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Modelling Bioeconomy Scenario Pathways for the Forest Products Markets with Emerging Lignocellulosic Products

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Abstract: The forest-based sector plays diverse roles among the emerging bio-based industries. The goal of this study is to examine how forest product markets could develop in the face of a growing bioeconomy and which interdependencies occur between traditional and emerging forest-based sectors. Therefore, we analyze the development of dissolving pulp together with lignocellulose-based textile fibres and chemical derivatives in a partial equilibrium model. For this purpose, we extend the product structure of the Global Forest Products Model (GFPM) and analyze three different bioeconomy scenarios from 2015 to 2050. The simulation results show that, in a scenario where the world is changing toward a sustainable bio-economy, wood consumption patterns shift away from fuelwood (−30% by 2050) and classical paper products (−32% by 2050) towards emerging wood-based products. In this context, the dissolving pulp subsector could outpace the continuously shrinking paper pulp subsector by 2050. To develop in this way, the dissolving pulp subsector mainly uses released resources from the decreasing paper pulp production. Simultaneously, wood-based panels are finding increasing application (+196% by 2050) and thus are taking over potential markets for sawn wood, for which production growth remains limited. Our results also show that, until 2050, the production of many wood-based products will take place mainly in Asia instead of North America and Europe.

Keywords: dissolving pulp; forest sector modelling; SSP scenarios; bioeconomy; cellulose textile fibres; global forest product markets

1. Introduction

Today, the shift from a petroleum-based to a more bio-based and sustainable industry is not primarily a matter of the (looming) depletion of fossil resources, but rather the response to demands from an increasingly ecologically conscious society. Among the bio-based resources, lignocellulosic biomass from wood is both an abundant and a very versatile raw material [1]. Wood serves to satisfy many needs of daily life, e.g., as a fuel for power and heating, or as input for the construction, furniture, paperboard, textile, and chemical industries. This lets the forest-based sector play diverse roles in a growing bioeconomy [2]. Former studies have shown that the production of forest products is demand-driven and influenced by technological developments and input demands from wood consuming sectors [3]. Proceeding digitalization decreases the demand for graphic papers at the same as the packaging industry is growing due to increasing online shop sales (the share of packaging paper on total paper production increased from 50% in 2008 to 59% in 2018; [4]). Wood-based panel production catches up to sawn wood production (the production of wood-based panels developed from 178 million t in 2000 to 387 million t in 2015, while the sawn wood production increased from 385 million t to 447 million t in the same time; [4]), and niche products like the ligno-cellulosic textile fibres or chemical derivatives gain more and more importance as substitutes for petro-based products [5]. The climate change debate and associated consequences propel the demand for sustainable forest products [6]. Since wood is a multifunctional raw material, the forest sector faces various and potentially conflicting demands from different traditional and emerging wood-using sectors. At the same time, different industries continuously improve their production efficiency and introduce innovative product developments such as sandwich panels [7] or new product applications based on, e.g., dissolved lignocellulose.

At present, dissolved lignocellulose (hereinafter referred to as dissolving pulp) is mainly used as raw material for the production of lignocellulose-based derivatives and regenerated ligno-cellulosic fibres (during the production process of lignocellulosic textile fibres, derived cellulose is converted into a solid fabric as filaments or staples. Like synthetic fibres, they can be formed into many textures and properties.) [8]. Especially the textile industry is a growing consumer of fibers from regenerated lignocellulose. With increasing global population and income, the global textile fiber demand will also increase further. At present, cotton is the most important natural cellulose fibre for the production of textile fibres [9]. However, future cotton production is likely to slow down due to the limited availability of arable land, its negative environmental impacts, and contribution to GHG emissions [10]. The resulting gap in cellulosic fibre demand may be compensated for by lignocellulosic materials. This, in turn, could result in a significant growth of dissolving pulp demand [11]. In addition to the factors above, an emerging bio-based economy may further drive the demand for more sustainable cellulose chemical derivatives and fibres made from dissolving pulp. Considering the growing economic importance of lignocellulosic products, their inclusion in wood products market modelling seems to be important in order to analyze raw material allocation and intra-sectoral developments adequately. This step extends scientific computer-based equilibrium analysis and thus, foster well-informed decision making and policy advice.

In the light of the above, the goal of this study is to examine how forest product markets could develop in face of alternative bioeconomy scenarios, and the effects of the emergence of new—and maybe competing—values of wood in global forest product markets. Until now, no studies have been available investigating scenarios which include lignocellulosic materials from dissolving pulp in global forest product market modelling. Therefore, we embed the development of dissolving pulp, lignocellulosic chemical derivatives, and textile fibres within the context of a partial equilibrium model for wood product markets. This methodological enhancement makes it possible to model and analyze the interdependencies that may occur between traditional and emerging forest-based sectors within the transition of a petrol-based economy to a more sustainable bio-based economy.

This study is structured as follows: first, the modelling framework is illustrated with a short description of the applied model. Thereafter, the bioeconomy scenarios used for this study are introduced and the integration of emerging lignocellulose-based products into the model framework is described. Then, the results are presented and discussed. Finally, the main findings are summarized, and future research tasks outlined.

