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Material substitution between coniferous, non-coniferous and recycled biomass – Impacts on forest industry raw material use and regional competitiveness

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ABSTRACT

The competitive advantage of traditional forest industry regions such as North America, Russia and the EU is based largely on the production and processing of coniferous (C) biomass. However, non-coniferous (NC) and recycled (R) biomass provide cost-effective alternatives to C biomass, which have already decreased the proportion of C biomass use and which can potentially have large impacts on the future development of the global forest sector. In this study, we investigate the impacts of material substitution between C, NC and R biomass on forest industry raw material use and regional competitiveness from 2020 to 2100. The analysis is based on a global spatially-explicit forest sector model (GLOBIOM-forest). Our results indicate that traditional forest industry regions can maintain their competitiveness in a baseline scenario where C and NC biomass remain imperfect substitutes, and the development of the circular economy increases the availability of R biomass. Limited availability of R biomass would increase the competitiveness of traditional forest industry regions relative to the baseline. On the other hand, a perfect substitution between C and NC biomass would decrease the competitiveness of traditional forest industry regions relative to the baseline, and increase the competitiveness of emerging forest industry regions such as South America, Asia and Africa. We also show that the increased availability of R biomass tends to decrease demand for pulpwood and might lead to an oversupply of pulpwood especially in traditional forest industry regions. This opens new perspectives for pulpwood use and/or forest management in these regions.

1. Introduction

Traditionally, coniferous (C) biomass has dominated non-coniferous (NC) and recycled (R) biomass in forest industry raw material use. The main reasons for this are the historical location of forest industry in North America, Russia and the EU, where C trees are the dominant species (FRA, 2015), and the suitability of C biomass for material processing. During the last 50 years, short-rotation forestry, globalization, and increasing demand for wood-based products in emerging economies has driven the growth of forest industry in new regions, such as Asia and South-America (Hurmekoski and Hetemäki, 2013). In these regions the dominant species are NC trees (FRA, 2015), meaning the proportion of NC biomass use in the global forest industry increased from 30 to 45% between 1961 and 2020 (FAO, 2020). At the same time, the development of the circular economy has increased the availability and utilization of R biomass such as R wood and R paper. This has had a particular effect on the paper and paperboard industry where the proportion of R pulp made from R paper increased from 20 to 50% of total pulp use between 1961 and 2020 (FAO, 2020).

If the proportion of NC and R biomass use continues to increase in the future, interesting issues for the future development of the global forest sector are: how could this affect forest industry raw material use, and what effect may this have on regional competitiveness. In particular, will traditional forest industry regions maintain their competitive advantage, which currently depends on the production and processing of C biomass? To analyze these issues, it is not sufficient to assess the historical development of NC and R biomass use and assume that the historical trends continue in the future. Instead, an integrated modelling approach that includes both forest industry and forestry sectors, and which takes into account the availability of different biomass types, the

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suitability of each biomass type for material processing, and the demand for final products produced from different biomass types, is required.

The availability of C and NC biomass differs between regions due to different climate conditions and forest management practices. C trees are dominant in the boreal zone, NC trees are dominant in the tropical zone, and in the temperate zone the dominance of C and NC trees varies between regions (FRA, 2015). In the boreal and temperate zones, rotation times are usually long, which favors the joint-production of sawlogs and pulpwood. In long-rotation forestry, pulpwood production is connected sawlogs production by thinnings, which are used to increase sawlogs harvest potential and decrease mortality (Zeide, 2001; Mäkinen and Isomäki, 2004). This type of joint-production might even lead to an oversupply of C pulpwood if the demand for C sawlogs continues to grow and the demand for C pulpwood stagnates due to increased availability of R biomass (Van Ewijk et al., 2017). In the tropical zone, rotation times are much shorter than in boreal and temperate zones, which favors separate production of sawlogs and pulpwood. In short-rotation forestry, early-thinning operations can be used to increase sawlogs harvest potential and decrease mortality, but the early-thinning biomass is not suitable for pulpwood (Noguerira et al., 2015; Acuna et al., 2017; Dobner and Huss, 2019). Short-rotation forestry can produce NC biomass cost-effectively (Carle and Holmgren, 2008; Cubbage et al., 2010; Payn et al., 2015), and could also produce C biomass cost-effectively (Cubbage et al., 2010). However, it is unlikely that tropical forestry would specialize in C biomass production, because NC biomass yields are higher than C biomass yields in the tropical zone, whereas C biomass yields are higher than NC biomass yields in the boreal and temperate zones (IPCC, 2003; FRA, 2015). This implies that the tropical zone has a comparative advantage in NC biomass production, whereas temperate and boreal zones have a comparative advantage in C biomass production.

The availability of R biomass depends less on climate conditions and forest management, and more on the wood-based products final consumption, and recycling of wood-based products after their final use. Paper and paperboard, which are the most commonly recycled wood-based products, can be collected after their final consumption and processed into recycled pulp, which can be used as a substitute for virgin pulp in paper and paperboard production. Material losses in recycled paper collection and processing as well as ageing of R biomass set limits to recycled pulp use in paper and paperboard production. Currently the share of recycled pulp from total pulp consumption is about 50% (FAO, 2020), but technically it could be increased up to 67–73% with current processing technologies (Van Ewijk et al., 2017). Mechanical forest industry products, such as sawnwood, plywood, particleboard and fiberboard, are less commonly recycled than paper and paperboard. Most mechanical forest industry products remains unused, or burned for energy after their final consumption (Leek, 2010). According to FAOSTAT 32 Mton of mechanical forest industry products were recovered as recycled wood in 2019 (FAO, 2020), which is less than 10-% of total annual mechanical forest industry products final consumption. Recycled wood can be used as a raw material in particleboard and fiberboard production instead of virgin fibers.

There are several reasons why C biomass is a more suitable raw material for biomass processing than NC or R biomass. The sawmill industry favors C biomass because C sawlogs usually grow faster than NC sawlogs in the boreal and temperate zones (IPCC, 2003; FRA, 2015). Moreover, C sawlogs are a more homogenous raw material than NC sawlogs, and they have a lower density, making them easily processable raw material for construction (Ramage et al., 2017, Swedish Wood, 2020). NC sawlogs are used mainly for value-added products like furniture and flooring where strength and durability are required, and heterogeneity of raw material matters less (Teischinger, 2017). In the paper and paper board industry, C biomass has more suitable material properties for certain paper grades (Chanhan et al., 2013). C biomass has long fibers, which provides good flexibility and strength properties needed in packaging materials and sanitary paper. On the other hand, NC biomass has short fibers and less lignin, which makes bleaching easier and provides good printing properties needed in newsprint and in printing and writing papers. The demand for packaging materials and sanitary paper has increased while the demand for newsprint and printing and writing papers has decreased over the last 20 years, which favors C biomass use. These trends are expected to continue in the future (Johnston, 2016; Latta et al., 2016). In paper and paperboard production, R biomass provides a cost-effective alternative for C and NC biomass, but the ageing and heterogenous quality of R biomass sets some limits to its use (Stawicki and Read, 2010; Van Ewijk et al., 2017).

Even if material properties and demand patterns for final products currently favor C biomass, the situation might change in the future since the material properties of NC and R biomass can be improved through technical progress in production processes, such as nanotechnology or laminated timber. Nanotechnology has not yet been implemented in commercial wood-based products production, but it could potentially improve NC biomass material properties and eliminate the ageing of R fibers (Viana et al., 2018; Balea et al., 2020; Jasmani et al., 2020). Laminated timber is currently produced mainly from C biomass, but in the future, it could be produced from NC biomass and potentially replace C sawnwood (Espinoza and Buelmann, 2018; Kühle et al., 2019).

Material substitution and its impact on the global forest sector is closely connected to the wood-based products supply chain and transport costs. Woody biomass is bulky material, which implies that transport costs account for a large share of total costs and minimizing transport costs is an important part of the wood-based products supply chain. The share of transport costs in the value of the product is typically higher for raw materials than for intermediate and final products (Buongiorno et al., 2003). Due to this, forest industry typically locates intermediate and final products production close to the raw material sources. More generally this means the competitive advantage of forest industry is based on the domestic raw materials utilization and regions are not able to improve their competitiveness by importing raw materials from other regions.[1]

Forest sector models (FSMs) are suitable tools to use in analysis of material substitution between C, NC and R biomass, and its implications to the forest sector. FSMs are dynamic partial equilibrium models, which simulate the operation of wood-based products markets, forest resources use and forest management. They were originally designed in the 1980s to analyze the development of forest industry but have subsequently been extended to include forestry (Toppinen and Kuuluvainen, 2010; Latta et al., 2013). Today, FSMs are commonly used for forest sector outlook studies and forest-related policy analysis (Hurmekoski and Hetemäki, 2013; Riviere and Caurla, 2020). FSMs do not usually distinguish between C and NC biomass, and they have limited representation of R biomass use. Schier et al. (2018) and Jonsson et al. (2020) included C/NC products separation in an FSM, but the separation was only applied for sawnwood and roundwood. Buongiorno et al. (2003) included recycled paper in an FSM, and showed that higher utilization of recycled paper led to lower virgin pulp demand. However, this model did not distinguish between C and NC biomass.

