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Assessing Impacts of Wood Utilisation Scenarios for a Lithuanian Bioeconomy: Impacts on Carbon in Forests and Harvested Wood Products and on the Socio-Economic Performance of the Forest-Based Sector

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Abstract: Climate change and transition towards a bioeconomy are seen as both challenges and opportunities for the forest-based sector in Europe. Transition towards a bioeconomy will in most cases rely on intensified use of renewable resources and/or advancement in technology. However, how can the intensified use of renewable resources be combined with climate change mitigation measures to increase carbon sinks in the forest-based sector? Additionally, what are the possible socio-economic and environmental impacts of intensified wood use? In this study, we examined the impacts of increased wood utilisation in Lithuania. The objective of this study was to assess the effects of increased domestic wood utilisation on: (i) employment; (ii) the economic performance of the sector; (iii) carbon in forest biomass and soil; and (iv) carbon in harvested wood products (HWP). The system boundaries were set in accordance with international greenhouse gas reporting to include only domestic wood flows. We assessed alternative wood utilisation scenarios using a forest resource model and a tool to assess sustainability impacts of (wood) value chains, using country specific data on wood (carbon) flows. Our results indicate that increased wood use could lead to trade-offs between six selected indicators. Opportunities for employment and the economic performance of the forest-based sector improved in all scenarios due to increased wood utilisation. However, when forest fellings increased, the carbon stored in forests decreased, the carbon stored in HWP increased, but overall the total carbon stored in forests and HWP decreased. When considering also additional substitution effects until the year 2100, the scenario with reduced wood exports generated larger total climate change mitigation effects than the baseline. Our results suggest that increased wood utilisation might support Lithuania's bioeconomy through increased socio-economic benefits. National positive climate change mitigation effects could be gained only if additional actions to utilise more domestic wood for long-life HWP will be taken.

Keywords: climate change mitigation; forest fellings; carbon stock; policy implications; ToSIA; EFISCEN

1. Introduction

The bioeconomy strategy for Europe aims to tackle societal challenges such as natural resource scarcity, fossil resource dependence, and climate change, while achieving sustainable growth. The current European bioeconomy includes sectors with an annual turnover of over €2 trillion annually and provides jobs to 22 million people [1]. The bioeconomy itself is a broad concept, and according to the European Union (EU) bioeconomy strategy the concept includes the sectors of agriculture, forestry, fisheries, and industries such as food, pulp, chemical, biotechnological, and energy industries. In this study, we focus on the forest-based sector only, which we understand to include the management of forests and the production and consumption of forest products and services [2–4].

European forests and the European forest-based sector play an important role in supplying a growing bioeconomy [5]. The forest-based sector also contributes to mitigation of climate change through sequestration of carbon in biomass and soil, and carbon storage in harvested wood products (HWP). Furthermore, wood and wood products may substitute fossil-based materials [6–8]. However, substitution effects of wood use are not reportable yet to the United Nation Framework Convention on Climate Change (UNFCCC) under the Land Use, Land-Use Change and Forestry (LULUCF) sector.

It is estimated that the forest sector in the EU currently produces an overall climate mitigation impact that amounts to about 13% of the total EU greenhouse gas (GHG) emissions. By 2030, this number could double if EU Member States would take action to enhance the role of EU forests in tackling climate change [9]. However, EU Member States have different capacities to contribute to the EU bioeconomy and climate change mitigation strategies. For example, Nordic countries (Sweden and Finland) have developed intensive forest management practices and utilised their forest resources at relatively high rates during the last few decades. At the same time, forest resources were underutilised in some eastern European countries including Lithuania. Several studies have recently highlighted that the European forest sector is recovering from the economic crises that started in 2008 and is also undergoing structural changes due to globalisation and changes in societal preferences [10,11]. In addition, many eastern European countries are also still recovering from the collapse of the Soviet system and are facing legislative reforms, privatisation of state forests, and the modernisation of the forest-based sector [12–17]. Lithuania is one such country facing these reforms.