2. Materials and Methods

The use of economic equilibrium models is of great benefit to show long term interdependencies between economic, social, and technical developments, which humans can hardly foresee in their complexity. For this reason, the present study utilizes the Global Forest Products Model (GFPM, originally developed by Buongiorno et al. [12]). The GFPM is a spatial dynamic economic equilibrium model that simulates the development of the forest and wood product markets in the mid- and long run. In order to enhance projections and inferences drawn from forest products market modelling, the present study implements emerging lignocellulosic-based products into the model framework of the GFPM. Since this paper tries to analyze the potential of lignocellulosic-based products and the resulting impact on other wood-based products, we do not apply a model for the textile markets, which considers different types of fibres. However, such a model could be of great importance to explain the demand side for lignocellulose-based textile fibres in a competitive environment.

For the present study, the basic model version is enhanced and includes emerging ligno-cellulosic products (see Section 2.2). The purpose of this work is to assess alternative bioeconomy scenarios. Each scenario bases on exogeneous model assumptions regarding the economic, demographic, and forest sector specific developments. For general economic and demographic developments, the present study orientates on the Shared Socioeconomic Pathways (SSP) as scenarios for country wise possible pathways of the GDP and population developments up to the year 2100 [13]. For forest sector related assumptions, this study refers to storylines made within the context of the German research project BEPASO (Bioeconomy pathways and societal transformation strategies). An overview will be introduced in Section 2.3.

2.1. GFPM

The Global Forest Products Model (GFPM) is a spatial dynamic economic equilibrium model designed to assess alternative forest sector developments under shifting market patterns, impacts of forest sector policies, or alternative forest management scenarios [14–16]. The model links wood product supply, manufacturing, consumption, and trade [17,18]. It simulates production, consumption, and trade volumes at the national to global level for 180 countries and 14 raw-, intermediate- and end products in competitive world markets [12,14]. The basis for our work is the enhanced version of the GFPM introduced by Schier et al. (2018) [19], which distinguishes 16 wood products. In addition to the original model version, industrial roundwood and sawnwood are split into two different products, while all subsequent commodities can be produced from a mix of coniferous and non-coniferous industrial roundwood. The resulting model structure for this study is depicted in Figure 1.

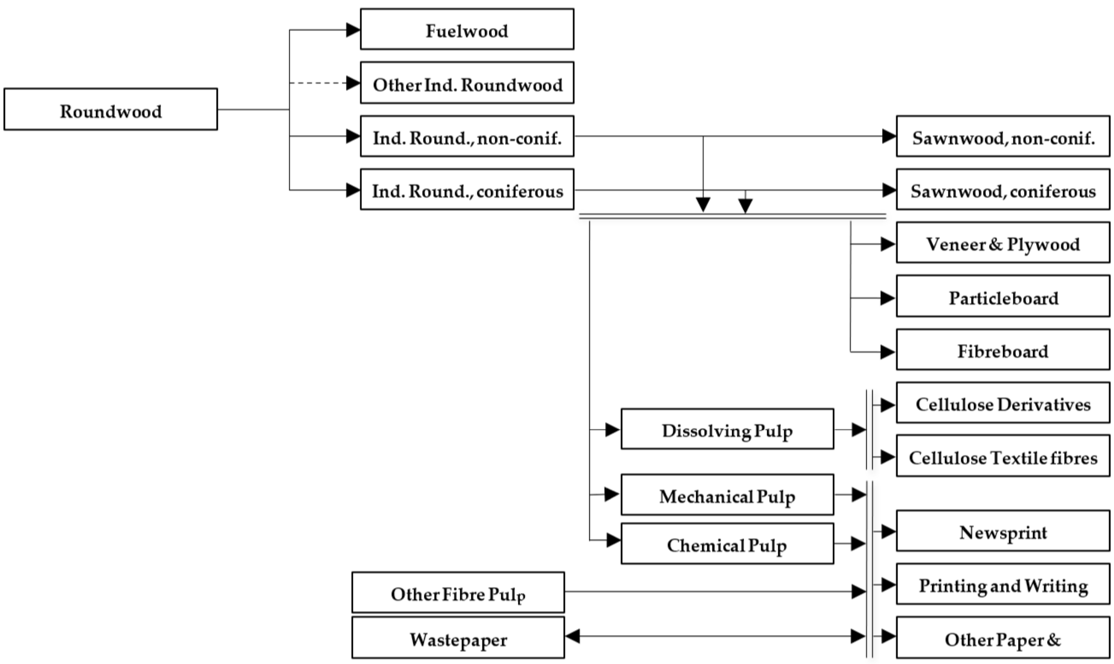

Figure 1. Suggested Model Structure and Transformation Processes in the GFPM. Note: Ind. Round. = Industrial Roundwood.

The input data for this model specification come from FAO forestry statistics [4], the FAO Forest Global Resources Assessment (FRA) [20], and the World Bank [21]. The FAOSTAT provides global and country wise data for the production and trade of forest products, while the FRA reports data for forest area and stock changes. To be consistent with the BEPASO modeling approach, data on GDP and GDP per capita are taken from the World Bank's "World Development Indicators" for a period between 1992 and 2015, and from the World Bank's "Global Economic Prospects" [21] for GDP outlook for the period between 2016 and 2019.

2.2. Implementation of Lignocellulose-Based Products in the GFPM Framework

The enhancement of the GFPM framework in the present study addresses the endogenous integration of emerging values from wood to the value chain. For this purpose, we further extend the model structure of the GFPM as introduced by Schier et al. (2018) [19] from 16 to 19 products in order to remodel and analyze wood-product market and forest sector transformation.