In this study, we investigate how material substitution between C, NC and R biomass would impact on forest industry raw material use and regional competitiveness. The analysis is based on a global spatially explicit forest sector model (GLOBIOM-forest).

The study extends the existing literature about FSMs by including a detailed description of C, NC and R biomass production, processing, and

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[1] High investment risk might limit forest industry investments to regions with large woody biomass resources and increase raw material outflow from these regions. However, this is usually not a permanent state since high investment risk regions can affect the investment risk and raw materials outflow by domestic policy. A good example of this Russia, who has succeeded to decrease the raw material outflow during the last dedicates by applying export tax on domestic roundwood (FAO, 2020).

consumption within the model. Moreover, we consider different material substitution scenarios, which provide some new perspectives on the future development of the global forest sector. The rest of the study is organized as follows: in section 2 we introduce the model and the methodology used in the analysis, section 3 presents the results of the model, section 4 includes some discussion on the results of the model, and section 5 provides conclusions. The results of the study are aggregated over regions and product categories to keep the analysis tractable for a scientific paper. For the same reason, the study does not include a full description of the model, but the documentation of the model is limited to issues that are relevant for material substitution analysis. A full description of the model and the disaggregated results of the analysis are provided online at github.com/iiasa/GLOBIOM_forest.

2. Method

2.1. GLOBIOM-forest model

The Global Biosphere Management Model (GLOBIOM) is a global spatially-explicit agricultural and forest sector model (Havlik et al., 2011, 2014). In this study, we use a version of the model called GLOBIOM-forest, where the agricultural sector is simplified to include just one product (energy crops), but the forest sector is modelled in more detail than in GLOBIOM. GLOBIOM-forest includes forestry, forest industry and bioenergy modules as described in Lauri et al. (2014, 2017, 2019). The model is solved recursively for each 10-year period by maximizing the economic surplus. The supply side of the model is based on the 0.5° grid resolution while the demand side and trade are based on 59 economic regions. The simplified structure of GLOBIOM-forest makes it possible to solve the model at a higher resolution than a 0.5° grid, but this option was not used in the study.

The model includes 26 wood-based products. The forestry module includes five harvested products (pulpwood, sawlogs, other industrial roundwood, fuelwood, logging residues) and one non-harvested product (deadwood). The forest industry module includes four paper and paperboard grades (newsprint, printing and writing papers, packaging materials, other papers[2]), four pulp grades (chemical pulp, mechanical pulp, recycled pulp, other fiber pulp), three mechanical forest industry products (sawnwood, plywood, fiberboard[3]), four forest industry by-products (woodchips, sawdust, bark, black liquor) and two recycled products (recycled paper, recycled wood). The bioenergy module includes two final products (traditional bioenergy, modern bioenergy) and one intermediate product (wood pellets).

Forest industry and wood pellets production capacities are based on FAOSTAT production data for 2000–2020 (FAO, 2020). After 2020, production capacities evolve according to investment dynamics, where investment decisions are made by comparing the current period income and annualized investment costs. Forest industry and wood pellets production is modelled by using Leontief production technologies, which have fixed input-output coefficients. Leontief production technologies can be combined, which allows imperfect or perfect substitution between the inputs. The substitution between inputs can be further controlled by defining minimum/maximum shares for their use.

Final products demands are based on constant elasticity demand functions, which are parametrized by reference volumes, reference prices and elasticity coefficients. Exceptions are modern bioenergy demand, which is based on the SSP-RCP scenario data (IIASA, 2020), and traditional bioenergy demand, which is assumed to stay constant over time. Reference prices are based on the world export prices and transport costs, so that net exporters face world prices, and net importers face world prices plus transport costs (Buongiorno et al., 2003). For simplicity, preference prices are assumed to stay constant over time. An alternative option would be to shift reference prices over time by using previous period prices, as in Buongiorno et al. (2003), but this might cause artificial price fluctuations in the model. Reference volumes are based on FAOSTAT for 2000–2020 (FAO, 2020). After 2020, the reference volumes are shifted over time based on GDP and population growth. The development of GDP and population is based on the SSP-RCP scenario data (IIASA, 2020). The elasticity parameters of the demand functions are based on econometric estimates from Buongiorno et al. (2003), Buongiorno, 2015) and Morland et al. (2018). Income-elasticities lie between 0 and 1, and differentiated for low-, middle- and high-income regions. Newsprint and printing and writing papers are assumed to have 0 income elasticity for all regions. Price-elasticities lie between −0.1 and − 1. Population elasticity is always 1. Trade is modelled by using bilateral trade flows. Bilateral trade volumes are based on BACI trade data for 2000–2020 (Gaulier and Zignago, 2010). After 2020, trade volumes evolve according to trade dynamics, which depend on constant elasticity trade-cost functions that are parametrized by historical trade volumes and transport costs. Transport costs are estimated from the difference between world import and export values similar to Buongiorno et al. (2003). The share of transport costs in the value of the product is higher for raw materials such as roundwood, woodchips and recycled paper than for forest industry final products.

Biomass supply is based on spatially explicit harvest potentials, spatially explicit harvest costs, spatially explicit transportation costs and forest/management type specific land-use change costs. Harvest potentials are based on increment data from the Global Forest Model (G4M) (Kindermann et al., 2006, 2008; Gusti and Kindermann, 2011). In long-rotation forestry, the whole increment (excluding harvest loss) can be used for pulpwood, but only part of the increment can be used for sawlogs. This is due to the joint- production of sawlogs and pulpwood, which implies that part of the harvest potential is biomass from thinning, which does not qualify as sawlogs. The joint-production increases the relative price of sawlogs and makes pulpwood a by-product of sawlogs production. In short-rotation forestry, sawlogs and pulpwood are produced separately, and the whole increment (excluding harvest loss) can be used for pulpwood or sawlogs. Short-rotation forestry can be used only in the tropical zone, while long-rotation forestry is possible in all regions. The harvest costs are based on G4M data. Transportation costs are based on Di Fulvio et al. (2016). Land-use change costs are linearly increasing, and are based on historical land-use change patterns. The purpose of land-use change costs is to control the transition between different forest and management types. The model includes three forest types (primary forests, secondary forests, managed forests) and three management types (low intensity, multifunctional, high intensity). Primary forests are forested land that has not been used historically for production. Managed forests are forested land that is currently actively used for production while secondary forests are abandoned managed forests. Management types differ in the proportion of increment that can be harvested. In high intensity management, the whole increment can be harvested while in multifunctional and low intensity management, only part of the increment can be harvested. Consequently, harvest volumes can be increased by increasing the managed forest area or by intensifying forest management within the managed forest area, i.e., changing the management type.

The allocation of forest area to different forest and management types is based on.

economic tradeoffs between different forest management types, and using additional data on initial forest management types. The economic optimization alone does not necessarily correctly allocate forest management since it typically allocates high intensity management to the most productive and easily accessible forest areas, and low intensity management and primary forests are allocated to less productive and remote forest areas. Therefore, the outcome of the economic optimization is improved in the model by using additional data on initial forest

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[2] Other papers include FAOSTAT categories household and sanitary papers and other paper and paperboard.

[3] Fiberboard includes FAOSTAT categories OSB, hardboard, MDF/HDF, other fiberboard and particleboard.