In Lithuania, forests cover 2.2 million ha, which corresponds to 33% of the land area. Almost 50% of forests are owned by the state, 40% are owned by private forest owners, and the remaining 10% of forests are reserved for restitution and are currently without forest management, except for sanitary fellings. The average annual harvest of roundwood for the period 2010–2015 was 7.3 million m^3, of which 6.1 million m^3 was industrial roundwood [18] that could be potentially used for manufacturing of long-life wood products and storing carbon in those products. However, around 30% of domestic industrial roundwood is exported, mainly as pulpwood, because there is no pulp industry in the country. Recently, the export of pulpwood decreased, while the export of sawlogs increased. The forest-based sector as a whole (including wood and furniture industry) contributes about 4% to the gross domestic product of Lithuania, and this contribution has been increasing over the last decade; forestry alone contributes about 0.6% to the GDP. On average, the forest-based sector provides around 59,000 jobs (2010–2015) mainly in the manufacture of furniture and the manufacture of wood products; forestry alone contributes about 10,000 jobs.

During the Soviet regime (1944–1991) the annual harvest in Lithuania was significantly lower than nowadays, on average only 3.2 million m^3. This was mainly because roundwood was imported from the other Soviet Union countries [19]. Forest resources in Lithuania have expanded significantly after the Second World War. On average, during the period 1951–1991 only 37% of the annual increment was felled [20]. After the collapse of the Soviet Union in 1991, use of forest resources has intensified. The forest fellings increased from 3 million m^3 in 1990 up to 7.6 million m^3 in 2014 [18]. The forest area and growing stock in Lithuanian forests have also continuously increased. In the period 1991–2015 the forest coverage increased from 29.8% to 33.4% and growing stock increased from 320 million m^3

to 529 million m^3 [18]. According to the national forest inventory, the gross mean annual increment in 2014 was 18.7 million m^3, and annual removals corresponded to only 52% of annual increment. The remaining increment is accumulated in the living biomass (33%) or associated with decaying wood (15%) [18]. It should be noted that 30% of forests in Lithuania are under protection status, where management activities are limited or even prohibited. The growing stock volume in mature stands (i.e., stands above the minimum rotation age) in forests available for wood supply has increased significantly (Figure 1). Therefore, there is a large volume of wood in mature and over-mature forest stands that should be harvested in the near future [21].

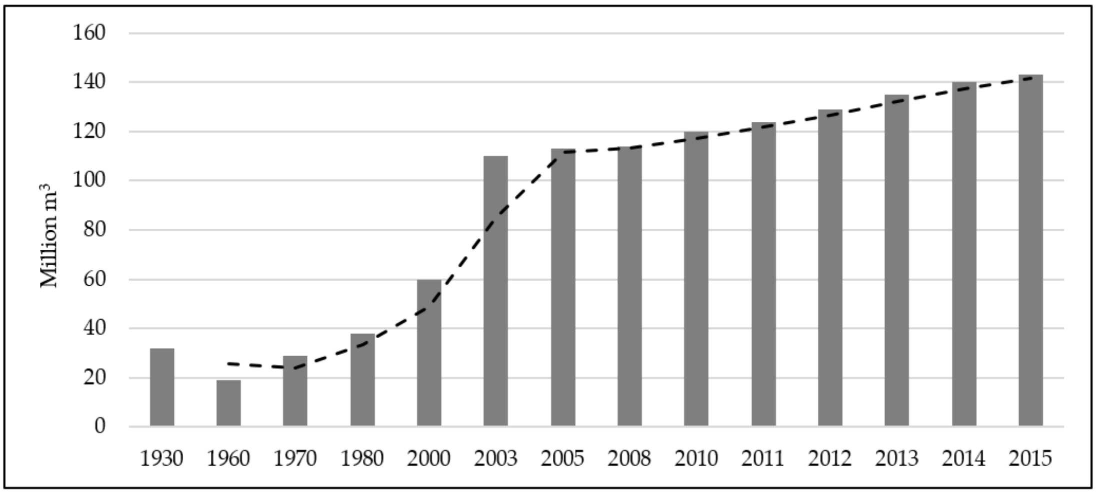


Figure 1. Growing stock volume in the mature forest stands available for wood supply (year 1930–2015) in Lithuania. A significant increase in the year 2003 is related to the change in inventory method from stand-wise forest inventory to national sample-based forest inventory. The national forest inventory presents more reliable data about growing stock volume and their changes. Source: Lithuanian Statistical Yearbook of Forestry [18].