Analogous to the existing intermediate products chemical and mechanical pulp, we implement dissolving pulp as an intermediate product in the GFPM. Both coniferous and non-coniferous wood are entirely suitable raw materials for the production of dissolving grade pulps. Lignocellulose-based chemical derivatives and textile fibres are added as two additional end products. Dissolving pulp is used as raw material to produce lignocellulosic chemical derivatives and textile fibres [8]. The structure of the adapted and enhanced version of the GFPM is given in Figure 1.

However, any change of the model structure and input data requires the reprogramming of the model calibration for input data harmonization [19]. The calibration of model input data prior to estimation of the base period strictly requires information on production and trade volumes of all products.

Thus, we need base year production and trade figures for the newly integrated products. Unfortunately, there is no freely accessible global database covering the national production volumes for lignocellulose-based chemical derivatives and textile fibres. However, the FAO reports global dissolving pulp production, import, and export data on country level [4]. Based on this data, the net domestic consumption of dissolving pulp can be calculated, which is, in turn, the source for the lignocellulose-based end products. Keeping this in mind, we collect data about import and export quantities of lignocellulose-based products from the UN Comtrade database [22]. We further collect data on the global production of lignocellulose-based textile fibers and chemical derivatives as well as country and regionally specific information [23–25]. We combine these data to estimate national production of lignocellulose-based products according to the following procedure (see Figure 2):

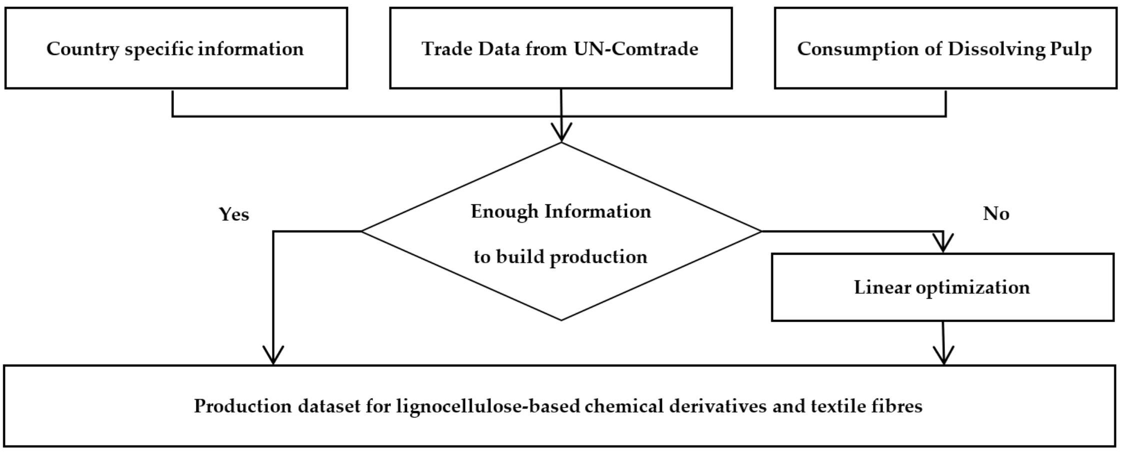

Figure 2. Scheme of production data generation for lignocellulose-based chemical derivatives and textile fibres.

First, we assume that the entire dissolving pulp consumption is distributed among lignocellulose-based chemical derivatives and textile fibers. This implies that that no other products are made from dissolving pulp. Second, the country specific information allows the definition of rough production quantities for most important producer countries. Third, data about trade with lignocellulose-based products in combination with information about regional and global developments define minima and maxima bounds for the domestic production of lignocellulose-based chemical derivatives and textile fibres in countries for which no specific information are available. We use this information to allocate global production of lignocellulose-based products over all countries via linear programming. As a result, we receive a country-wise approximation for the use of domestic consumption of dissolving pulp for the production of lignocellulose-based derivatives and textile fibers. To obtain the production quantity of these products, the input quantity of dissolving pulp must be multiplied with a product and country specific manufacturing coefficient. For the production of cellulose chemical derivatives and textile fibres from dissolving pulp, we assume a manufacturing coefficient of one. Table A1 presents the country specific data used to build the linear programming for the domestic production of lignocellulose-based textile fibers in selected countries. Table A2 shows the results obtained from this procedure for the same countries.

Beside the base year production, consumption, and trade data, the GFPM depends on demand and supply elasticities as well as exogenous parameters that set the framework for the model behavior and developments during scenario simulations. Elasticities used for the present study are either taken from the latest versions of the GFPM [12] or from recent econometric studies for supply and demand in traditional forest markets [3] and for lignocellulose-based products [26].

2.3. Future Pathways for Bioeconomy Scenarios

Meaningful scenario simulations must build on plausible development paths, which we introduce in the following sections. In this study, we model three bioeconomy scenarios combining story lines elements from the SSP scenarios and the BEPASO project.

The subject of the BEPASO project was to develop alternative bio-economy pathways and social transformation strategies up to the year 2050. The scenarios were developed in an interactive participation process with stakeholders and citizens. The resulting scenarios were named: "Bioeconomy islands", "Bioeconomy on the drip", and "Bioeconomy change" [27]. To embed these BEPASO storylines into a macroeconomic framework, they were assigned to the scenarios of different SSP storylines [27].

The SSP scenarios describe five narratives for future developments and the accompanying driving forces [13]. In the present paper, we focus on the implementation of GDP and GDP per capita developments from three (SSP1, SSP2, SSP4) of the five SSP scenarios up to the year 2050 (see Table 1). For this purpose, we use data from the SSP data base (within the SSP Data base we used data from the OECD Env-Growth model for GDP and population) on the projection of GDP [28] and population development [29] for more than 200 countries. The data are the key assumptions to build a consistent and global socioeconomic framework for the scenario simulation in this paper.