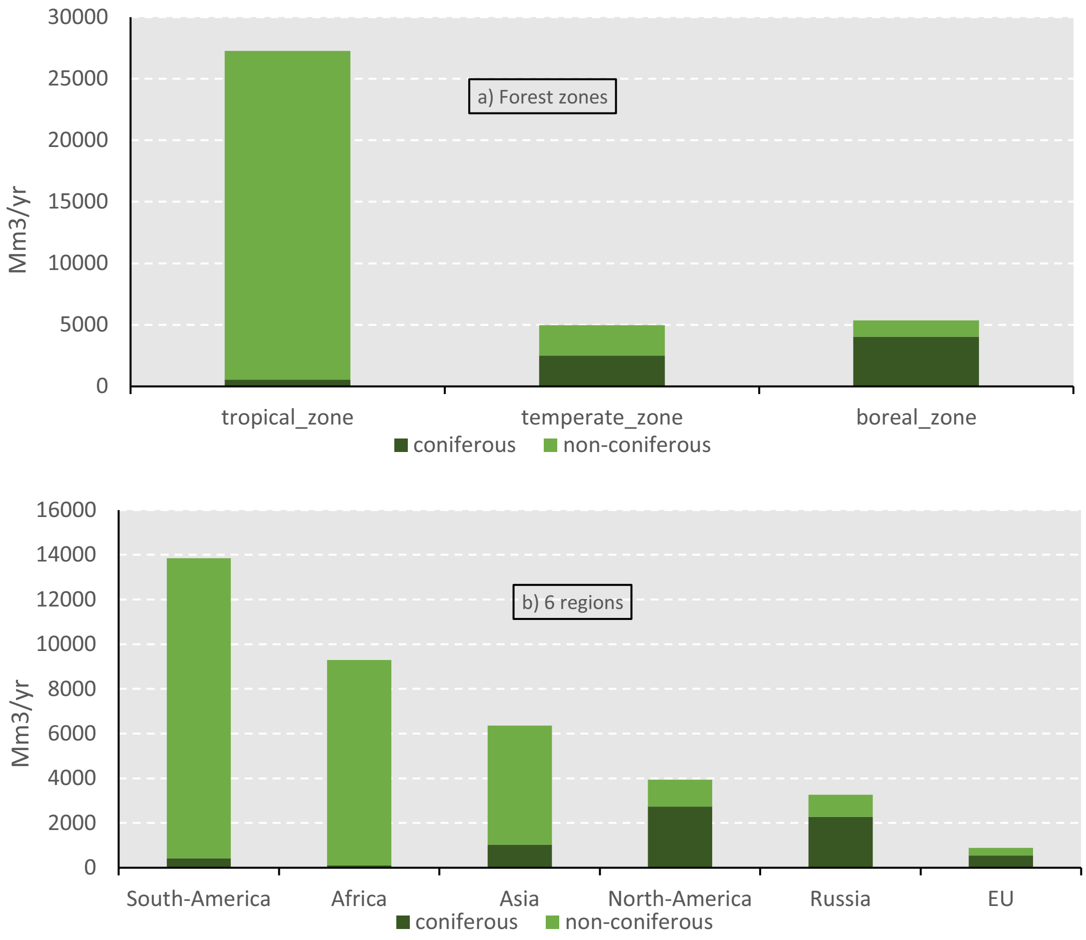

Fig. 1. GLOBIOM roundwood harvest potential divided to C and NC biomass.

management types such as Global Forest Resources Assessment (FRA, 2015), World Database on Protected Areas (WDPA, 2020) and Nature Map Explorer (IIASA, 2020b).

2.2. Representation of coniferous and non-coniferous biomass in GLOBIOM-forest

Including coniferous (C) and non-coniferous (NC) biomass separation in the model.

increases the number of wood-based products from 26 to 38. The separation is applied for all products except fiberboard, paper and paperboard and bioenergy products. The separation is not applied for these products, because they are often produced from a mixture of C and NC biomass. The separation is based on FAOSTAT data where available (FAO, 2020), or when FAOSTAT data is not available, the separation is approximated by using regional C and NC biomass resource balances. Using wood resource balances to determine missing wood flows is a common methodology in forest sector analysis (Mantau et al., 2010; Jochem et al., 2015; Jonsson et al., 2021). For fiberboard, newsprint, printing and writing papers and bioenergy production C and NC biomass are assumed to be perfect substitutes, which implies that the share of C and NC biomass can vary between 0 and 100%. For packaging materials and other papers production the minimum share of C biomass is assumed to be 75%.

Harvest potential separation for C and NC biomass is based on the FRA (2015) country level growing stock data. For the EU, we use a separate spatially-explicit tree species dataset (Brus et al., 2012). Tree species distribution is assumed to stay fixed over time, with C trees dominant in the boreal zone and NC trees in the tropical zone. In the temperate zone, C trees are dominant in some regions, and NC trees in other regions. This implies that the majority of NC biomass harvest potential is located in the tropical zone, while the majority of C biomass harvest potential is in the boreal and temperate zones. At the regional level,[4] the majority of North-America, Russia and the EU harvest potential is C biomass while the majority of South-America, Africa and Asia harvest potential is NC biomass (Fig. 1b).

2.3. Representation of recycled biomass in GLOBIOM-forest

Recycled (R) biomass can be used to substitute virgin fibers in wood-based products production. Due to material losses and the ageing of recycled biomass it is not possible to substitute all virgin fibers with R biomass, but there are maximum technical shares for R biomass use. The model includes three R products: R wood, R paper and R pulp. R wood is recovered from mechanical forest industry products, which are re-used as a raw material in fiberboard production or burned for energy. R paper is recovered paper and paperboard, which is re-used for R pulp production. R pulp is used as a raw material in paper and paperboard production.

The supply of R wood is based on the final consumption of

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[4] The world is divided into six regions as follows: South-America (South America + Central America +Mexico), Africa (Africa), Asia (Asia +Oceania), North-America (Canada + USA), Russia (Russia + rest of European countries), and the EU (EU28). The six regions are further subdivided into traditional forest industry regions (North-America, Russia, the EU) and emerging forest industry regions (South-America, Africa, Asia) based on their historical development (FAO, 2020).

Table 1
Different scenarios.

Scenario	Description
Baseline	C and NC biomass remain imperfect substitutes after 2020. High circular economy.
C/NCsub	C and NC biomass perfect substitutes after 2020. High circular economy.
LowCircu	C and NC biomass remain imperfect substitutes after 2020. Low circular economy.
C/NCsubLowCircu	C and NC biomass perfect substitutes after 2020. Low circular economy.

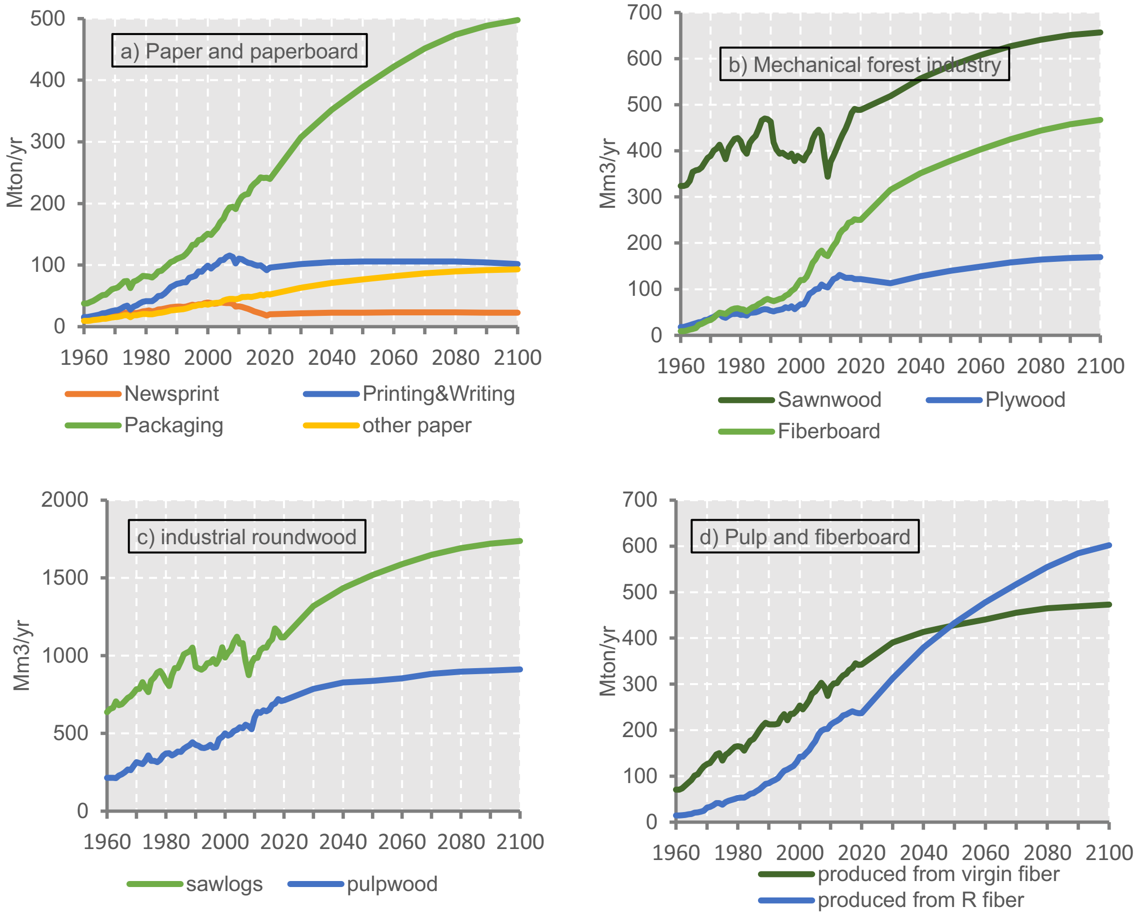

Fig. 2. Global wood-based products consumptions in the baseline scenario.
In Fig. 2d fiberboard volumes are converted from m^3 to ton by using conversion factor 0.6 ton/m^3.