There are a number of reasons for the relatively low harvest in Lithuanian forests: (i) over 10% of forests are still reserved for restitution and forest management in these areas is prohibited; (ii) strict environmental protection policies; and (iii) negative public opinion on forest harvest (annual harvest rates for state forests are approved by the national government and influenced by environmental non-governmental organizations) [22]. In the Lithuanian Forestry Sector Development Programme, four major forest-based sector development objectives are foreseen for the period leading up to 2020. These objectives mainly focus on preserving forest resources and enhancing socio-economic functions of the forest-based sector [23]. In the context of the bioeconomy, possible options for the forest-based sector in Lithuania would be to: (i) increase forest harvest practices that might bring additional benefits for society and mitigate climate change; or (ii) continue accumulation of carbon in forest biomass—however, there is an increased risk of release of carbon in the case of natural disturbances. It should be noted that unutilised forest resources are more vulnerable to natural disasters and in the event of a disturbance may emit more carbon than if harvested [24].

The objective of this study was to assess impacts of increased domestic wood utilisation in Lithuania on employment, economic performance of the sector, and carbon balances in forest biomass and soil and in HWP. For the purpose of this study we posed the following research questions: (i) How do alternative resource use scenarios affect policy targets in Lithuania and internationally? (ii) How can Lithuanian forest policy reconcile climate change mitigation with development of the national and EU bioeconomy?

2. Method

2.1. Wood Value Chains

To examine the effect of increased wood utilisation we built four alternative wood value chains and projected future development under different wood utilisation scenarios. We developed these value chains following the latest Intergovernmental Panel on Climate Change (IPCC) guidelines [25] for carbon accounting in forest biomass, soil, and HWP to ensure relevance with international greenhouse gas reporting. According to these guidelines, carbon used in imported wood cannot be accounted for in a country. Carbon in exported wood can be accounted for, but it is difficult to calculate, as this would require an analysis of wood flows in countries where (Lithuanian) roundwood is exported to. According to the IPCC guidelines, countries would be allowed to account for carbon stored in HWP manufactured from domestic roundwood even where the roundwood is exported. However, there is no data indicating the life-time of the wood products manufactured from the exported roundwood. Therefore, carbon storage and other related effects cannot be attributed to the national budget. Our value chains include processes starting from the forest harvest until the end of production of semi-finished HWP (sawnwood, wood-based panels, cross laminated timber (CLT), and EURO pallets) (Figure 2). Pulp and paper are not considered for future scenarios, as paper products in Lithuania are produced from imported pulp and this commodity is therefore excluded from our chains. We collected data on wood flows by surveying wood companies manufacturing semi-finished HWP (Supplementary Material A). In this way, we collected data on material flow corresponding to 63% of domestic industrial roundwood used by the local industries. Data on production of finished HWP (wood products that have been further processed including furniture, carpentry products, etc.) are not available. Therefore, our value chains end with semi-finished HWP and full impacts of alternative scenarios on the wood-processing industries are excluded from the analysis.

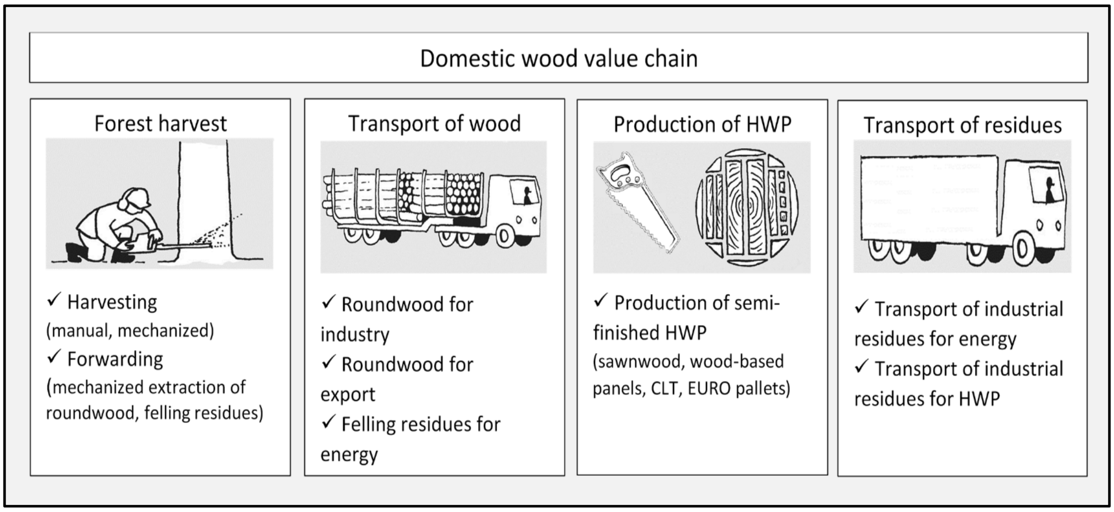


Figure 2. Process included in the investigated wood value chains and the related activities. CLT—cross laminated timber; HWP—harvested wood products.