Table 1. Assumptions on future forest sector developments (displayed as global averages).

	Country Related (GDP per Capita [1])		Forest Products Related (Technological Change [2])		Global Growth of Forest Stock from 2015 to 2050	
High sustainability scenario	SSP1	3.655%	Bioeconomy Change	1.586%	Bioeconomy Change	27.707%
Mid sustainability scenario	SSP4	2.887%	Bioeconomy Islands	0.378%	Bioeconomy Islands	28.462%
Low sustainability scenario	SSP2	3.018%	Bioeconomy on the Drip	0.042%	Bioeconomy on the Drip	27.945%

Note: [1] Global mean growth rate per year between 2015 and 2050 as calculated by SSP [28,29]; [2] growth rate of technological efficiency per year as global mean over all products; Technological change is calculated separately for each product in 180 countries via the GFPM to catch up with the BEPASO storylines

Basically, in the "Bioeconomy on drip" scenario, biomass plays a minor role as a raw material in the global industrial production process. Globally, subsidies and customs tariffs either remain constant or increase due to trade disputes. At the same time, no real technological breakthrough regarding green innovations takes place. Thus, the world only experiences a slight increase in the efficiency of resource use. This scenario is assigned to the SSP scenario 2 "Middle of the Road" [30], which describes the continuation of past dynamics. In the other two scenarios, the demand for biomass for non-nutrition purposes is growing. The main aspects for the modelling approach, beside GDP and population development from the SSP 2, are the relative slow technological progress mirrored in only slightly decreasing input–output ratio of raw wood in the transformation process throughout the wood-based sectors, constant to increasing trade barriers and a constant energetic use of wood compared to present levels. Several other side aspects of this scenario can be found at [27].

In the scenario "Bioeconomy islands", biomass is mainly used to produce energy in order to replace a fossil-based economy. Here, technological developments occur but take off primarily in high- and middle-income countries. This scenario is aligned with SSP scenario 4 "Inequality—A Road Divided" [31], which describes social and economic inequality between regions where environmental and sustainable sound development is only a priority for a few affluent regions. The main aspects for the modelling approach, beside GDP and population development from the SSP 4, are the inequality of technological progress in high- and middle- to low-income countries, decreasing trade barriers, and an increasing energetic use of wood. Several other side aspects of this scenario can be found at [27].

In the "Bioeconomy change" scenario, biomass is mainly used as input to produce diverse industrial and everyday products. This development goes along with a globally efficient exchange of research and development activities and breakthroughs in green technologies. In this scenario, the world benefits from an optimization of resource use. This scenario is assigned to the SSP scenario 1 "Sustainability—Taking the Green Road" [32] where global cooperation goes along with an increasing focus on environmental and forest protection as well as a shift in human dietary and energy production. The main aspects for the modelling approach, beside GDP and population development from the SSP 1, are the fast and global technological progress, a concentration for regional production, and a decreasing energetic use of wood. Several other side aspects of this scenario can be found at [27]. Table 1 gives a brief summary of the exogenous macroeconomic and forest related development assumptions from these bioeconomy scenarios for the implementation into the enhanced GFPM. These assumptions include, among others, the development of GDPs and GDPs p.c., fuel wood demand, and technological changes over time. A more detailed summary on the assumptions on future forest sector developments for the top ten producers of industrial roundwood is given in Table A3.

3. Results

In the following, we present selected results from the simulation of the three bioeconomy scenarios with the enhanced version of the GFPM. We refer to the bioeconomy scenarios according to the nomenclature of the BEPASO storylines: "Bioeconomy on the Drip" ("Drip") as description for less sustainable global developments, "Bioeconomy Islands" ("Islands") for a partially change into a more bio-based and sustainable world, and "Bioeconomy Change" ("Change") for a global shift to a sustainable bioeconomy. In general, we observe a larger increase in total wood consumption in the two scenarios promoting a progressive and bio-based development of the future economy ("Change" and "Islands"), while the total wood consumption in the "Drip" scenario increases only slightly on global level. However, the way wood is used differs between the scenarios. Table 2 summarizes the main results.

Table 2. Scenario results from the simulation of three alternative bioeconomy scenarios.