mechanical forest industry products and on R wood collection rates. The maximum R wood collection rate is assumed to be 50% based on Leek (2010). The supply of R paper is based on FAOSTAT statistics for 2000–2020. After 2020, R paper supply is endogenous and is determined by paper and paperboard consumption and R paper collection rates. The maximum R paper collection rate is assumed to be 80% based on observed maximum national collection rates (CEPI, 2019). The supply of R pulp depends on the supply of R paper and R pulp yield from R paper. R pulp yield from R paper depends on the filler content of R paper, and the ageing effect of R biomass (Stawicki and Read, 2010; Van Ewijk et al., 2017). The average R pulp yield with the ageing effect is about 90%. Connecting this to the filler content of different paper grades (packaging materials 0%, newsprint 10% and printing and writing papers 20%) gives recycled pulp yield of 70–90% depending on the paper grade.[5] Other papers are assumed to have zero yields, since they mainly include sanitary papers, which are usually not recycled. Connecting the R pulp yields to maximum collection rates and the consumption shares of different paper grades implies that the maximum technical share of R pulp varies from 60% to 65% at the global level.

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[5] R pulp yields of 70–90% are based on the technical properties of recycling process, which are assumed to be same for all countries. This type of “best available technology” approach is a common simplification in forest sector analysis to avoid complications between country level efficiency differences. Alternatively, R pulp yields could be estimated separately for each country using FAOSTAT data, material balance analysis and conversion factors. This approach tends to imply somewhat lower R pulp yields (55–90%) (Jochem et al., 2021).

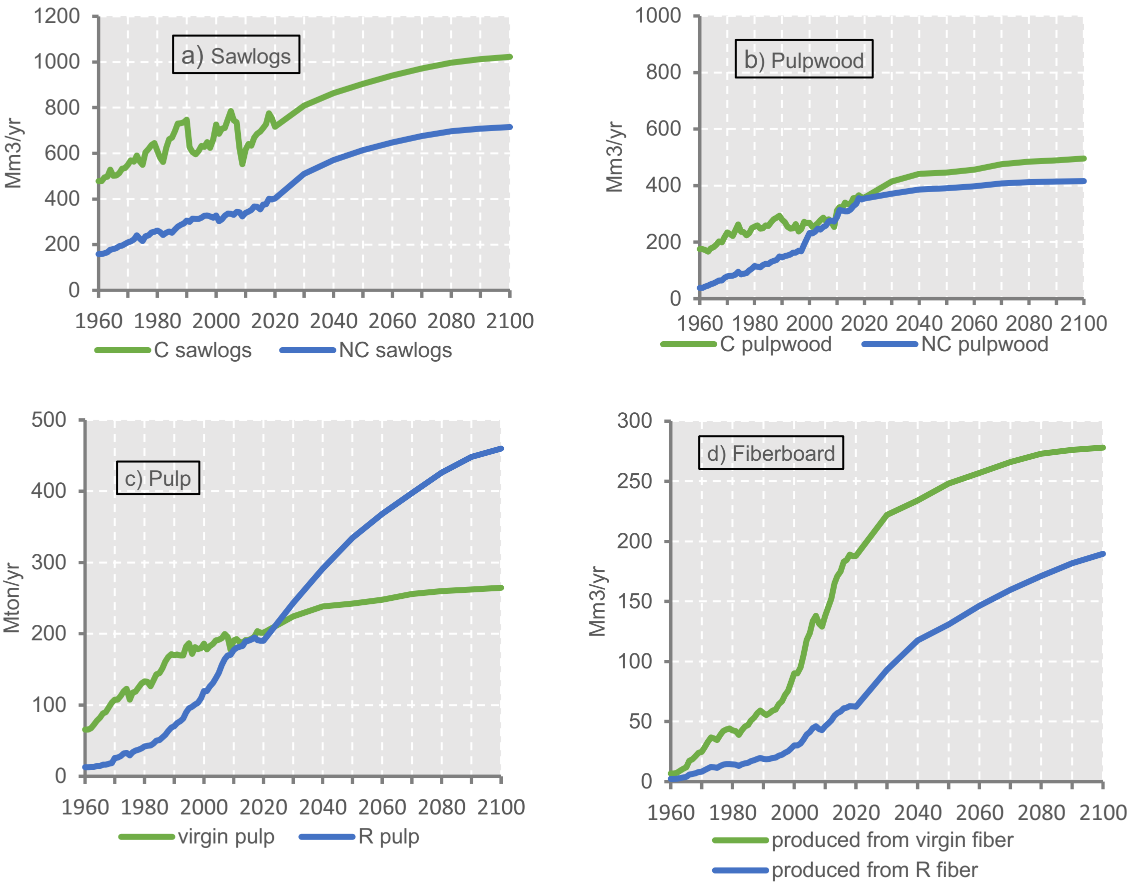

Fig. 3. Global forest industry raw material use in the baseline scenario.

2.4. *Forest industry regional competitiveness*

Regional (or national) competitiveness is a commonly used term in international trade analysis, but it does not have a clear economic definition and there is no commonly agreed method how to measure it in quantitative terms (Gordeev, 2020). In general, regional competitiveness can be measured by results-oriented or determinant-oriented indicators (Dieter and Englert, 2007). Result-oriented indicators measure the realized competitive situation of a region, while determinant-oriented indicators measure factors that are correlated with the realized competitive situation. For a forest sector analysis, a result-oriented indicator is more suitable than determinant-oriented indicators, as the latter which are usually used to analyze the competitiveness of the economy as a whole, and would require a general equilibrium analysis. Result-oriented indicators are usually based on export data since exports show the strength of a region's ability to compete in international markets. The most commonly used result-oriented indicator is revealed comparative advantage (RCA). However, this indicator is mostly a measure of regional specialization than of regional competitiveness (Dieter and Englert, 2007).

In this study, we measure forest industry regional competitiveness by using the value of wood-based products net exports. This indicator measures regional competitiveness rather than the regional specialization, takes into account exports as well as imports and allows aggregation over different wood-based products. The value of net exports is calculated from using world market prices, which are endogenous in the model. An alternative way to aggregate over different wood-based products would be to use roundwood equivalent units (Ervasti, 2016; Jochem et al., 2021). The advantage of measuring net exports by roundwood equivalent units instead of values is that roundwood equivalent units reflect better the amount of roundwood that is used for their production.

This becomes a relevant issue if the environmental sustainability perspective is included in the regional competitiveness analysis (Pendrill et al., 2019; Zhang et al., 2020).

The model-based value of net exports might differ from the FAOSTAT export and import values (FAO, 2020), because the model does not take into account the regional differences in the quality of traded products, but assumes that all traded products have the same quality and world market price. In reality, the quality and value of traded products might differ between the regions. Quality differences could be included in the analysis by increasing the number of products in the model. For example, traded sawnwood could be separated to high/low quality sawnwood by using export and import values. However, this would complicate the model, and would require additional data on high/low quality sawnwood raw material use and final consumption, which is not generally available.

2.5. *Scenarios*

We consider four scenarios for the period 2020–2100. The scenarios are defined by assumptions about the future development of material substitution between C,NC and R biomass (Table 1). In the baseline scenario, C and NC biomass are assumed to remain imperfect substitutes in biomass processing and final products consumption after 2020. This means that forest industry final products have separate demand functions for C and NC products, and C pulp cannot be fully replaced by NC pulp in the paper and paperboard production. Moreover, the development of the circular economy continues after 2020, which means that the proportion of R pulp in paper and paperboard and the proportion of R wood in fiberboard production are allowed to increase after 2020.

