the range of 15–133 million m^3, corresponding to 2%–21% of the current industrial roundwood use in the selected countries.

Key words: bioeconomy, competitiveness, forest industry, new wood-based products, value chain.

Résumé : Cette étude identifie de nouveaux produits à base de bois ayant un grand potentiel de développement ainsi que des marchés attrayants, tels que les textiles, les biocarburants liquides, les produits chimiques porteurs, les plastiques et les emballages. Nous avons utilisé une revue des méthodes mixtes pour analyser comment la position de l'industrie forestière dans une chaîne de valeur donnée détermine la production de valeur pour les produits sélectionnés. On présente une évaluation des chances que ces nouveaux produits puissent compenser le déclin envisagé dans le marché du papier graphique dans quatre principaux pays producteurs de bois : les États-Unis, le Canada, la Suède et la Finlande. Une augmentation de 1 à 2 % des parts de marché dans des secteurs précis représente un gain potentiel de revenus de 18 à 75 milliards d'euros par année d'ici 2030, et ce pour les quatre pays. Cela représente 10 à 43 % de la valeur de la production des industries forestières en 2016 comparativement à une diminution projetée des revenus de 5,5 milliards d'euros pour l'industrie du papier graphique d'ici 2030. Les impacts respectifs sur l'utilisation du bois sont nombreux, puisque plusieurs de ces nouveaux produits utilisent des sous-produits du bois comme matière première. L'augmentation de l'utilisation primaire du bois, qui est presque entièrement attribuable à la construction et jusqu'à un certain point aux marchés du textile, représenterait 15 à 133 milliards m^3, ce qui représente 2 à 21 % de l'utilisation actuelle du bois pour la transformation industrielle dans les pays sélectionnés. [Traduit par la Rédaction]

Mots-clés : bioéconomie, compétitivité, industrie forestière, nouveaux produits du bois, chaîne de valeur.

1. Introduction

The 17 global sustainable development goals (United Nations (UN) 2015*a*) and the Paris climate agreement (UN 2015*b*) set internationally recognized goals that require transforming towards more sustainable business practices. Avoiding adverse long-term impacts requires industries to guarantee that investments are in line with these internationally recognized goals (Hetemäki et al. 2017). At the same time, the industrial use of wood biomass is expected to become increasingly diversified (Confederation of European Paper Industries (CEPI) 2011). Due to stagnating or declining graphic paper markets (Johnston 2016), forest industries strive to expand their scope beyond paper and other established products, as well as towards new geographic markets (Export Development Canada (EDC) 2017). In this expansion, innovation plays an important role (Hansen et al. 2018).

Innovation can take the shape of a new or significantly improved product, process, marketing method, or business practice (Organisation for Economic Co-operation and Development (OECD) 2005). New wood-based products may result from any of these changes (Cai et al. 2013). For example, aiming to increase the value added from an existing feedstock flow can be achieved by developing alternative products (product innovation) or production processes (process innovation) or by moving downstream in the existing value chains (organizational innovation). Not only may

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Table 1. Production of main forest products in 2016 with comparison to 2000 (source: FAOSTAT).

	USA	Canada	Sweden	Finland	Total	Change since 2000	% of world 2016
Sawnwood, Mm^3	78	50	18	11	157	–14	34
Wood-based panels, Mm^3	35	14	1	1	50	–14	12
Wood pulp, Mt	50	17	12	11	89	–19	50
Dissolving wood pulp, Mt	1.1	0.5	0.5	0.4	2.6	+1.3	40
Paper and paperboard, Mt	72	10	10	10	102	–29	25
Graphic papers, Mt	16	6	4	6	31	–29	25
Packaging paper and paperboard, Mt	47	3	6	4	61	+1.7	26
Industrial roundwood, Mm^3	357	158	67	54	636	–91	34

changes in the business environment provide any of the previous opportunities, they could also allow more effective marketing (marketing innovation) (Gupta et al. 2016). Thus, in this study, the term "new wood-based products" is seen to encompass all "new" products, regardless of whether the products themselves are novel, the products utilize novel technologies, or the changes in the operating environment increase demand for established products, e.g., digitalization and environmental regulation increasing the demand for wood-based packaging materials.

The most significant emerging wood-based product markets are expected to be construction, textiles, chemicals (including polymers), biofuels, and a number of small upstream niche markets such as cosmetics, food additives, and pharmaceuticals (Näyhä et al. 2014; Natural Resources Canada 2017). With the new products, industry boundaries are becoming increasingly indistinguishable as chemical, energy, and forest industries to a certain degree use the same feedstocks and develop products for the same markets (Jonsson et al. 2017). Entirely new value chains are also feasible.

The gross value added of the forest industry has declined by 35% in North America and by 20% in western Europe between 2000 and 2011 (Lebedys and Li 2014). Moreover, long-term projections suggest that while the global demand for most forest products is expected to continue growing, owing to economic and demographic growth, it may increase the demand proportionately more for lower added value packaging materials compared with higher added value paper products (Pöyry Inc. 2015). This is somewhat at odds with the objectives of bioeconomic strategies, which tend to emphasize the role of high added value products and services (Bioökonomierat 2015). Conclusions drawn from these trends and projections, however, carry a risk of omitting the value creation potential embedded in the possible diffusion of new wood-based products.

Research in the field of new wood-based products has mostly addressed the question of what can be made of lignocellulosic biomass, while questions of which (intermediate) products will be produced, how much, where, for what reasons, and with what (environmental) consequences have gained less attention (Hetemäki and Hurmekoski 2016; Korhonen et al. 2018). Previous assessments of the hypothetical market potential of new wood-based products are focused on bio-based substitutes for fossil oil derivatives (Schipfer et al. 2017), biorefining (Näyhä and Pesonen 2014), bio-based chemicals, polymers, and fibers (Nattrass et al. 2016), construction products (Hildebrandt et al. 2017), and highly diverse novel wood-based products and production technologies based on, e.g., nanocellulose and lignin (Cai et al. 2013; Shatkin et al. 2014). A few studies examine the potential impacts of emerging products on the forest sector, at least in the context of second-generation biofuels (Trømborg et al. 2013; Kallio et al. 2018) and construction (Eriksson et al. 2012). Kruus and Hakala (2017) and Graichen et al. (2017) represent another stream of literature highlighting the results of the research and development work by specific industrial research institutes. Strategic innovation and research agendas also touch upon the topic (Bio-based Industries Consortium (BIC) 2013); however, holistic studies on the possible role of new products in the transformation of the forest industry are scarce (Antikainen et al. 2017), and those assessing the simultaneous impacts of a wide array of new products under a single framework seem to be missing entirely. In response, this study provides an overall assessment of the possible scope and implications of new wood-based products in the context of established forest industries.

To this aim, we set out to (*i*) identify new wood-based products with considerable potential and attractive markets based on explicit criteria and to evaluate salient factors affecting their market potential, (*ii*) outline corresponding value chains, and (*iii*) build an understanding as to the extent that these products can compensate for maturing core business areas (particularly graphic papers). This is done by deriving quantitative estimates for a possible range of impacts of new product diffusion on industry revenue and the demand for woody biomass.

2. Methods and data

2.1. Scope

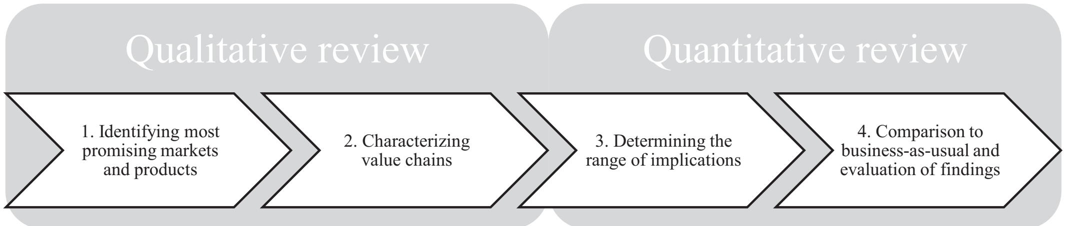
The geographical scope of the study needs to be limited due to the contingency of resources on a given institutional environment in which firms operate (Fuentelsaz et al. 2015) such as the availability of cascaded biomass resources from a sawmill to a biorefinery (Purkus et al. 2018). As such, this study takes the perspective of the four major forest industry countries — USA, Canada, Sweden, and Finland. Each of these countries has a long history of important forest industry sectors, based on domestic forest resources and to a significant extent relying on northern bleached softwood kraft (NBSK) pulp and paper production. Their forest industries are also facing very similar structural changes (Hetemäki et al. 2013; Näyhä and Pesonen 2014) in that these countries have been the main global producers of graphic paper and are actively seeking new businesses to replace the loss of turnover resulting from declining graphic paper demand. For this reason, biorefineries in this region are likely to rely on lignocellulose feedstocks. While keeping in mind that the comparison of volumes across time is highly sensitive to the years selected, in 2016, these four countries together produced 50% of the global wood pulp and 33% of the sawnwood (see Table 1).