Commodity	Unit	Global Consumption in 2015	Global Consumption in 2050 and Growth from 2015 to 2050 in Percentage					
			Drip Scenario		Islands Scenario		Change Scenario	
Roundwood	mil m^3	3833.40	4332.87	13.0%	4812.13	25.5%	5479.08	42.9%
Fuelwood	mil m^3	1847.42	2400.32	29.9%	2394.08	29.6%	1265.06	−31.5%
Industrial Roundwood	mil m^3	1832.62	1734.66	−5.3%	2219.77	21.1%	4019.40	119.3%
Industrial Roundwood C	mil m^3	1066.82	996.38	−6.6%	1199.33	12.4%	2252.11	111.1%
Industrial Roundwood NC	mil m^3	765.82	801.21	4.6%	1163.41	51.8%	1767.30	130.8%
Sawnwood	mil m^3	464.84	456.61	−1.8%	527.54	13.5%	545.06	17.3%
Sawnwood C	mil m^3	328.95	318.24	−3.3%	369.99	12.5%	365.44	11.1%
Sawnwood NC	mil m^3	135.88	138.36	1.8%	157.55	15.9%	179.62	32.2%
Wood-based panels	mil m^3	420.71	433.86	3.1%	676.10	60.7%	1243.24	195.5%
Fiberboard	mil m^3	128.35	132.29	3.1%	226.84	76.7%	508.40	296.1%
Particle Board	mil m^3	113.15	112.53	−0.6%	144.76	28.0%	214.52	89.6%
Veneer Sheets and Plywood	mil m^3	179.20	189.04	5.5%	304.50	69.9%	520.32	190.4%
Paper pulp	mil t	174.36	186.32	6.9%	149.67	−14.2%	122.45	−29.8%
Newsprint	mil t	26.70	27.82	4.2%	22.85	−14.5%	14.60	−45.3%
Other Paper and Board	mil t	282.56	322.51	14.1%	304.47	7.6%	212.66	−24.7%
Printing and Writing Paper	mil t	103.44	115.95	12.1%	85.93	−17.1%	60.26	−41.8%
Dissolving Pulp	mil t	6.79	7.26	6.9%	81.33	1097.5%	217.27	3099.1%
Cellulose derivatives	mil t	2.00	2.28	14.0%	11.56	477.4%	10.38	418.3%
Cellulose regeneratives	mil t	4.94	5.47	10.7%	73.58	1388.4%	207.06	4088.9%

The global energetic use of wood is decreasing from 2015 to 2050 in the “Change” scenario (by −31.52%) and increasing in the “Drip” (by −29.59%) and “Islands” (by −29.59%) scenarios. On the other hand, the global material use of wood is increasing in “Change” (by +119.33%) and “Islands” (by +21.06%) scenarios from 2015 to 2050, while it is decreasing in the “Drip” scenario (by −5.35%). Counterbalancing these developments, changes in total roundwood removals amount to +13.0%, +25.5%, and +42.9% in the “Drip”, “Island”, and “Change” scenario, respectively. This is in line with the BEPASO storylines described above. Increasing demand for industrial roundwood results mainly from demand shifts in the further processed wood products. Especially the “Change” scenario is driven by an increasing demand for wood-based panels (+195.51% compared to 2015) and dissolving pulp (+3099.12% compared to 2015) in 2050. At the same time, the paper consumption in this scenario drops by −30.33% between 2015 and 2050. This reduces the consumption of wood-based pulps as input in paper production by −34.30%.The increasing material use of wood until 2050 in the “Island” scenario is mainly driven by increasing demand for dissolving pulp (+1097.49%) and wood-based panels (+60.72%), while simultaneously the paper pulp, and thus paper production consumption, is decreasing (−14.84%) within this scenario. The nearly constant material use of wood in the “Drip” scenario results mainly from near constant demand for sawnwood (−1.77%), wood-based panels (+3.13%), and dissolving pulp (+6.91%).

4. Discussion

In the following, we will discuss the scenario results. Depending on the scenario, the global roundwood production in this study was calculated to lay between 4.3 and 5.5 billion m^3 per year. However, there are outlook studies that calculate global roundwood production scenarios, of which some show even stronger increases, e.g., [33] where the global roundwood production lay between 3.6 and 11.2 billion m^3 in 2060. Even if we would assume that the roundwood production would follow a linear trend, in 2050, it would lay between 4.7 billion m^3 (trend 2000–2019) and 5.8 billion m^3 (trend 2015–2019) (own calculation based on [4]). Therefore, we conclude that the future roundwood production as calculated in the present study seems to be feasible.

In 2015, the global production of dissolving pulp amounted to 7 million tons, while the global production of wood-based pulp for paper and paperboard amounted to 178 million tons [4]. In our scenario simulations, the dissolving pulp production increases up to 217 million tons within the next 35 years (see Figure 3). This development would indicate that the dissolving pulp sector could climb out of its current niche and become a relevant player within the forest-based industries. However, this development depends on the external scenario setting over the coming decades. In a scenario where the growth of a bioeconomy stagnates (“Drip” scenario), the share of the dissolving pulp sector in overall wood-based pulp (i.e., paper and dissolving pulp) output would stay constant, while in the more sustainable “Island” scenario the share rises to 35% in 2050. In the “Change” scenario, the production volumes of the dissolving pulp would exceed the production volumes of paper pulp (see Figure 3) and account for 64% of total wood-based pulp production. Between 2008 and 2018, the mean annual growth rate of the global dissolving pulp production was 10% (own calculation based on [4]). In order to reach the global production level of 81 million tons simulated in the “Island” scenario by 2050, a mean annual production growth of 6.9% would be required. Vice versa, a global production level of 217 million tons of dissolving pulp in 2050 implies a mean annual production growth of 9.8%. Even though we observed such a dynamic growth during the last decade, its continuation is closely related to the natural textile fibre markets, which in turn depend highly on GDP and Population developments [34]. However, the long-term projection of the currently dynamic development and limits of these markets for another three decades is almost impossible. Therefore, the results of this study should be interpreted as potential input from forest product markets to the textile fibre markets. This, especially as we know that the ongoing growth path of the dissolving pulp sector in the “Change” scenario, seems not to be in line with the expected limits of consumption in its long-term product cycle. Here, a refinement of exogenous long-term parameters within the model frameworks should be considered for future works.