In the C/NCsub scenario, C and NC biomass are assumed to be perfect

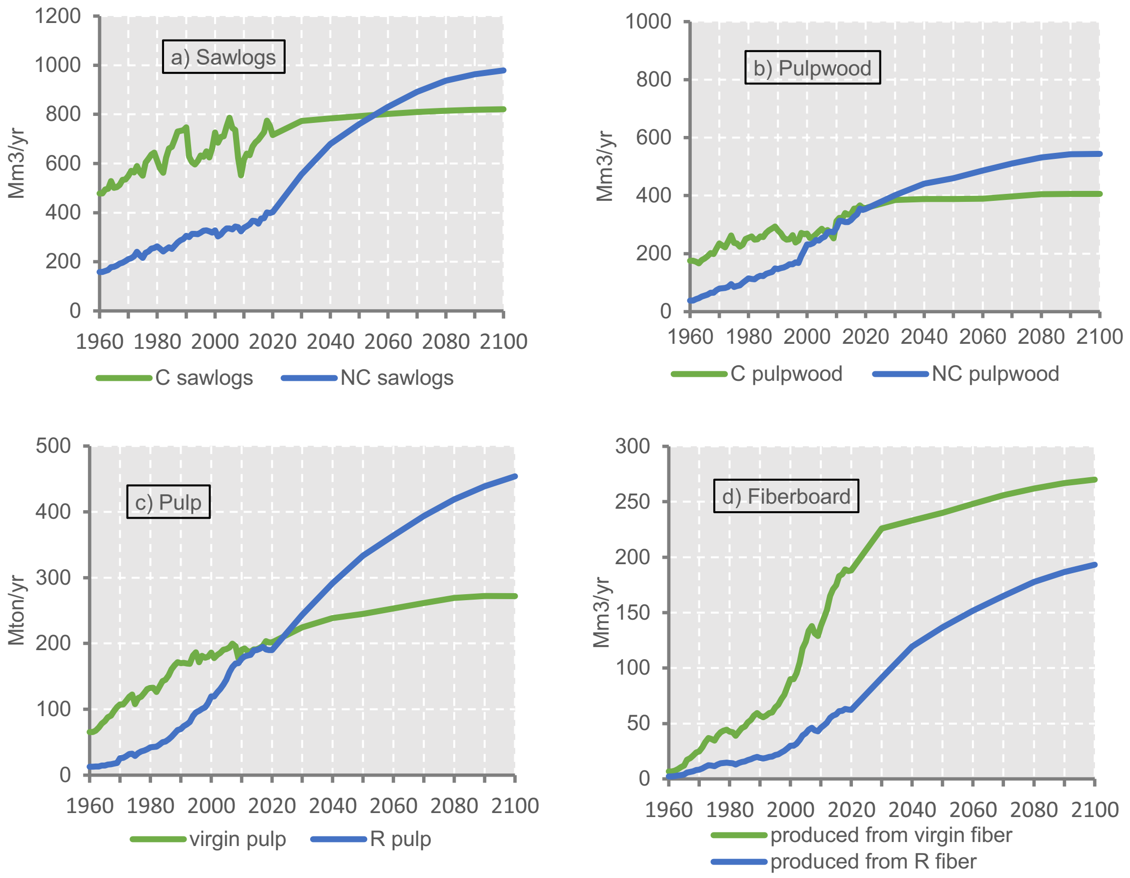

Fig. 4. Global forest industry raw material use in the C/NCsub scenario.

substitutes in biomass processing and final products consumption after 2020. This means that forest industry final products have common demand functions for C and NC products, and C pulp can be fully replaced by NC pulp in the paper and board production. In the LowCircu scenario, the development of the circular economy is assumed to stagnate at the 2020 level. This means that the proportion of R pulp in paper and paperboard production is limited to 50% and the proportion of R wood in the fiberboard production to 25%. In the C/NCsubLowCircu, C and NC biomass are perfect substitutes, and the development of the circular economy is low, i.e., it is a combination of C/NCsub and LowCircu scenarios.

The socioeconomic development (SSP2) and climate pathway (RCPref) are assumed to be the same for all scenarios. Consequently, all scenarios have the same wood-based products demand, and the scenarios differ only in terms of material substitution between C, NC and R biomass. SSP2 represents intermediate socioeconomic development where population growth is expected to stagnate after 2050 (IIASA, 2020). This tends to slow down the growth of forest production consumption in the future. RCPref is a no mitigation climate pathway where the temperature is expected to increase by 3.8 °C relative to the pre-industrial level (IIASA, 2020). In this scenario, bioenergy demand does not increase much in the future, which implies that the development of woody biomass use is determined by changes in material use rather than changes in energy use. Moreover, carbon prices are zero, implying that there are no carbon taxes, which would affect woody biomass use.

3. Results

3.1. Baseline scenario

Fig. 2 presents the development of global wood-based products consumption in the baseline scenario. The period 1960–2019 is based on FAOSTAT data (FAO, 2020) while the period 2020–2100 is based on the model outcome. Paper and paperboard consumption has increased constantly in the past 60 years excluding graphical papers (newsprint + printing & writing) (Fig. 2a). Graphical papers consumption has stagnated in the past 20 years due to the information technology revolution, which has decreased the need for newsprint and printing and writing papers. This development is expected to continue in the future. On the other hand, consumption of packaging materials and other papers is expected to increase in the future. This is caused by the growing need for packaging materials and sanitary papers, as global trade and living standards continue to rise according to SSP2 socioeconomic development.

Mechanical forest industry products consumption has increased constantly in the past years excluding temporary business cycle fluctuations (Fig. 2b). The growth rate of consumption is expected to decrease somewhat in the future due to saturation of population growth in the SSP2 scenario. Fiberboard (fiberboard + particleboard) consumption is expected to increase more in the future than sawnwood and plywood consumption due to technical improvements in fiberboard material properties and lower raw material costs.

Sawlogs and pulpwood consumption increased in the past years following the increase in final products consumption (Fig. 2c). Sawlogs consumption is expected to continue increasing in the future while pulpwood consumption is expected to stagnate. This is caused by decreasing demand for graphical papers and increasing use of recycled

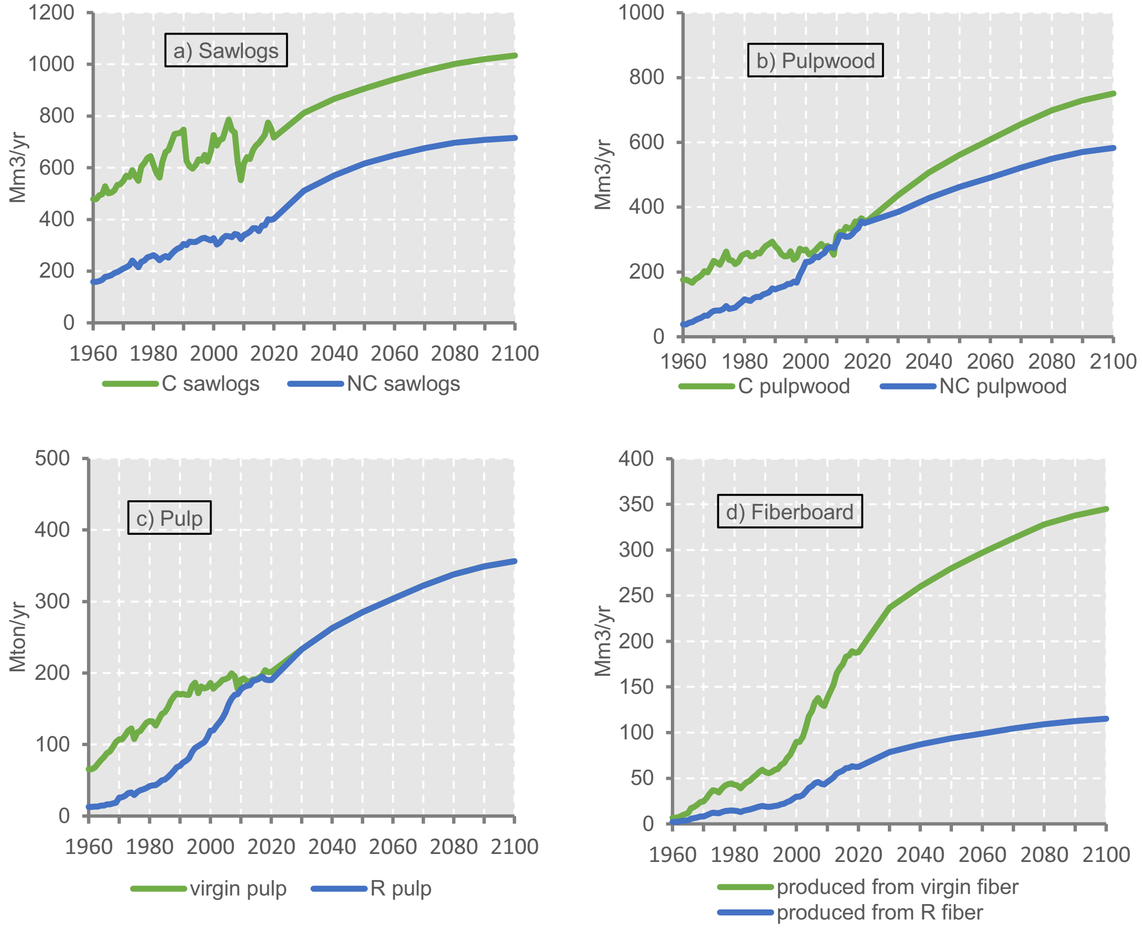

Fig. 5. Global forest industry raw material use in the LowCircu scenario.

biomass in the pulp and fiberboard production (Fig. 2d).