We adopt 2030 as the time horizon for this study. This allows a long enough time span for markets to adapt to changing demand, yet restricts the analysis exclusively to new products that are already in the market or soon to be introduced to the market, which reduces the uncertainty of the analysis. Furthermore, the year 2030 is a common threshold for current bioeconomy agendas as set by international organizations (e.g., European Commission (EC) 2012).

2.2. Mixed-methods review process

This study applies a mixed-methods review process (Grant and Booth 2009). A mixed-methods review can refer to any combination of methods in which at least one of the components is a

Fig. 1. Review process.



literature review and where the aim is to collect and analyze data, integrate the findings, and draw inferences using both qualitative and quantitative approaches in a single study (Grant and Booth 2009). Synthesizing the insights of different types of data into a cohesive picture provides a broader understanding compared with using a single method or data source (Johnson and Onwuegbuzie 2004; Tashakkori and Creswell 2007). The mixed-methods review process, as implemented in this study, involves four interlinked steps (Fig. 1).

2.2.1. Selection of markets and products

The first step was to identify the most significant new wood-based products markets in terms of value and volume. Literature unanimously considers textiles (Food and Agriculture Organization for the United Nations (FAO) 2016; Antikainen et al. 2017), construction (ibid.), biochemicals (Nattrass et al. 2016; ECORYS 2017), biofuels (ibid.), and packaging and plastics (Aeschelmann and Carus 2015; Carus et al. 2016) as the most promising markets for emerging wood-based products. All of these generic markets were included in the analysis. Due to a staggering number of possible combinations of end uses, intermediates and end products, conversion pathways, and feedstocks for new wood-based products, it became necessary to further select specific products and technologies to allow quantitative assessment of the diffusion of new products (production volume and revenue and wood use) and to maintain a manageable range for the analysis.

To identify individual representative products and technologies, we made use of more technically explicit literature and current investment plans. We also considered activities of the main developers of new wood-based product technology in this sector, namely, VTT in Finland, Innventia in Sweden, FPInnovations in Canada, and the Forest Products Laboratory of the U.S. Department of Agriculture. Here, we also consulted one or two industry experts per country in unstructured face-to-face and teleconference meetings. Open-ended questions enquired into the extent of innovation activities related to wood-based industries in the given region and which new products or technologies in the area are considered to have the largest potential. The aim of these meetings was to validate the overall picture on new product development that was attained by screening the official information sources of the institutions and in various media and seminars. As such, the outcomes of these brief interactions are not reported in detail.

Market potential is a function of various demand side (market pull) and supply side (technology push) factors (Lee and Geum 2017). In striving for improved validity and reliability of the product selection process, a number of criteria were used to guide the selection based on the analytical framework of the study, previous market studies, and discussions among the authors and with the external industry informants. The most important single indicator was the technology readiness level (TRL). For a product or technology to qualify for further analysis, it needed to be at least in the pilot scale (TRL ≥ 6) because successfully reaching TRL8 from TRL5 could take, depending on the product, around 10 years even in a supportive policy environment (Taylor et al. 2015). The TRL scores have been identified through literature (Taylor et al. 2015; Biddy et al. 2016; Kruus and Hakala 2017), although in principle, TRL may also be judged based on the commonly agreed scale and thresholds (EC 2017). TRL is also the only clearly measurable indicator, while others serve as more general guidelines. The following criteria were considered in the selection of products:

- TRL score of at least 6 out of 9; time-to-market of less than 5 years;
- volume potential;
- feedstock availability;
- market attractiveness (competition and competitiveness);
- cost competitiveness; and
- sustainability aspects.

Despite the explicit selection criteria, the selection process may not be entirely repeatable due to lack of information, the wide array of alternatives, and the consequent need for applying judgment. For example, cross-laminated timber (CLT) was chosen over glue-laminated timber (glulam) because of the former's significantly higher growth rate during the past decade despite the financial downturn (Espinoza et al. 2015). However, in terms of the drivers, unit values, or the position in the value chain, it does not make a large difference which one of such products is selected. The same logic applies for all selected and excluded products. The assumptions were somewhat relaxed in reference to chemicals markets due to their complexity and uncertainty. Many of the identified platform chemicals clearly exceed the TRL threshold for biomass feedstocks, but the TRL specifically for lignocellulosic feedstocks is often not explicitly stated and may only be close to reaching the threshold soon.

2.2.2. Characterization of value chains

The second step was to create an understanding of the value chain organization for the selected products. The importance of value chain characterization is heightened by determining the possible implications of the new product diffusion on the businesses, as the unit value of a good is directly linked to the assumed position of the firm in a given value chain.

A comprehensive evaluation of a given product requires understanding the entire pathway from forests to customers (end users or industry customers) (Wang 2015), not just the production sector and conversion technologies (Olson 2014). A specific function of value chain analysis is to diagnose the appropriate position of a firm in a value chain (Wang 2015). Jernström et al. (2017) outline the stages of a value chain where the renewal can happen: raw material supply, intermediate or semi-finished products, end products, finished products or whole value-chain management. While forest industries typically position themselves as raw material suppliers (Antikainen et al. 2017), some of the new business opportunities may require firms to move away from traditional industry practices and their current position in the value chain (Wang 2015). The further downstream in a value chain the organization is positioned, the more value added is typically created (Ali-Yrkkö and Rouvinen 2013). The analysis of value chains is entirely based on literature. Some of the propositions such as the role of the industries in the respective value chains are assump-

Table 2. Key variables and data sources for determining quantitative implications.

Parameter	Data source
Overall market volume in 2030, or current market size and annual compound growth rate	Various literature sources (see Supplementary Table S1[1])
Market share of wood-based products CAN + FIN + SWE + USA	Intersectoral market share based on (Piotrowski et al. 2015); international market share based on FAOSTAT
Unit value (€·t^{-1})	Weighted 5-year (2012–2016) averages of import and export nominal value and volume flows with SITC rev4 3-digit codes using Finnish customs data (ULJAS 2017); for missing data and for benchmarking, also various literature sources
Roundwood equivalent (RWE) coefficients Biomass utilization efficiency (BUE) coefficients Input–output coefficients	UNECE/FAO (2010), Iffland et al. (2015), patent data, investment plan data, personal communications, and various literature sources

tions; although they can be supported by evidence, they do not portray the entire scope of possibilities created by innovations not included in the review.

In characterizing the value chains, the following questions were emphasized (modified from Wang 2015).

- Which products and production technologies have the largest potential in the respective value chains?
- Which target markets does the value chain in question serve, and what do the wood-based products substitute?
- Which factors in the operating environment hinder or support value chain development?
- What are the main competing innovations?
- What are the product characteristics that each target market seeks?
- What are the comparative advantages of the value chain in question?
- What is the likely or possible role of the forest industries in the respective value chain?
- What are the pathways from source to each end market?

2.2.3. Determining the range of implications and benchmarking of findings

As the third step of the review process, we connected the qualitative review into an assessment of the potential implications of wood-based products entering the global markets, based on existing statistical data and projections and additional spreadsheet computations. The key variables in the calculations, as well as their data sources, are outlined in Table 2. Product-specific assumptions, data sources, and exact computations are detailed in the Supplementary material[1]. Generally, the computations were produced based on the following logic, modified from WEASTRA (2012).

1. To estimate the production volume of a product in the selected countries in 2030, data and assumptions are required as to the size and growth rate of the overall market, the share of wood products of the market, and the share of the four countries of the market.
2. Many of the products included in the review can be assumed to be produced from by-products. If the hypothetical production volumes are constrained by estimated by-product availability, contingent upon produced quantity of the main product, data on the availability of by-products (output coefficient for the main product) and biomass utilization efficiency of the product in question are additionally required.
3. To estimate the production value, data on unit values (prices) are required.
4. To estimate the demand for woody biomass, data on the efficiency of roundwood conversion (roundwood equivalent) or biomass utilization efficiency are required.