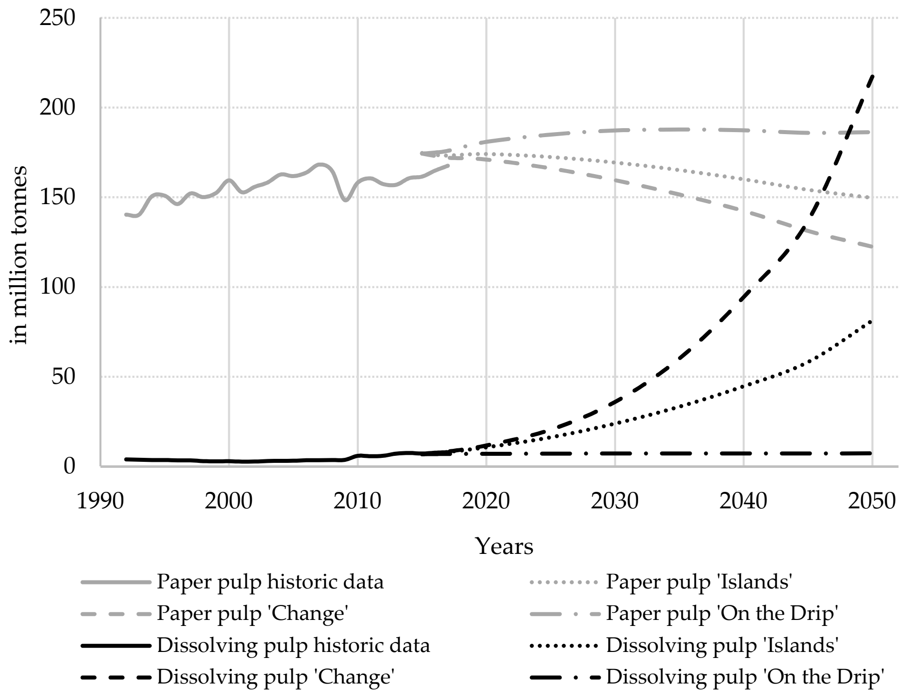

Figure 3. Paper pulp and dissolving pulp production globally.

In light of sector-specific projections for future textile fibre demand, we compare our results with other forecasting studies. In this context, the International Cotton Advisory Committee [35] projects a world fibre demand of 121 million tons for the year 2025, while, according to Textile World, the demand for textile fibres could reach 125 million tons [36] in 2030. In 2018, the share of lignocellulosic fibres in the total fibre mix accounted for 6.2% [37]. Thus, and if this fibre mix does not change over the next decade, the demand for ligno-cellulosic fibres would hover around 7.5 million tons in 2030 and thus be in line with the results we obtain with the "Drip" scenario.

In the "Island" and the "Change" scenarios, the production of lignocellulosic fibres reaches 24 million tons and 31 million tons, in 2030, respectively. We would need a growing share of lignocellulosic fibres in the total fibre mix from currently 6.2% to 19% in in order to reach the simulated production level in the "Island" Scenario. In the same manner, the share of lignocellulosic fibres had to grow to 25% in order to reach the production level of roughly 31 million tons of lignocellulosic fibre simulated in the "Change" scenario.

However, due to technological developments in wood processes that reduce the required wood input and the expected level of digitalization in production processes, the global increases in dissolving pulp production are not negatively correlated to the sawn wood and wood-based panels sectors in our simulations. While we observe that the global production of sawn wood only changes to a minor extent, the global production of wood-based panels even increases compared to the levels of 2015 in the "Change" and "Island" scenarios. Nevertheless, the increasing demand for lignocellulose-based textile fibers and the assumption that regional production will become more and more important (as described in "Change" and "Island" story lines), lead, in our simulations, to a shift in the production of dissolving pulp from North America and Europe to Asia (see Figure 4) until 2050. Practically, this would lead to decreasing importance of North America and Europe in global dissolving pulp markets. Today, Asia is the biggest importer of dissolving pulp, where it is mainly used for the production of lignocellulosic textile fibres, while North America and Europe are the biggest exporter of dissolving pulp [4]. Actually, global players of the industry invest in the establishment of new plants in Asia, which should lead to an expansion of production facilities for dissolving pulp in this region. In order to maintain or even increase its market share, North America and Europe would, e.g., have to concentrate on the development of new products from lignocellulose-based derivatives, like bioplastics or the investment in local textile industries rather than the export to Asia.