3.2. Forest industry raw material use in different scenarios

Forest industry raw material use differs between the scenarios due to different scenario assumptions about material substitution between C, NC and R biomass. Socioeconomic development is assumed to be same in all scenarios, which implies that final products consumption (Fig. 2a and b) is the same for all scenarios and does not affect raw material use between the scenarios.

Figs. 3-6 present the development of forest industry raw materials use in different scenarios. The period 1960–2019 is based on FAOSTAT data (FAO, 2020) while the period 2020–2100 is based on the model outcome. The proportion of C sawlogs has decreased in the past 60 years from 75% to 65%, while the proportion of C pulpwood from 80% to 50% (Fig. 3a and b). This is due to the growth of forest industry in regions, which has increased NC biomass supply. Over the same period, the proportion of R pulp increased from 15% to 50% due to an increase in R paper collection and utilization (Fig. 3c). The proportion of R pulp has been around 50% during the last 10 years, which indicates possible saturation of R pulp utilization. The proportion of fiberboard produced from R wood has increased less, and is currently around 25% (Fig. 3d).

In the Baseline scenario, it is assumed that C and NC biomass remain imperfect substitutes after 2020 and the development of circular economy continues. The proportion of C sawlogs declines only slightly from 65% to 59% and C sawlogs remain the main raw material for sawnwood and plywood production in the future (Fig. 3a). This especially benefits especially the boreal zone, which can utilize its large C biomass harvest potential (Fig. 1). The proportion of C pulpwood increases from 50% to 54% (Fig. 3b), due to increasing consumption of packaging materials and other papers, which are mainly produced from C pulp. However, C pulpwood use increases less than C sawlogs use, due to the development of the circular economy, which increases the availability of R biomass and reduces the demand for pulpwood. This tends to lead an oversupply of C pulpwood, since the joint-production of C sawlogs and C pulpwood increases the availability of C pulpwood more than is needed. The proportion of R pulp continues to increase in the future, and reaches the maximum technical upper bound of 63% in 2100 (Fig. 3c). The proportion of R fiber used for fiberboard increases from 25% to 41% (Fig. 3d).

In the C/NCsub scenario, it is assumed that C and NC biomass are perfect substitutes after 2020 and the development of circular economy continues. The proportion of C sawlogs declines significantly from 65% to 46% (Fig. 4a), due to perfect substitution, which allow an increase in NC sawlogs utilization in sawnwood and plywood production. This especially benefits the tropical zone, which can utilize its large NC biomass harvest potential (Fig. 1). The proportion of C pulpwood declines from 50% to 43% (Fig. 4b), due to perfect substitution, which allows increasing NC pulpwood utilization in the paper and paperboard production. The development of pulp and fiberboard use is similar to the baseline scenario (Fig. 4c and d).

In the LowCircu scenario, it is assumed that C and NC biomass remain imperfect substitutes after 2020 and the development of the circular economy stagnates at the 2020 level. The development of sawlogs use is similar to the baseline scenario (Fig. 5a). Pulpwood use continues increasing after 2020 and the proportion of C pulpwood increases from 50% to 56% (Fig. 5b), due to lower availability of R biomass, which increases the demand for pulpwood in pulp and

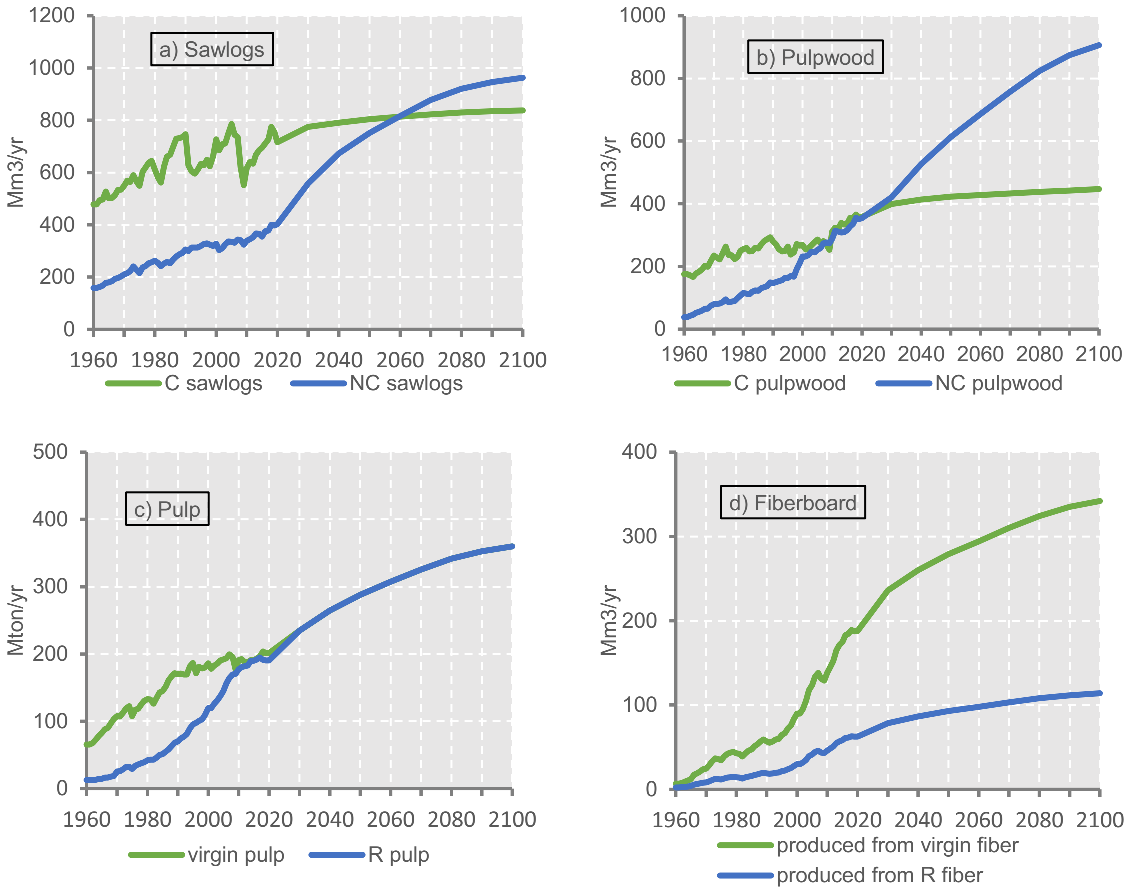

Fig. 6. Global forest industry raw material use in the C/NCsubLowCircu scenario.

fiberboard production. This especially benefits the boreal zone, because it corrects the oversupply of C pulpwood caused by joint-production of C sawlogs and C pulpwood. The proportion of R pulp stays at 50% and the proportion of R fiber used for fiberboard remains at 25% (Fig. 5c and d).

In the C/NCsubLowCircu scenario, it is assumed that C and NC are perfect substitutes after 2020 and the development of circular economy stagnates at 2020 level. The development of sawlogs use is similar to the C/NCsub scenario (Fig. 6a). Pulpwood use continues increasing after 2020, but in contrast to the C/NCsub scenario this causes a decline in the proportion of C pulpwood from 50% to 33% (Fig. 6b), due to perfect substitution, which allows increased NC pulpwood utilization in paper and paperboard production. Hence, in this case, higher demand for pulpwood benefits the tropical zone instead of the boreal zone. The development of pulp and fiberboard use is similar to the LowCircu scenario (Fig. 6c and d).

3.3. Forest industry regional competitiveness in different scenarios

Fig. 7 presents the value of wood-based products net exports, which can be used to measure forest industry regional competitiveness. The historical values of net exports are not included in the analysis, since the FAOSTAT export and import values might differ somewhat from the export and import values in the model as discussed in section 2. In 2020, all regions except Asia are net exporters of wood-based products. The largest net exporter is North-America ($15 Billion) followed by Russia ($9.3 Billion), the EU ($8.9 Billion), South-America ($6.7 Billion) and Africa ($0.1 Billion) (Fig. 7). After 2020, the value of net exports develops differently in each region. In particular, the net exports trends are qualitatively different in traditional and emerging forest industry regions.