When deriving demand estimates, one needs to consider both (*i*) the market volume development of the products to be substituted and (*ii*) the competitiveness of the wood-based products compared with substitute products and other regions. If point estimates or market growth rates for the overall market size in 2030 were missing, we used the annual global growth rates determined by Piotrowski et al. (2015): 3.5% for chemicals and plastics, 3% for textiles, and 1%–2% for other products. Taking the transition scenarios in Piotrowski et al. (2015) as a baseline, we assume a 10% increase in the bio-based product market share in 2030. We additionally assume that wood-based products could cover up to half of the bio-based markets — thus, in cases of missing or inconsistent estimates for market shares, we assume an apparent increase in the global market share of wood-based products that corresponds to 5% of the global market by 2030. This translates to less than doubling the market share in the textile and construction markets, while for most chemicals and other novel wood-based products, this would roughly equal the market share by 2030[2]. Regarding international competitiveness, the market share of the selected four countries has been assumed to be consistent with the shares of current major wood-based products (e.g., sawnwood for construction, pulp for textiles) and, in the absence of a clear benchmark, 25% of the global total market, corresponding to the market share of the four countries in graphic paper production. Together these assumptions, considering both the sectoral and international market shares, would imply a market share of around 1%–2% of the total global market for the forest industries of the four selected countries (Table 3).

Rather than deriving single-point estimates, a range of estimates was produced by providing minimum and maximum values, when available, for those variables involving the most uncertainty. The results are more reliable for products that have some prior data and for which clear substitute products exist

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2018-0116.

[2]While there are no exact data on the market share of wood construction, Hildebrandt et al. (2017) argue that it remains globally still below 10%. It varies significantly, however, from one region to another, with the share in northern Europe and in North America being above 80% in small-scale construction. The share of man-made cellulosic fibers was 7% of the total textile market in 2015 (Comité International de la Rayonne et des Fibres Synthétiques (CIRFS) 2018). In other markets, the share is assumed to be near zero for products derived from woody biomass in the mid-2010s.

Table 3. Market share assumptions for different product categories.

Market	Assumed market share of wood-based products (A), %	Assumed market share of four countries (benchmark) (B), %	Assumed market share of the global total market (A × B), %
Textiles	5.0	40 (dissolving pulp)	2.00
Construction	5.0	34 (sawnwood)	1.70
Fuels	3.6 (EU mandate for advanced biofuels)	25 (graphic papers)	0.90
Chemicals	5.0	25 (graphic papers)	1.25
Packaging	5.0	26 (packaging and paperboard)	1.30
Wood–plastic composites	100.0	26 (packaging and paperboard)	26.00

compared with novel products with no price data or volume estimates. It should be emphasized that the quantitative ranges serve to create an understanding of the possible scale of the diffuse impacts and should not be regarded as forecasts as such.

The final stage of the scenario process was to benchmark the quantitative estimates to the existing industry and its assumed business-as-usual development. To provide a reference outlook for the traditional products, trend forecasts for pulp, paper, and sawnwood production were computed based on data from FAOSTAT and growth rates suggested in literature.

3. Results

3.1. New wood-based value chains

Literature indicates that the most promising markets for emerging wood-based products are textiles and construction (FAO 2016; Antikainen et al. 2017), biochemicals and biofuels (Nattrass et al. 2016; ECORYS 2017), and packaging and plastics (Aeschelmann and Carus 2015; Carus et al. 2016). Table 4 shows the selected products and technologies associated with these key markets.

While the value chains differ significantly from each other in terms of raw material consumption, as well as their length and complexity, the assumed role of the forest industries is tilted towards the upstream of the value chains. In the following sections, the value chains are characterized further, following the guiding questions based on Wang (2015). Figures 2–6 and Appendix Table A1 summarize the findings.

3.1.1. Textiles

The textile industry is one of the world's largest industrial sectors in terms of volume, with rapidly growing global demand driven by increases in population and average income (Antikainen et al. 2017). The global market is dominated by synthetic fibers (mainly polyester) with a 69% market share, followed by cotton (23%), and man-made cellulosic fibers (MMCF) (7%) (Comité International de la Rayonne et des Fibres Synthétiques (CIRFS) 2018). Nordic countries produce dissolving pulp, an intermediate product for MMCF, mainly for export. The MMCF market is dominated by viscose with a 96% share (Vehviläinen 2015). Contemporary viscose was introduced in the late 19th century; new MMCF processes based on alternative solvents aim to replace this (Vehviläinen 2015).

Wood-based fibers are closer substitutes for cotton than for synthetic fibers, in terms of both technical properties and production processes. Some studies recognize a potential "cellulose gap" in global textile markets (e.g., Chen et al. 2016), referring to stagnating cotton production. This stagnation originates from competition for land between food crop and cotton production, the intensive use of increasingly scarce freshwater resources for irrigation in arid regions, and the use of pesticides (Hammerle 2011).

Some of the potential rivals for MMCF include bio-based polyester (Alkhagen et al. 2015), functional and antibacterial textiles (Manda et al. 2015), or novel innovations such as textiles made from spider web or fermented tea. In a more distant future and in niche markets, smart fabrics are expected to communicate, transform, and conduct energy, resulting in, for example, drug-

Table 4. Selected new wood-based products.

Market	Selected products
Construction	Lignin as concrete admixture Cross-laminated timber (CLT) Industrially prefabricated modular elements
Textiles	Spinnova IONCELL-F
Fuels	Renewable diesel based on tall oil Ethanol based on sawdust
Platform chemicals	Lactic acid Furfural 1,4-butanediol (BDO) Succinic acid Ethylene
Plastics and packaging	Flexible plastic packaging (e.g., Paptic) Rigid plastic packaging (e.g., SULAPAC, ARBOFORM) Wood–plastic composites (WPC)

releasing medical textiles and fabrics with moisturizer, perfume, and anti-aging properties (e.g., Singh et al. 2012).

Besides the possible advantageous environmental profile of the new MMCF processes, the key comparative advantages of wood-based fibers relate to the availability of the feedstock material compared with cotton and, in the long-term, with oil production. Technically, the main advantages of cellulosic fibers (including cotton) over synthetic oil-based fibers are high hydrophilicity and breathability, i.e., efficient moisture wicking properties that improve the comfort of the textile on the skin (Hammerle 2011). The main disadvantages of viscose relate to shrinkage, wrinkling, and wet tenacity (Shen et al. 2010). According to Michud et al. (2016), the main achievements of the new solvent technologies for dissolving pulp compared with contemporary viscose relate particularly to the tensile strength and water absorption capacity, in addition to the use of nonhazardous and recyclable chemicals.

Shen et al. (2010) argue that all MMCFs have better environmental profiles than the main competing products. However, contemporary viscose production in Asia based on (eucalyptus) market pulp may also have adverse environmental impacts related to embodied energy and carbon. New wood-based regenerative fibres may be able to overcome the disadvantages of contemporary viscose and thereby achieve uncompromised environmental gains (Judl et al. 2016). Similar to construction, most emissions during the life cycle of a textile are caused in the use phase, due to washing, which is affected by laundry temperatures (Manda et al. 2015).

The textile value chains are typically long and complex, while the use time of textiles is relatively short due to low pricing and fast fashion cycles (Antikainen et al. 2017). The industry is further characterized by a high share of labor costs (Antikainen et al. 2017). The unit value of production could be 10 times higher if the firms were also responsible for the design and manufacture of textiles up to garments (Fig. 7). The textile value chain further serves as an example of how the diminishing industry boundaries may manifest themselves in practice. For example, the Spinnova

Fig. 2. Overview of the selected products.

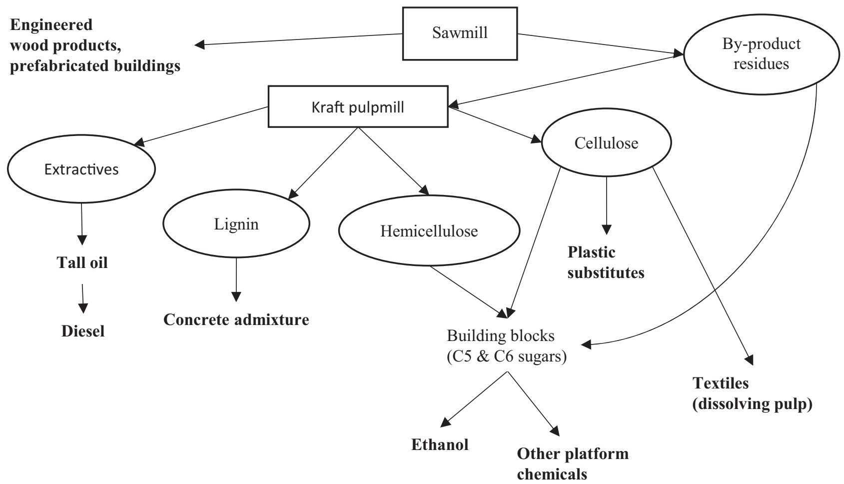


Fig. 3. Textile value chain.