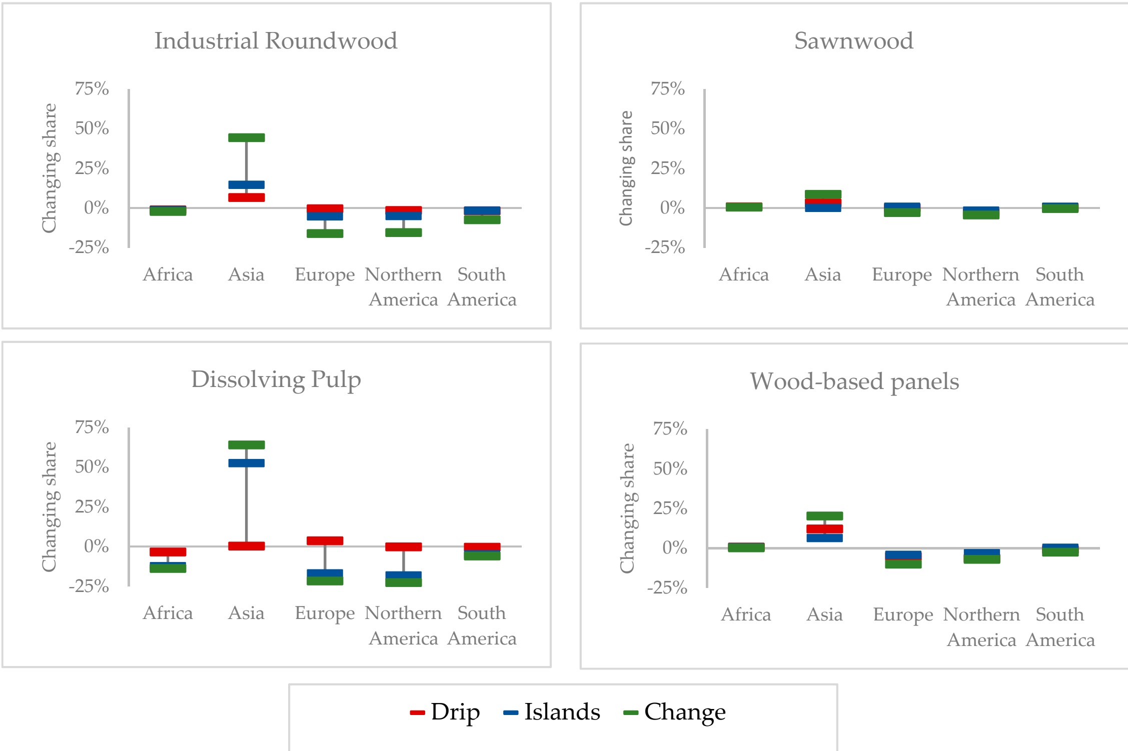

Figure 4. Change in the global market shares of a specific product between 2015 and 2050, by product; Note: market shares are calculated by dividing aggregated continental production of a product through the global production of the same product.

Similar shifts can be observed for several other forest products, too. Today, Asia is a net importer of roundwood, sawn wood, as well as paper and paperboard, while North America and Europe are net exporters for these product groups [4]. Our assessment suggests that, until 2050, the production of many wood-based products will take place directly in Asia instead of being imported from other continents such as North America and Europe. The shift in global production pattern is displayed in Figure 4. The figure shows that most product categories in nearly all scenarios are affected by these changes. However, the magnitude of the shifts is product specific: for sawn wood or wood-based panels, it is in general weaker, as for dissolving pulp or industrial roundwood (see Figure 4). Especially with regard to industrial roundwood, we observe decreasing shares of global production across all continents except Asia, where the shares of global production are increasing.

Eventually, we will discuss some weaknesses of the present approach. This study builds on the use of a partial equilibrium model and underlying scenario assumptions. These approaches have several inherent limitations: First, a general limitation for this kind of modelling is that all input data for the model rely on historical developments. This led to the conclusion that the GFPM in structure and its parameters is not sensitive to possible structural changes or idiosyncratic shocks in future, because it is built to describe the past and current state of the world.

A second limitation of the present study is that the scenarios highly depend on assumptions about the future developments like population and GDP growth rates from the SSP scenarios and other exogenous changes from BEPASO storylines. A priori, it is not possible to judge about the probability and accuracy of the underlying scenario assumptions.

The last issue is that the GFPM does not model competing end product markets. Thus, the production of lignocellulose-based products in this study should be interpreted as a potential supply of these products and not as its end consumption.

Despite these limitations, we consider that the present approach allows for important insights into the possible future developments of wood product markets and thus, foster well-informed decision making and policy advice.

5. Conclusions

Traditional forest product markets are changing. Wood product market analysis needs to consider these changes by implementing emerging values from wood such as innovative usages of wood, like sandwich panels, or the emerging lignocellulose-based products like dissolving pulp. The present study did this by adapting global forest product modelling and implementing emerging lignocellulose-based products into the extended version of the GFPM. In such an enhanced forest sector modelling approach, the application of scenario-based analysis and the assessment of bioeconomy developments becomes possible for the first time. We analyze alternative bioeconomy pathways and their future market effects by integrating socioeconomic and technological developments from the SSP and BEPASO story lines up to 2050 into the framework of the enhanced version of the GFPM.

Our findings suggest that, if the world could change toward a sustainable bioeconomy, consumption of roundwood could shift from fuelwood or classical paper production towards more efficient production of wood-based panels or lignocellulose-based materials. However, we further suggest that such a development must be accompanied with technological changes to reduce the total amount of wood input in the final products. This would generate additional resources potentials for new wood-based products. In our scenario simulations, the growth of sawn wood production remains limited compared to the increasing importance of wood-based panels. Additionally, we found that the dissolving pulp subsector has the potential to outpace at least today's paper pulp subsector. Thereby, the increase in dissolving pulp production would not impact the resource base and production volumes of the sawn wood and wood-based panels sector compared to the level of 2015. This is, among other reasons, because ongoing digitalization and technological progress set free fibre resources that were formerly used for, e.g., paper production. In addition, non-coniferous wood is an entirely suitable raw material for the production of dissolving pulp. This reduces the competition for scarce coniferous resources needed for material wood processing.

We can conclude that in the case of the "Change" scenario, wood could play an increasingly important part in everyday life. Contrary to this, the results from the "Island" and "Drip" scenarios show that wood product markets could also adhere to the present pattern if the transformation is not fostered by socio-economic and technological development. The "Island" scenario further demonstrates that, in dependence of the market settings, wood could even increasingly be used for energetic purposes instead of being processed as input for material wood products.