In the baseline scenario, the value of the EU net exports increases from $8.9 Billion to $10.5 Billion in 2080 and then decreases back to $8.9 Billion in 2100 (Fig. 7a). This indicates that the EU forest industry can maintain its competitiveness as long as C and NC biomass remain imperfect substitutes. The decline in the EU net exports towards the end of the century is caused by limited forest resources, which restrict the expansion of sawlogs harvests in the EU. In the LowCircu scenario, the limited availability of R biomass increases the demand for C pulpwood. This improves the competitiveness of the EU forest industry and increases the value of net exports up to $12.6 Billion in 2100. In the C/NCsub scenarios, perfect substitution between C and NC biomass weakens the competitiveness of the EU forest industry and decreases the value of net exports to -$2 Billion in 2100. In the C/NCsubLowCircu scenario, perfect substitution between C and NC biomass weakens the competitiveness of the EU forest industry. Moreover, the limited availability of R biomass result in much benefit for forest industry in the EU, since the perfect substitution between C and NC directs the growth of demand for pulpwood to NC pulpwood instead of C pulpwood. The value of net exports decreases to -$1 Billion in 2100, which is slightly less than in the C/NCsub scenario.

The development of North-America and Russia net exports is comparable to the EU (Fig. 7b and c), because the EU, North-America and Russia all have large C biomass harvest potentials, which benefits them if C and NC biomass remain imperfect substitutes. The value of net exports from Russia does not decrease in the C/NCsub and C/NCsubLowCircu scenarios, because the Russian forest industry is less developed than the EU and North-America forest industries. The majority of wood-based products exports from Russia consists of low value-added products such as roundwood and sawnwood, which are less affected by material substitution. On the other hand, the EU and North-America export more high value-added products such as pulp and paper and paperboard, which are more affected by material substitution.

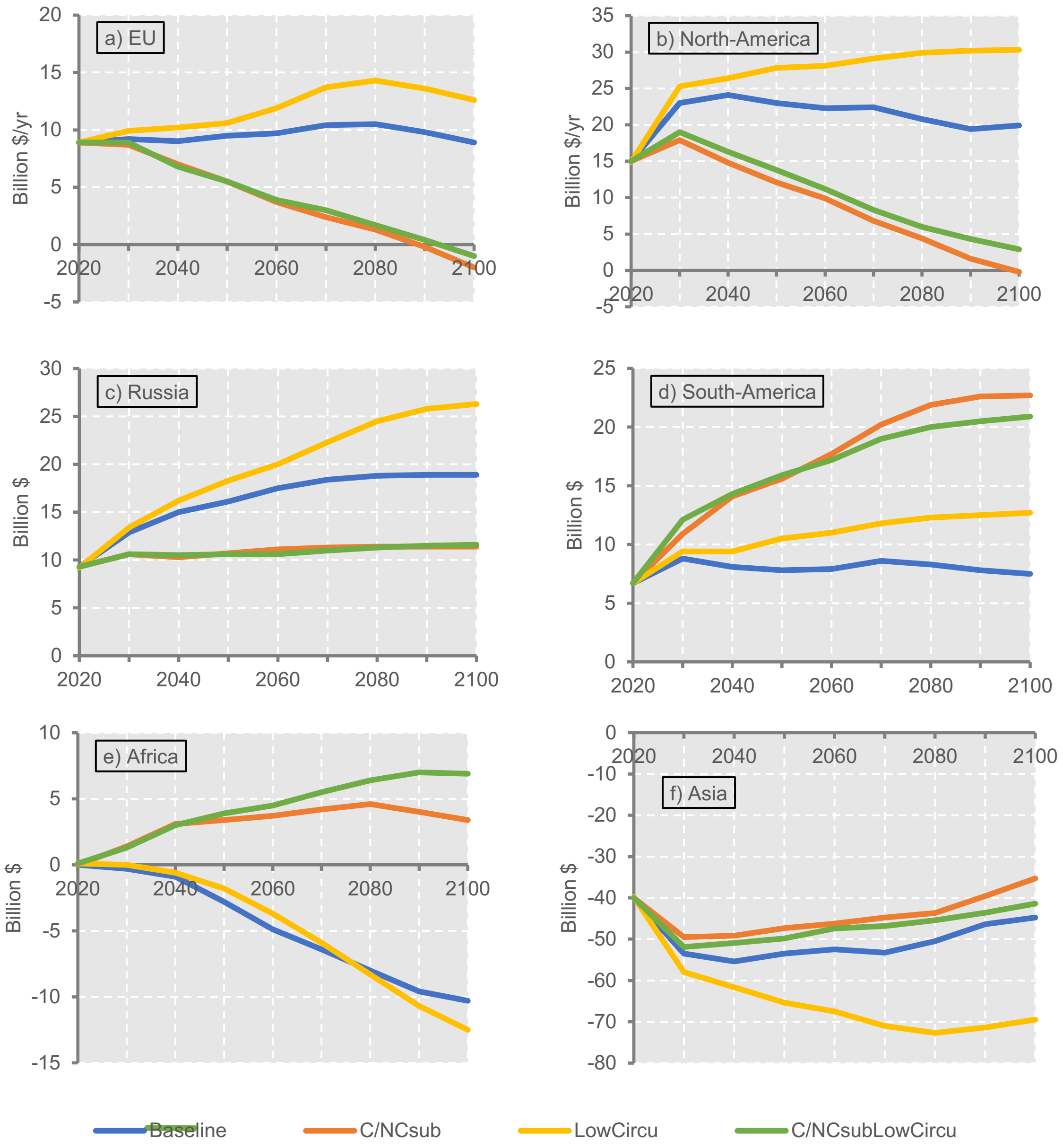

Fig. 7. The value of wood-based products net exports.

Despite the low added value, the total value of Russia exports is high, because Russia is the biggest roundwood and sawnwood exporter in the world.

The development of net exports from South-America and Africa is the opposite of trends in the EU, North-America and Russia (Fig. 7d and e). The value of South-America and Africa net exports is highest in the C/NCsub and C/NCsubLowCircu scenarios, implying that these regions benefit from perfect substitution between C and NC biomass, because they have large NC biomass harvest potentials. The value of net exports from Africa is lower than the value of South-American net exports, because the African forest industry is less developed than the South-American forest industry. Africa exports low value-added products such as roundwood and sawnwood while South-America exports more high value-added products such as pulp. Moreover, South-America has larger C biomass harvest potential than Africa, which increases the competitiveness of the South-American forest industry in the baseline and LowCircu scenarios.

The value of net exports from Asia is highest in the C/NCsub and C/NCsubLowCircu scenarios, implying that Asia benefits from perfect substitution between C and NC biomass, in a similar way to South-America and Africa (Fig. 7f). However, the value of Asia net exports remains negative in all scenarios. This should not be interpreted directly as low competitiveness of the Asian forest industry, since Asia is a net importer of wood-based products due to high domestic demand for wood-based products and limited domestic harvest potentials in countries such as China, Japan and South Korea.

Fig. 8 presents the volume of wood-based products net exports divided to roundwood and forest industry products. Forest industry products are measured in roundwood equivalent units and include wood pellets and recycled paper. The difference in roundwood net exports is small between the scenarios, which implies that regional adaptation to material substitution happens through trade in intermediate and final products rather than in raw materials. More generally, this means the competitive advantage of regions in the model is based on domestic raw material use, and regions are not able to improve the competitiveness of their forest industry by importing raw materials from other regions. This is because transport costs, which account for a larger share of the price of raw materials than for the price of forest industry products, i.e., it is