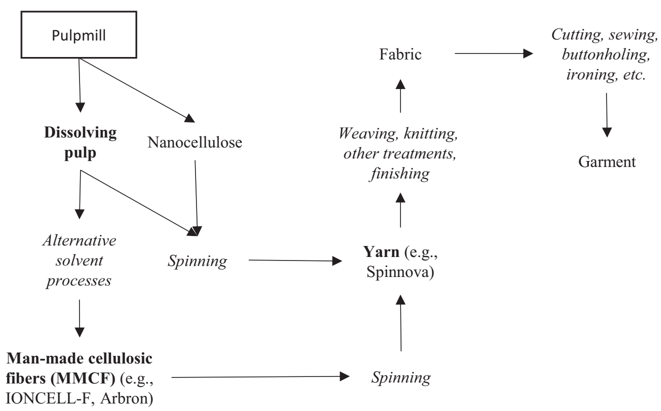
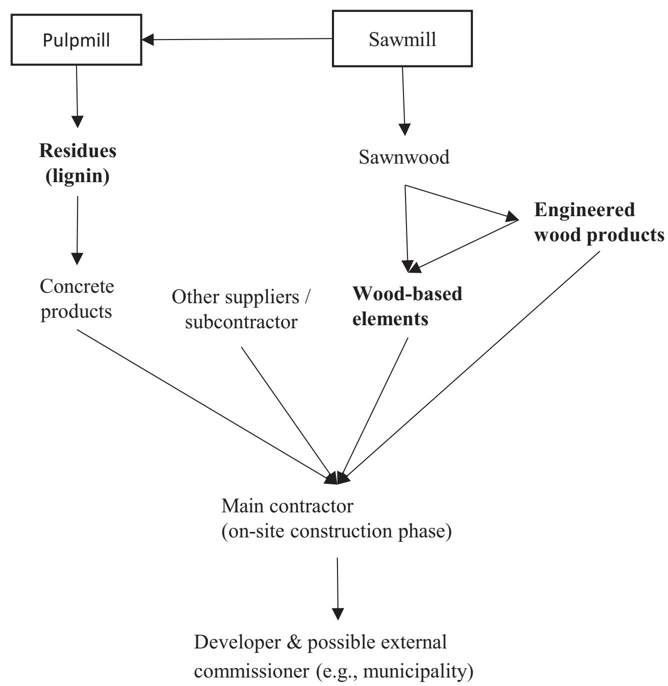


Fig. 4. Construction value chain.



process positions the firm as a part of the textile sector, as opposed to a raw material supplier (Fig. 3).

3.1.2. Construction

Wood-based construction is an important driver for raw material availability for pulp and paper and for emerging industries, as sawmilling generates raw materials for these industries (wood chips, bark, sawdust, and forest residues). Research literature suggests an almost unanimously positive outlook for modern wood construction (Hurmekoski 2016). Wood has traditionally been used to build single-family homes. However, the move towards industrial prefabrication and standardization of wood construction in Europe and North America has made it more straightforward to utilize wood in large-scale construction as well. Industrial prefabrication refers to a shift from on-site construction to off-site manufacturing of elements and components, i.e., combining several work phases in a single off-site location, which can result in productivity benefits (Malmgren 2014). Engineered wood products (EWP) that have emerged over the last few decades further enhance the competitiveness of wood in multistorey buildings and industrial halls (Bühlmann and Schuler 2013; Hildebrandt et al. 2017). EWPs can thus directly compete with steel and concrete due to their more homogeneous technical properties in terms of loadbearing capacity and dimensional stability as compared with sawnwood.

The possible uptake of environmentally stricter national regulation driven by, for example, the voluntary EU LEVELs framework and the Biopreferred Products policy in the USA or supportive measures favoring wood in public procurement in the building sector may also further the uptake of wood construction (Toppinen et al. 2018). Yet the fragmented, culture-dependent and risk-averse nature of the construction sector may prevent radical changes globally in a time scale of a decade or two (FAO 2016; Hurmekoski 2016). The structural inertia of the construction sector arises from existing norms and institutions, investments in the existing infrastructure, expertise, capital-intensive machinery, and the large number of loosely coupled small actors in the construction value chain (Mahapatra and Gustavsson 2008). This makes the actors in the value chain unwilling to accept new practices that potentially could cause extra work and associated costs in the short run (Arora et al. 2014).

Construction markets are strictly regulated, as well as influenced by tradition, culture, and the availability of local resources. In this highly established market, cost competitiveness is a major driver. Due to the complexity of products and production processes, it may be even more important to guarantee a low-risk investment with as few possible financial and technical hazards as possible. Consequently, innovation uptake and the resulting pro-

Fig. 5. Platform chemical and biofuel value chains (dashed line refers to processes that could be relevant past 2030).

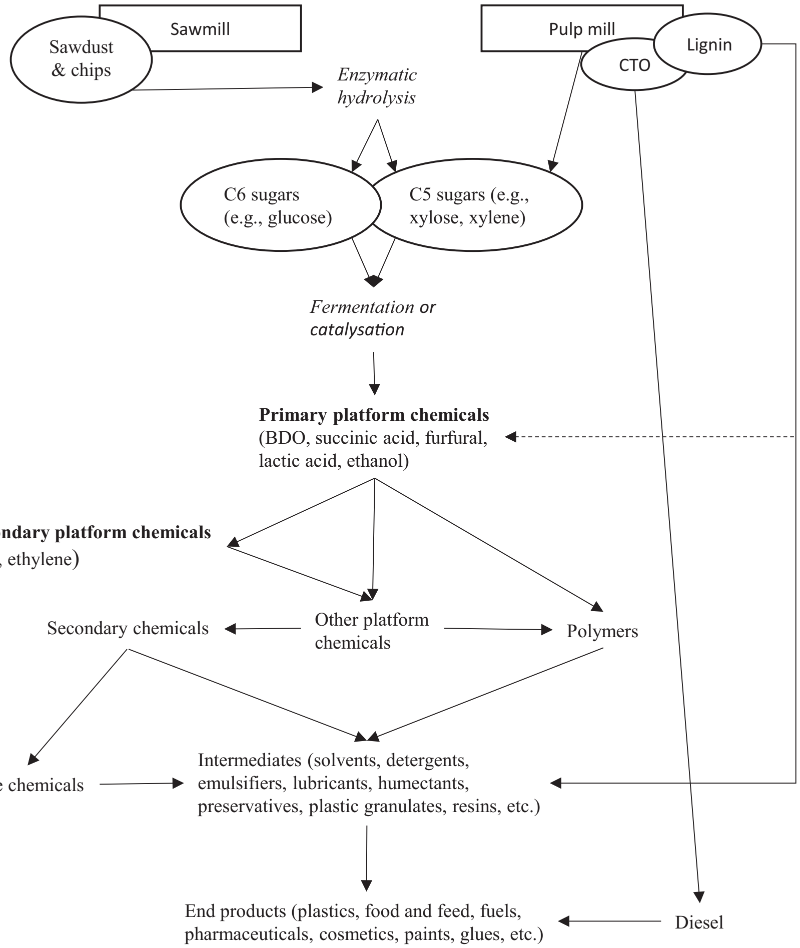
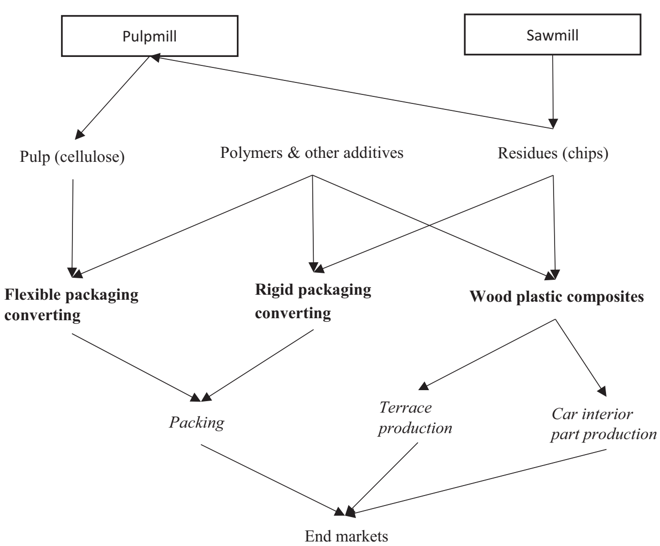


Fig. 6. Plastics and packaging value chain.



ductivity growth have been fairly low in construction compared with other sectors.