The BEPASO project shows that the public is largely willing to move towards a sustainable and bio-based world [38]. However, one essential finding is that potential impacts of the transformation into a bio-based economy must be clearly communicated. Also important to support the social acceptance and make a bio-based economy happen is a public-oriented dialogue about the conditions and added values [38]. With this study in mind, we show that modelling is an important tool here. It makes long-term interactions visible and graphically tangible for people. Thereby, modelling helps to support reasonable and well-informed decision making in policies, since it shows interdependencies between markets, socio-economics and technological developments, especially in the long run, which humans can hardly foresee in their complexity.

This study is an initial step to include the emerging lignocellulose-based products into wood products market scenarios and analysis. While the dissolving pulp sector is well documented in terms of production, trade, and demand, we found considerable gaps in (freely) accessible information for ligno-cellulose-based textile fibres and, in particular, chemical derivatives. Future research needs to tackle this challenge and possibly provide refined scenario storylines and simulations on the development of these sectors in the context of global forest products market modelling.

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Appendix A

Table A1. Selection of country specific information about Cellulose-based textile fibers (TF).

Country	Country Specific Information about TF	Share of Global Production [25]	Dissolving Pulp (DP) Consumption in t [4]
Austria	400 kt Capacity [24]	9% in Europe	355,274.00
Germany	238 kt Production in 2011 [23]	9% in Europe	424,000.00
United Kingdom	45 kt Capacity [24]	9% in Europe	48,468.00
China		66%	4,495,676.00
India		9%	828,875.00
Indonesia	Viscose Production 320 kt [24]	9%	360,286.00
Thailand		3%	141,129.00
USA		1% in North America	411,000.00
Canada		1% in North America	101,512.00
Japan		1%	167,629.00
World	5.6 mt Production in 2016 [39]	100%	8,251,431.00

Table A2. Dissolving pulp (DP) input for the production of lignocellulose-based textile fibers (TF) as a result of the linear optimization procedure for the year 2015.

Country	DP Input for TF in t	in % of Global
Austria	319,747	5.1%
Germany	251,651	4.0%
United Kingdom	45,075	0.7%
China	4,046,108	64.3%
India	580,213	9.2%
Indonesia	360,286	5.7%
Thailand	141,129	2.2%
USA	41,100	0.7%
Canada	10,151	0.2%
Japan	83,815	1.3%
World	6,294,984	100%

Table A3. Assumptions on future forest sector developments for the top ten producers of industrial roundwood (displayed as country specific averages).

Sceanrio	ISO Code	Country	GDPpC growth [1]	TechChange [2]	Forest Growth [3]
Bioeconomy Change	BRA	Brazil	3.14%	0.28%	0.21%
Bioeconomy Change	CAN	Canada	1.07%	0.91%	0.31%
Bioeconomy Change	CHN	China	4.99%	0.23%	1.79%
Bioeconomy Change	DEU	Germany	1.35%	0.91%	1.66%
Bioeconomy Change	FIN	Finland	1.41%	0.91%	1.65%
Bioeconomy Change	IDN	Indonesia	5.56%	0.31%	0.57%
Bioeconomy Change	IND	India	5.35%	0.28%	1.65%
Bioeconomy Change	RUS	Russian Federation	3.13%	0.66%	0.17%
Bioeconomy Change	SWE	Sweden	1.42%	0.73%	1.36%
Bioeconomy Change	USA	United States of America	1.44%	0.76%	1.10%
Bioeconomy Islands	BRA	Brazil	2.25%	0.15%	0.22%
Bioeconomy Islands	CAN	Canada	1.33%	0.25%	0.32%
Bioeconomy Islands	CHN	China	4.18%	0.14%	1.88%
Bioeconomy Islands	DEU	Germany	1.48%	0.23%	1.64%
Bioeconomy Islands	FIN	Finland	1.60%	0.26%	1.60%
Bioeconomy Islands	IDN	Indonesia	4.45%	0.10%	0.57%
Bioeconomy Islands	IND	India	3.95%	0.13%	1.70%
Bioeconomy Islands	RUS	Russian Federation	2.86%	0.25%	0.20%
Bioeconomy Islands	SWE	Sweden	1.59%	0.24%	1.35%
Bioeconomy Islands	USA	United States of America	1.53%	0.25%	1.11%
Bioeconomy on the Drip	BRA	Brazil	2.18%	0.13%	0.22%
Bioeconomy on the Drip	CAN	Canada	1.11%	0.14%	0.32%
Bioeconomy on the Drip	CHN	China	4.01%	0.14%	1.88%
Bioeconomy on the Drip	DEU	Germany	1.22%	0.14%	1.64%
Bioeconomy on the Drip	FIN	Finland	1.30%	0.14%	1.60%
Bioeconomy on the Drip	IDN	Indonesia	4.31%	0.12%	0.54%
Bioeconomy on the Drip	IND	India	4.14%	0.13%	1.69%
Bioeconomy on the Drip	RUS	Russian Federation	2.54%	0.13%	0.20%
Bioeconomy on the Drip	SWE	Sweden	1.32%	0.13%	1.35%
Bioeconomy on the Drip	USA	United States of America	1.13%	0.14%	1.11%

Note: [1] mean growth rate per year between 2015 and 2050 as calculated by SSP [28,29]; [2] growth rate of technological efficiency per year as country specific mean over all products; Technological change is calculated separately for each product in a country via the GFPM to catch up with the BEPASO storylines; [3] Mean growth of forest stock per year from 2015 to 2050 [27].

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