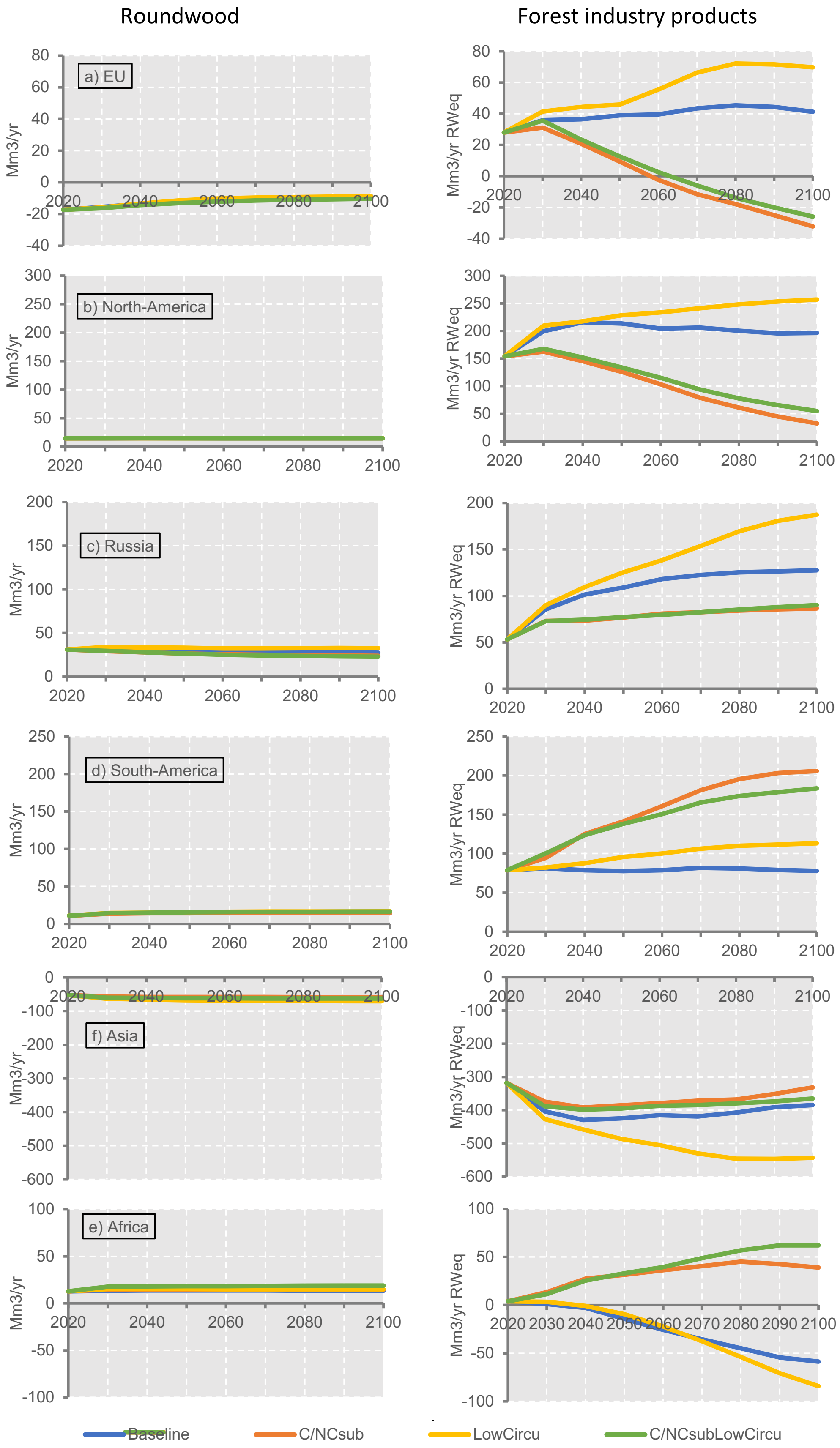

Fig. 8. The volume of wood-based products net exports divided to roundwood and forest industry products.

more profitable to change the location of forest industry than to import raw materials to compensate missing domestic raw material supply.

In 2020, net exports from North-America cover about 50% of global net exports volume (Fig. 8b) but only about 40% of global net export value (Fig. 7b), while net exports from the EU cover only about 10% of global net exports volume (Fig. 8a) but about 20% of global net export value (Fig. 7a). This is because North-America is exporting large amounts of wood pellets and recycled paper, which have low added value but high roundwood equivalent volume. On the other hand, the EU is exporting higher value-added forest industry products such as paper and paperboard.

4. Discussion

Historically, C biomass has been a preferred raw material in the global forest industry due to its material properties, which has created a competitive advantage for regions with large domestic C biomass resources. NC and R biomass provide a cost-effective alternative to C biomass, but they have not yet been able to replace C biomass in global forest industry raw material use. It is possible that the utilization of NC and R biomass increases in the future, which would decrease the competitiveness of regions with large domestic C biomass resources and direct forest industry investments to the regions with large domestic NC biomass resources. However, this depends much on technical development in the material properties of C, NC and R biomass, which is uncertain. The uncertainty is smaller for R biomass, since the utilization of R biomass is more limited by the recycling efficiency than by its material properties (Stawicki and Read, 2010; Van Ewijk et al., 2017). It is less likely that the material properties of NC biomass could be significantly improved in the future, because they are connected the biophysical properties of NC biomass such as density and fiber length, which cannot be easily changed. There are some promising new technologies that could improve NC biomass material properties such as nanotechnology (Balea et al., 2020, Jasmani et al., 2020,) and laminated timber (Espinoza and Buelmann, 2018; Kühle et al., 2019), but it is unclear how much these technologies could increase material substitution between C and NC biomass in the future. Therefore, the baseline scenario of the model assumes that C and NC biomass remain imperfect substitutes, and the development of the circular economy increases the availability of R biomass.

Material substitution between different biomass types also affects forest industry raw material use. In particular, an increased availability and utilization of R biomass due to the development of the circular economy development tends to reduces the demand for pulpwood in traditional forest industry regions. This opens new perspectives for pulpwood use and forest management in traditional forest industry regions. First, the oversupply of pulpwood could be used for modern bioenergy. Using pulpwood for energy is controversial (Schulze et al., 2012). However, if the demand for sawlogs exceeds the demand for pulpwood, using pulpwood for energy might be reasonable, because without thinning operations the harvest potential of sawlogs would remain lower (Zeide, 2001). Second, the oversupply of pulpwood could be used for new products such as wood-based textiles (Verkerk et al. 2020, Kallio, 2021, Schier et al., 2021). Third, forest management could be changed to avoid the oversupply of pulpwood, for example by moving from even-aged management to uneven-aged management tends to increase sawlogs harvest potential and decrease pulpwood harvest potential (Kellomäki et al., 2019; Vauhkonen and Packalen, 2019; Schwaiger et al., 2019). Another management option could be to covert coniferous monocultures to mixed-forests (Schwaiger et al., 2019; Huuskonen et al., 2021).

The main limitations of our analysis are in the representation of forestry sector, which includes simplifications in respect to forest management and environmental sustainability modelling. First, harvest potentials are based on the G4M increments, which were calculated in G4M by assuming that all forests are normal forest (Reed, 1985). Normal forests have a uniform distribution of age-classes and in each period the oldest age-class is removed by harvesting or by natural mortality. From the normal forest assumption, it follows that increments are independent of harvest volumes, and they stay constant over time. In reality, forests are seldom normal forests, which implies that increments are not independent of harvest volumes. It would be possible to calculate G4M increments by solving G4M for the actual age-class distribution of forests without the normal forest assumption. However, in this case increments depend on harvest volumes and the G4M increments should be solved separately for each level of harvests, which would significantly complicate the model. Second, the transition between different forest and management types is assumed to happen within a 10-year period without explicit transition dynamics. An alternative option would be to include age-class dynamics in the model, which would allow modelling the transition dynamics between the forest and management types in the model. However, this option would complicate the analysis significantly and was not used in this study. Third, environmental sustainability may impact the availability of different biomass types and material substitution between them. For example, several studies have shown that tropical short-rotation forestry may not be a sustainable solution for biomass production (Cossalter and Phy-Smith, 2003, Pawson et al., 2012, Heilmayer, 2014, Kremer and Bauhaus, 2020). This might decrease the competitiveness of tropical short-rotation forestry relative to temperate and boreal zone long-rotation forestry. Fourth, the concept of competitiveness could be extended to also account for sustainable development goals (Baumgarther, 2019) and timber harvest footprints (Pendrill et al., 2019; Zhang et al., 2020). Including the environmental sustainability perspective in the analysis of material substitution and forest industry regional competitiveness remains a subject of further study.

5. Conclusions

In this study we investigate material substitution between C, NC and R biomass using a global forest sector model: GLOBIOM-forest. Our results indicate that traditional forest industry regions can maintain their competitiveness in the baseline scenario where C and NC biomass remain imperfect substitutes, and the availability of R biomass increases. A limited availability of R biomass would increase the competitiveness of traditional forest industry regions relative to the baseline while a perfect substitution between C and NC biomass would decrease it. We also show that the increased availability of R biomass tends to decrease the demand for pulpwood and might lead to an oversupply of pulpwood in traditional forest industry regions.

Our analysis has great importance for long-term forest sector outlook studies, especially those based on forest sector models (FSMs). First, forest sector outlook studies are often criticized for lacking tools to analyze the implications of changing production and consumption patterns (Hetemäki and Hurmekoski, 2016). In this study, we have shown that FSMs are able to analyze the implications of changing production and consumption patterns, such as material substitution between C, NC and R biomass. In the analysis of this issue, it is not sufficient to rely on historical trends and empirical estimates of demand and supply elasticities. Instead, an integrated modelling approach that includes sufficiently detailed descriptions of forest sector fundamentals, such as forest industry production processes, forest products final demands and forest managements practices, is required. Second, many forest sector outlook studies and FSMs do not take into account imperfect substitution between C and NC biomass, i.e., they assume that C and NC biomass are perfect substitutes in biomass processing and final consumption. According to our findings this might overestimate the future competitiveness of short-rotation forestry and emerging forest industry regions. Moreover, many forest sector outlook studies and FSMs do not take into account the development of the circular economy and the increasing availability of R biomass. According to our findings this might lead an overestimation of the future demand for pulpwood especially in traditional forest industry regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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