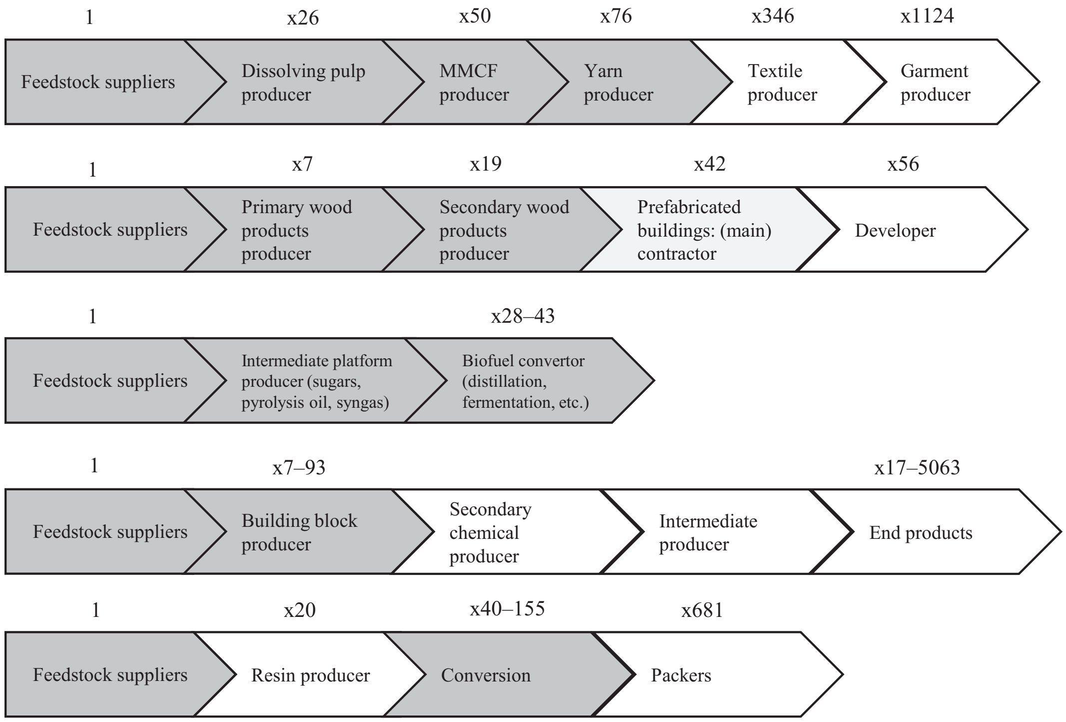
According to meta-analyses (e.g., Sathre and O'Connor 2010), research literature almost invariably concludes that wood-based construction practices cause less environmental burden compared with the main alternatives, although depending on the assumptions, the difference in terms of CO_2 emissions can be rather small towards the end of the life cycle. However, such comparisons may be influenced by a possible uptake of competing innovations. For example, molten salt chemistry has been reported to allow zero CO_2 emission in calcination and at lower projected cost than the existing cement industry process (Licht et al. 2012).

In the construction sector, industrial prefabrication allows wood-product suppliers to move further downstream in the construction value chain by combining several subcontractor phases on the same assembly line. The modular building element suppliers can act as the main contractor, as is typically the case in Sweden (Fig. 4). As the path dependencies of the sector are plausibly preventing major diffusion of industrial prefabrication practices in the short to medium terms, one relevant option for integrating forest-based and construction value chains is to use wood industry by-products such as lignin as an admixture for concrete, which reduces the need for cement and water in concrete (Kruus and Hakala 2017). Using solid wood products as structural frame material to replace concrete and using lignin as a concrete admixture are not mutually exclusive pathways.

3.1.3. Biochemicals

The growth rate of the global bio-based chemicals market in the period 2009–2015 was estimated at 5.3% (Natural Resources Canada 2016). There has been a shift from technology push led by major chemical companies to market pull created by leading consumer brands such as P&G, IKEA, LEGO, and the Coca Cola Company, which have set specific targets on replacing fossil-based

Fig. 7. Relative value created in each step of the respective value chains compared with logs (construction) or pulpwood (the rest). The scores are indicated above the boxes and the assumed position of forest industries is indicated in grey.



chemicals with more sustainable alternatives (Biddy et al. 2016). Regardless, the markets for biochemicals remain largely uncharted, which is at least partly due to their sheer complexity arising from the large number of possible combinations of feedstock, pretreatment options, sugars, conversion technologies, and downstream processes (Taylor et al. 2015). Here, we adopt the categorization of bio-based chemicals used by Carus et al. (2017):

(*i*) bio-based drop-in chemicals such as ethylene and propylene that are chemically identical to existing fossil-based chemicals with established markets;

(*ii*) smart drop-in chemicals refer to a special subgroup of drop-in chemicals such as 1,4-butanediol (BDO) and succinic acid whose bio-based pathways provide advantages compared with the conventional petrochemical pathways, notably a comparably high biomass utilization efficiency, low embodied energy, noncomplex pathway, or low toxicity; and

(*iii*) dedicated bio-based chemicals such as lactic acid that do not have an identical fossil-based counterpart may offer unique and superior properties unattainable with fossil-based products.

The selected chemicals are platform chemicals that are used to produce a large variety of downstream chemicals and end-use products by other actors in the chemicals value network. Drop-in bio-based chemicals may have an easier access to markets compared with dedicated chemicals as they avoid the extensive and time-consuming validation of technical properties required for the commercialization of dedicated chemicals (de Jong et al. 2012). However, the competitiveness of drop-in chemicals is weakened by comparably high running and investment costs (Kruus and Hakala 2017). That is, the bio-based counterparts would need to compete against petrochemical processes optimized for decades with investments that may already have been amortized (Carus et al. 2016). Lignocellulosic feedstocks also require a larger number of processing steps (pretreatment and enzymatic hydrolysis) than sugar crops, so both the operating and investment costs are bound to be higher. The relative prices may be affected by policy incentives for second-generation biorefining, as well as increasing prices for oil and CO_2.

Dornburg et al. (2008) identify ethylene (typically refined further to polyethylene) as the most important bio-based platform chemical. While the above arguments do not support the selection of bio-based ethylene, the matter is more complex, as ethylene production could fit in the overall product portfolio of lignocellulose biorefineries if certain parts of the feedstock had no use otherwise (Vis et al. 2016). That is, a biorefinery needs to produce a spectrum of products to ensure profitability and to aim for zero waste generation (de Jong et al. 2012). It is also worth considering that ethylene is the largest of the currently produced petrochemicals by volume. If there is a price premium for bio-sourced ethylene, even a minute share of the global market could have a significant impact on the profitability of a Nordic biorefinery.

Rather than competing primarily with petrochemicals, wood-based chemicals are seen to mostly compete with biochemicals made from first-generation feedstocks and other second-generation feedstocks, which results in fairly low volume estimates. The sugars produced in lignocellulosic biorefineries for fermentation processes are much more expensive compared with sugar from sugar beet or sugar cane (Carus et al. 2016). This cost disadvantage would need to be balanced by a full utilization of lignin, which seems to be feasible only beyond 2030 (Carus et al. 2016). Beyond 2030, completely new forms of competition are also likely to arise such as using CO_2 as a feedstock for the elaboration of platform chemicals (Alper and Orhan 2017).

The main route in the chemical value chain is based on producing acids and alcohols by fermenting monomeric (C5 and C6) sugars contained in sawdust and chips, as well as hemicelluloses from prepulping liquids. Despite superior energy balance and easy scalability for thermochemical routes, the selected chemicals follow mostly biochemical routes, because they provide relatively pure products with high conversion efficiency. In addition, many side products from biochemical routes are also notable platform

Table 5. Implications on revenue and wood use.

	Textiles	Construction	Biofuels	Biochemicals	Plastics and packaging	Total
Production value, billion €	1–6	4–46	4	4	4–15	18–75
Unit values, €·t^{-1}	769–2228	209–2245	815–1250	1000–2725	843–2500	
Sawlog demand, Mm^3		7–117				7–117
Pulpwood demand, Mm^3	7–15				2	8–16
Wood chips and sawdust demand, Mt			27–37	33–45	2	63–85
Lignin demand, Mt		2				2
Tall oil demand, Mt			1			1

chemicals. In contrast, thermochemical routes mainly provide rather heterogeneous mixtures that need further fractionation. Based on current investment plans, we assume that forest-based industries will produce platform chemicals such as lactic acid, while the chemical cluster refines it further to, e.g., polylactic acid and, ultimately, plastic products (Fig. 5).

One essential end use of biochemicals is liquid fuels for transport. The demand for advanced biofuels is chiefly driven by international and national policies. It seems that the demand for biofuels will continue to increase towards 2030, before the electric cars can fully substitute for conventional petrol engines (ECORYS 2017). In particular, for heavy-duty road and maritime transport and aviation, electric engines need to develop significantly to provide practical alternatives. Biofuels can also be biodegradable, nontoxic, and free of aromatics and sulfur (Schipfer et al. 2017). This said, the production of biofuels typically requires complementary production of biochemicals (or selling residues to such uses) to make the business profitable (FitzPatrick et al. 2010).

While the biofuel value chain is comparatively short, unit values remain relatively low in this highly commoditized market. The tall oil based technology route to renewable diesel seems economically competitive compared with the thermochemical route, yet its long-term viability remains somewhat uncertain due to possible changes in the EU climate and energy legislation (Deane and Pye 2018) and particularly due to competition from the established tall oil chemical converters. Also, as a minor by-product flow of kraft pulping, crude tall oil (CTO) volume remains limited by the production of kraft pulp. This is true to some extent also for the production of other fuels and chemicals, which are constrained by the availability of by-product flows from sawmills and pulp mills, although some of the processes may also use forest residues or small-diameter wood. Here, we assume that most of the ethanol produced serves the chemicals market as a precursor to ethylene, while the rest of the ethanol production is used as a petrol mix component.

3.1.4. *Plastics and packaging*

According to Hämäläinen et al. (2011), the largest potential of biochemicals is in polymers, particularly used as building blocks for plastics. The share of bio-based plastics of all plastics was around 0.4% in early 2010s but is expected to reach 5% within 20 years (Byun and Kim 2014). In terms of value, the bioplastics market is expected to reach 4.3–6.7 billion euros in 2030 (Aeschelmann and Carus 2015). The bioplastic market is at least partly driven by the projected quadrupling of plastic markets, which also translates to a fourfold increase in plastic pollution, all other things being equal (World Economic Forum (WEF) 2016). However, achieving production scales over 100 000 tonnes for a plastic with a technical function and complex supply chain takes several decades (de Jong et al. 2012).

Plastics do not seem to be a key business opportunity for the forest-based industries as such. Combined with the technical and economic issues raised for the biochemical market and the likely role of forest industries as a platform chemical provider, it may be that indirect substitute products for the plastic market — plastic-mimicking products using existing industrial infrastructure (Fig. 6) — will have more potential by 2030. Product categories highlighted in the literature in this context include wood–plastic composites (Carus et al. 2015), paper-resembling films for flexible packaging (Kruus and Hakala 2017), and other plastic resembling wood or fiber-mix materials for rigid packaging (Nägele et al. 2002).

As one of the most important downstream sectors of bioplastics, the drivers, competitors, and competitive advantages in the packaging market are similar to the drivers in the biochemical market. Generally, the packaging market is driven by global population and GDP growth, as well as increasing e-commerce and demand for take-away products. Together with the constrained supply in the long term, the increasing polymer prices may lend advantage for the indirect substitute products. In the EU, a further driver will be regulation, with a proposed ban for short-lived plastic products requiring the uptake of alternative materials (EC 2018). Desired product characteristics include at least biodegradability or recyclability, lightness, durability, and product safety. As well as lowering greenhouse gas emissions, plastic substitutes may have the additional benefit of reducing microplastics (WEF 2016).

By producing indirect substitute products for plastic, the forest industries are effectively skipping one step — granulate producer — in the packaging value chain (Fig. 7). Hence, we focus on a number of new wood- or fiber-based materials and wood–plastic composites, which may resemble the properties of plastics and thereby substitute for them. Of the total global plastic market in 2015 (322 million tonnes), 40% ended up in packaging, while up to 70% of bioplastics are used for packaging (PlasticsEurope 2016). Plastics and paper and paperboard each account for around 35% of packaging markets (Neil-Boss and Brooks 2013). The main subsectors in the packaging business include food, healthcare, and cosmetics.

3.2. Implications on revenue and wood use

Subject to the assumptions detailed in Supplementary Table S1[1], these five markets add up to an apparent increase in the revenue stream of the forest industries in the four countries of 18–75 billion euros per annum by 2030 (Table 5). In terms of volume potential, even with relatively cautious assumptions, construction clearly stands out as a key sector due to the unparalleled size of the global construction product markets. The estimated volume only corresponds to 0.1% of the total global concrete market by mass, yet this would require producing up to 40 million m^3 of wood products. Based on an assumed range of mill capacities, in the construction markets, it would take up to 1000 mills per country to fulfill the demand as indicated in Table 5. The large variance for the construction sector is a result of a large difference between the intensity of wood use between a massive frame and a light frame structure, which is further escalated by the larger need for wood material per unit of product for engineered wood products compared with sawnwood. The estimate could possibly be made more realistic by adopting growth curves for the production of engineered wood products to approximate the share of massive frames compared with light frames. For example, Espinoza et al. (2015) indicate a global demand for CLT of a mere 3 million m^3 by

Table 6. Approximate number of mills per sector required to meet the hypothetical demand.

Sector	Assumed mill size	Approximate number of production facilities per country
Textiles	200 000–650 000 t·year^{-1}	1–3
Construction	10 000–450 000 m^3·year^{-1}	2–1000
Biofuels	50 000–500 000 t·year^{-1}	5–50
Chemicals	150 000 t·year^{-1}	5–6
Plastics and packaging	250 000–500 000 t·year^{-1}	1–2
Reduction of graphic paper	500 000 t·year^{-1}	4

Table 7. Estimated by-product availability in the four countries in 2030.

	Value	Unit
BSKP production	47.2	Mt
Lignin availability from pulping	16.0	Mt
Hemicellulose availability from pulping	5.9	Mt
CTO availability (for diesel)	0.94	Mt
Wood products production	83.5–101.9	Mt
By-product availability	76.8–126.2	Mt
Wood chips	58.0–95.3	Mt
Sawdust	18.8–30.8	Mt

Table 8. Forest products production in Canada, Finland, Sweden, and USA in 2016 (source: FAOSTAT).

	Production value, billion €	Production volume, Mt	Production volume, Mm^3
Sawnwood	35	79	157
Wood-based panels	18	25	48
Wood pulp	48	89	
Paper and paperboard	74	102	
Total wood and paper products	175	295	
Graphic papers	20	31	
Industrial roundwood production		318	636

Table 9. Projected development of the graphics paper market in Canada, Finland, Sweden, and USA (source: FAOSTAT; Pöyry Inc. 2015).

	Value	Unit
Production value in 2016	20	billion €
Production volume in 2016	31	Mt
Production in 2030 (assuming –2% per annum)	23.6	Mt
Unit value, graphic paper	718	€·t^{-1}
Wood use, chemical pulp	4.55	m^3·t^{-1}
Estimated reduction in production 2016–2030	7.7	Mt
Reduction in production value 2016–2030	5.5	billion €
Reduction in wood use 2016–2030	35.2	Mm^3

2030. Replacing the purely hypothetical maximum value of around 40 million m^3 by the suggested 3 million m^3 would result in a range of 7–8.7 million m^3 of roundwood, which further translates to 2–85 additional sawmills per country. In comparison, for textiles, the estimated volume appears comparably realistic, if not outright cautious, with only one new pulp mill per country (Table 6).

The spreadsheet calculations suggest an apparent increase in demand for roundwood ranging from 15 to 133 million m^3 (some 2%–21% of current use of industrial roundwood), all other things being equal, mostly owing to increasing sawlog use for engineered wood products (Table 5). These calculations would imply a clear imbalance in the demand for sawlogs and pulpwood. Many of the new products are based on existing by-product flows of sawmilling and pulping industries, so that feedstock supply is to some extent constrained by the demand for and ensuing production of sawnwood and Kraft pulp, unless the pulping industry utilizes sawlogs. Here, the large production volume in the wood products markets would result in generous amounts of by-products made available for the biofuels, biochemicals, and plastics and packaging sectors (Table 7); the wood products sector would, in turn, benefit from the increased demand for these by-products.

Unit value tends to be inversely proportional to volume. Indeed, while some chemicals and packaging products could have comparably high unit values, the biochemicals market, in particular, is expected to be comparably small in volume terms towards 2030. In this sample of products and with the specified assumptions, the overall unit value is relatively uniform (mostly between 1000 and 2000 €·tonne^{-1}), so that the largest volume potential translates to the largest production value potential. Thus, our analysis reveals no silver bullets for multiplying the production value of the industries.

Figure 7 summarizes the value chains and the relative value created vis-à-vis the feedstock material (sawlogs for construction, pulpwood for the rest). The unit value potential would vary significantly from one market to the other, but in a notable scale only if the industries were able or willing to move further downstream in the value chains, ultimately towards brand ownership.

Subject to the hypothetical assumptions, new wood-based products would account for 10%–43% of the production value compared with the current wood products and pulp and paper industries (cf. Table 8). As indicated in Table 9, the production value of graphic paper is estimated to reduce by 5.5 billion euros from 2016 to 2030. Comparing this with Table 5 reveals that almost any of the single selected markets could roughly compensate for the structural change caused by declining graphic paper markets. It is important to note in this context that the graphic paper markets and the development of new wood-based products are interdependent, as the turnover of the graphic paper industry finances the research and development and investments for new products. Thus, for many companies, the target is not to quickly replace graphic paper production with new products, but rather to find a balance between both product categories.

4. Discussion

There is inherent uncertainty in the results, which originates from the necessity to rely, at least partly, on hypothetical assumptions, the large number of steps in the research process, and the extensive scope of the analysis. Already the definition of "new wood-based products" used may influence the results. Most importantly, assumptions regarding the position of the industry in the value chains (and consequently unit values) and the market share of wood-based products (and subsequent volume estimates) have decisive impacts on the results. Another critical uncertainty relates to climate, energy, and land use policies, for example, in deciding the role of bioenergy and biofuels in the desired future energy mix and its multiplicative impacts on the industries.

This review covers but a fraction of the wide array of potential new wood-based products. Despite focusing on more than one market, the selected products together form but one case study, and the results need to be interpreted accordingly. A more comprehensive set of products might have to be incorporated to more specifically judge the possible balance between the deteriorating graphic paper market and the emerging markets. This said, the markets were selected using explicit prioritization criteria and should reflect reasonably well the major new wood-based product opportunities. Also, the unit values may be indicative of the range attainable from each market, as the price levels of the competing products — that the new products need to match — can be expected to change mostly due to business cycles and changes in the price of crude oil or CO_2 emissions in the long run. Despite several explicit assumptions, major uncovered uncertainties remain. For example, the analysis did not consider the quality or purity aspects of the feedstocks for specific applications, which may affect supply constraints, not least through pricing (Sathre and Gustavsson 2009). Moreover, the information sources can be criticized for their bias towards northern Europe, despite efforts to avoid it. Cooperation among technological research facilities across continents reduces the possible bias in this regard.

There are increasing difficulties in defining sectoral boundaries and actors included in forest-based value chains in the future. The established forest industries already portray the whole range from raw material and intermediate product producers (e.g., energy chips, sawnwood, pulp) through high-value intermediate product producers (e.g., graphic papers, RFID labels) to end-product producers and brand managers (many hygiene and tissue papers). However, as noted by Antikainen et al. (2017), the primary strategy in the forest industries has been a "scale efficiency paradigm". Consequently, in the majority of the selected markets, we have assumed the forest industries to play a role as primary or intermediate product suppliers. In principle, it would be possible to move further along the value chain by acquiring established firms from the target sector. Naturally, the opposite could happen as well by, for example, chemical industries acquiring forest-based firms to ensure competitive feedstock supply. Individual firms coming from outside the traditional forest sector may assume roles that differ from the mainstream.

New wood-based product value chains, as presented in this study, can be classified based on upstream and downstream operations. In reference to the upstream operations, most of the value chains depart from that of an existing pulpmill or sawmill (Fig. 2). However, a few processes require stand-alone investments that may originate from outside the traditional forest sector (notably Paptic and Spinnova) or the process may accommodate either of these options (notably platform chemicals). For some value chains (notably platform chemicals), the vicinity of the facility relative to the downstream processing industry may pose extra constraints. In reference to downstream operations, the end uses are determined either in later phases of the processing chains (notably platform chemicals) or already in the initial stages of the value chains (the rest). These classifications display the relative complexity of the chemical value chain, as well as its extensive overlap with the other value chains.

There are few comparable studies available in terms of scope and research problems (e.g., Schipfer et al. 2017). However, the current study supports the finding of Stern et al. (2015) that the limitations for the use of hemicellulose (and extracts) relate to markets rather than technology, while the opposite holds for lignin (Bruijnincx et al. 2016). Even products such as activated lignin for adhesives to substitute phenolic resin show a low technological readiness level, let alone platform or fine chemicals based on the thermochemical conversion of lignin (Kruus and Hakala 2017). Further along the lines of Stern et al. (2015), almost unlimited amounts of hemicelluloses could be used for ethanol and ethylene production, but these highly commoditized markets translate to a low unit value compared with some dedicated biochemicals.

As shown in the calculations, pulping produces significant amounts of prepulping liquids and by-products containing hemicellulose, lignin, and tall oil, while sawmilling produces sawdust, bark, and forest residues. Yet the assumed demand for new wood products may be constrained by the availability of by-products, particularly in the case of tall oil based renewable diesel, but also as regards ethanol and drop-in chemicals (ethylene). Given that most of this by-product flow already has a use for particle board, wood pulp, and wood-based energy production, the available domestic by-product flow may not be sufficient to sustain the production of all new wood-based products. In the case of constrained by-product availability, the market reaction could be one of the following, or a combination thereof: (*i*) the production of new products is lower than what the initial assumptions indicate, e.g., only a few demonstration facilities are operational by 2030; (*ii*) by-products are traded internationally; (*iii*) greater ethanol demand allows greater ability to pay for by-products in the new value chains compared with established uses of by-products, resulting in some displacement of the latter; or (*iv*) roundwood and (or) logging residues are used for ethanol production, either displacing other uses thereof or resulting in the mobilization of extra primary woody biomass.

This study points to several future research priorities. Perhaps most urgently, the assessment of market reactions to the diffusion of new products and the interlinkages between existing and emerging markets should be subjected to economic and physical constraints posed by industry structure, ideally by sectoral modelling. A sectoral model could potentially capture the trickle-down impacts of increased production of new wood-based products on other parts of the forest sector by market adjustments through pricing and international trade. For example, significantly different developments for pulp and sawmilling capacities may pose issues due to integrated pulpwood and log procurement, as biorefinery products can secure the competitiveness of the pulp and paper industry and thereby also the sawmilling industry (Stern et al. 2015). Indeed, modelling could help to resolve the apparent imbalance for pulpwood and log demand. Moreover, sectoral modelling would better allow quantifying the potential impact of the critical uncertainties in the operating environment. Notably, the prices for crude oil and CO_2 directly affect how competitive new wood-based products are compared with the established industries, particularly in the biorefining business (Näyhä and Pesonen 2014).

However, the lack of data intrinsic to emerging products hinders economic forest-sector modelling. Data are simply not available on emerging products to an extent that allows deriving econometric-based demand functions, cost structures, and trade flows similar to those of the established products or even extrapolative exponential or logistic models. As a result, there have been few efforts to comprehensively incorporate new wood-based products in sectoral models. There are, however, alternative ways of approximating emerging products in the models, depending on the position of the given products in the typical product life cycle curve (Hurmekoski and Hetemäki 2013; Hurmekoski and Sjølie 2018).

More generally, a classical probabilistic time series approach based on past observations is not necessarily a valid approach for producing long-term demand estimates, as the circumstances and model assumptions used with the observed data to estimate the model can be structurally different in the future. Thus, one avenue of future research could be to focus on uncertainties of product market development by combining structural change models (Papailias and Dias 2015), Bayesian analysis and forecasting (Freeman and Smith 2011), or integrating time series modelling and expert judgements (Leskinen and Kangas 2001; Hildebrandt et al. 2017). Because of the large number and diversity of markets considered and the large amount of uncertainties involved in the quantitative estimates, this study followed a mixed-methods review process providing both qualitative and quantitative bases for future modelling efforts.

Though out of the scope of our analysis, it is important to factor in the environmental (Myllyviita et al. 2012) and social (Mattila et al. 2018) sustainability implications of the diffusion of new wood-based products, accounting for the expected decarbonization of the economy (Rockström et al. 2017), which is likely to cause the wood-based products to lose much of their environmental advantage against the competitors in the long term. Similarly, while of great interest, it is an exhausting exercise to reliably estimate value added in the absence of comprehensive data (Rosenkranz et al. 2015).

A further important issue is the time horizon, which critically affects the results. By 2030, the forest-based industry is expected to still rely, to a considerable extent, on major traditional pulp and paper value chains — as a result of long investment cycles and the upsurge of recent investments — while a large-scale diffusion of novel wood-based products (with a low technology readiness level) is highly unlikely. When looking further to 2050, one would need to consider also the wide range of novel products and select representative conversion pathways for them, which is speculative. On top of the obvious uncertainties related to competing innovations, many markets are expected to quadruple by 2050. Still, these projections, based on population and GDP growth estimates, may mostly serve to show the unprecedented consequences if no actions are taken to reverse the trends. That is, the longer the time scale is, the more uncertainty there is also for the overall market sizes, in addition to market shares and macroeconomic fluctuations. What lies between the somewhat undramatic outlook towards 2030 and the potentially much bigger changes towards 2050?

5. Conclusions

This study identifies key growth markets and new products for the wood-based industries in the USA, Canada, Sweden, and Finland towards 2030 and contrasts the outlook of those markets to the expected dwindling of the graphic paper industry. The main contributions of this study are that it (*i*) covers as comprehensive a set of new products markets as possible under a single framework, (*ii*) uses explicit criteria for selecting new markets and new products, (*iii*) incorporates value chain analysis to the determination of unit values and possible barriers for the uptake of new products, and (*iv*) provides a quantitative range of implications based on the above.

Construction, textiles, biofuels, platform chemicals, and (plastic) packaging are considered the most important new wood-based markets. Summed up, these markets could result in an increase in revenues of forest industries ranging from 18 to 75 billion euros per annum in the four selected countries by 2030, depending on the product portfolio and the position of the firms in the value chains. This corresponds to 10%–43% of the current production value of forest industries in these four countries. Given a projected decline of global graphic paper industry revenue of 5.5 billion euros by 2030, any of the identified product groups could roughly compensate for this decline by gaining a 1%–2% share of global markets. The contribution of new products could be even greater if the firms are also prepared and equipped to accommodate more downstream operations of, for example, the textile and chemical value chains.

The respective impact on primary wood use is estimated to range from 15 to 133 million m^3, corresponding to 2%–21% of the current industrial roundwood use. Most of the roundwood demand is attributable to the construction markets. As many of the new products are based on the existing by-product flows of the sawmilling and pulping industry, feedstock availability remains constrained by the by-product flows of projected sawnwood and pulp supply. Important synergies between, mainly, wood-based construction on one side and wood-based textiles, biofuels, platform chemicals, and plastics and packaging on the other are apparent. At the same time, many of these emerging markets compete with each other, as well as with energy, wood-based panels, and pulp and paper industries, for the same by-product feedstocks.

The existing products are likely to retain a significant role in 2030, irrespective of the rate of new product diffusion. While the past decade has seen investments in bioenergy, construction, and textiles, a major uptake of new wood-based products remains to be realized. Future developments of traditional large volume forest-based products, let alone emerging ones, are fraught with considerable uncertainty. Consequently, the quantitative estimates presented here are not to be considered forecasts as such, but rather the outcome of "what if" analysis, providing an estimate of the potential scale and a basis for further scrutiny and detail regarding the possible role of emerging wood-based products.

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Appendix A

Appendix Table A1 appears on following pages.

Table A1. Value chain characterization.

	Textiles	Construction	Fuels	Chemicals	Plastics and packaging
Market size in 2030 (*2015*)	130 Mt (*90 Mt*)	28 000 Mt (*21 500 Mt*); 3.16 billion m^2 (*2.24 billion m^2*)	2300 Mt (*2100 Mt*)	600 Mt (*330 Mt*)	130 Mt (72 Mt)
Technologies or products	—New solvents for dissolving pulp, e.g., IONCELL-F —New fiber spinning technologies, e.g., Spinnova	—Engineered wood products (cross-laminated timber, laminated veneer lumber) —Industrially prefabricated construction elements (including modular elements) —Concrete admixtures (lignin)	—Renewable diesel: based on distilling tall oil —Ethanol: based on fermenting sugars (hemicelluloses and celluloses)	—Drop-in substitutes for petrochemicals: ethylene —Smart drop-in substitutes for petrochemicals: succinic acid, BDO —Dedicated bio-based chemicals: lactic acid, furfural	—Wood–plastic composites (WPC): extrusion and injection molding —Pulp-based, paper-resembling films for flexible packaging —Other plastic-resembling wood or wood fiber based materials for rigid packaging
Target markets and substitutes	—Garments —Substituting primarily cotton and possibly polyester	—Residential and nonresidential buildings —Substituting concrete, steel, and established wood construction technologies in the load-bearing frames of buildings	—Energy carrier for transport, particularly long-haul truck transport, maritime transport, and jet fuel —Substituting first-generation biofuels and fossil fuels	—Main downstream markets include plastics, food and feed ingredients, and pharmaceutical industries —Substituting first-generation (starch-based) biochemicals and petrochemicals	—Rigid and flexible plastic substitutes: food, healthcare, and cosmetics packaging, carrier bags —WPC: decking (67%, substituting mostly tropical wood), car interiors (24%, substituting mostly plastics)
Main drivers	—“Cellulose gap” — constrained farming area for cotton due to land competition with food production, coupled with rapid growth in demand for textiles —Large freshwater consumption in cotton irrigation in arid areas	—Efficiency gains in industrial prefabrication —Favorable policies in certain regions	—Climate and energy policies —Crude oil and CO_2 price in the long run	—Major firms targeting renewable feedstocks —Coproduction with biofuels	—Growth in population, GDP, e-commerce, and take-away products —Rising polymer prices —Policies to restrict the use of plastics
Main barriers	—Some of the technical attributes (product properties) of MMCF	—Risk perceptions of key decision makers (CEOs of main contractor and developer firms) —Fragmented and path-dependent industry structure	—Feedstock availability —For many processes, conversion efficiency —Investment and running costs	—REACH and other regulation —Extensive validation required for dedicated compounds —Investment costs —Path dependency of petrochemical industries	—Uncertain legislative environment
Competing innovations	—Cotton recycling technology —Other bio-based fibers, e.g. based on spider web —Functional textiles, e.g., antibacterial, anti-odor, or electric properties	—Low-emission cement —3D printing of recycled concrete and similar	—First- and third-generation fuels —Electric engines —Hydrogen engines	—CO_2 as a feedstock for chemicals —First- and third-generation chemicals	—First- and third-generation bioplastics —Recycled or biodegradable plastics —Natural fibre composites
Desirable product characteristics	—Technical properties: avoiding wrinkles and electricity, good moisture absorption, etc. —Environmental properties: avoiding hazardous chemicals, less pollution, increased recycling, etc.	—No need for major changes in the construction practices —No technical or economic hazards	—Drop in fuel: existing distribution infrastructure and existing car fleet without a need for major modification	—Low cost —Nonhazardous and nontoxic	—WPC: natural feel; easy maintenance —Packaging: biodegradability or recyclability; lightness; product safety
Comparative advantages	—Feedstock availability (compared with virgin cotton) —Ability to convert existing pulp mills to dissolving pulp —Environmental footprint	—Lightness of the material, allowing efficient industrial prefabrication and the resulting productivity benefits —Renewable material	—Policy pull —Does not directly compete with food production —Can be biodegradable, free of aromatics and sulfur, and nontoxic	—Interest towards bio-based alternatives —In smart drop-in and dedicated chemicals, reduced costs, and (or) environmental footprint	—Reduced costs compared with pure plastics —Combination of biodegradability and thermoplasticity
Position of the forest-based firms in the value chain	—Raw material supplier (dissolving pulp) —Textile fiber producer (MMCF) —Yarn producer	—Admixture supplier —Subcontractor (product or element supplier) —Main contractor or developer (managing whole value chain)	—End-product producer	—Primary and secondary platform chemical producer	—Packaging: converter of shopping bags and solid packages —WPC: converter of intermediate–end products
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