2.2. Simulation and Assessment Tools

In this study, we projected forest harvest and the associated forest carbon stock changes (carbon in living biomass and soil) until 2100 using the European Forest Information Scenario Model—EFISCEN, version 4.1 [26,27]. For a more detailed model description and methodology please see the manual for the model [27]. EFISCEN is a large-scale forest resource model, which can project forest resource development and carbon stocks in biomass and soil [28–30]. We used up-to-date forest inventory data and current forest management practices in Lithuania [18].

To estimate socio-economic and environmental impacts of alternative wood use in Lithuania we applied the Tool for Sustainability Impact Assessment (ToSIA). This process-based tool focuses on differences in material flows and indicator values by comparing alternative options. ToSIA has been developed as a holistic framework for sustainability impact assessment [31,32] and allows for tracking wood (or carbon) flows from forest establishment until the end-of-life of used products (including disposal, recycling, or incineration). Wood (carbon) flows are defined as chains of production processes (e.g., harvesting, transport, production of HWP), which are linked with products (e.g., sawnwood, wood-based panels, CLT). Sustainability is determined by analysing environmental, economic, and social sustainability indicators for all the production processes along the wood value chains. The tool calculates sustainability values as products of the relative indicator values (i.e., indicator value expressed per unit of material flow) multiplied with the material flow entering the process. The system boundaries of ToSIA applications can be specified depending on the main study objectives. For a more detailed tool and methodology description please see [31].

In this study, alternative wood value chains were built according to assumptions foreseen in the wood use scenarios. ToSIA value chains were used to estimate carbon inflow into the pool of HWP. Based on the carbon inflow into the pool and half-life values of HWP that were found during this study (Supplementary Material B), we estimated indicator values on the carbon stock in HWP by adopting the flux data method and a first-order decay function, as proposed by the IPCC guidelines [25] (Supplementary Material B). The initial carbon stock is based on the average carbon inflow during the first 5 years for which data are available.

To assess impacts of alternative wood use, we defined and quantified six indicators related to economic, social, and environmental sustainability (Table 1). Detailed methods for the calculation of the indicator values are presented in the Supplementary Materials B and C. We selected those indicators based on the relevance for the EU bioeconomy strategy and national objectives foreseen in the Lithuanian Forestry Sector Development Programme. In both cases, socio-economic performance of the forest-based sector is emphasised, whereas climate change mitigation effects are highlighted more in the EU bioeconomy strategy than in the national programme.

Table 1. Tool for Sustainability Impact Assessment (ToSIA) indicators used in this study. Indicators are accounted for in different processes, such as forest harvest, transporting wood, manufacturing HWP, etc. Indicator values were multiplied with the material flows in the alternative wood value chains.

Indicator	Description
Gross value added (GVA)	The gross value added from processes in the value chains in €, at basic prices in 2013.
Employment	Number of employees per year from processes in the value chains in full time equivalent.
Greenhouse gas (GHG) emissions	Total GHG emissions (Mt of CO_2 equivalents) from all processes in the value chains. CO_2, CH_4, and N_2O emissions are converted to the CO_2 equivalent by applying global warming potential factors. (CO_2 = 1, CH_4 = 25, N_2O = 298) [33].
HWP carbon stock	Total carbon stock (Mt of C) in the pool of semi-finished HWP. The main factors influencing carbon stock are annual carbon inflow into the pool and half-life values of the products.
Forest carbon stock	Total carbon stock (Mt of C) in the forest (living biomass and soil). The main factors influencing forest carbon stock are fellings and age class structure of the forest.
Substitution effect	Material and energy substitution effect (Mt of C). When wood replaces more energy-intense materials or fossil fuels, the average displacement factors for material and energy use were applied [34].

2.3. Wood Use Scenarios

To assess sustainability impacts of alternative wood use, we developed four scenarios reflecting wood use from 2020 to 2100 and the reference situation that illustrates values in 2015. All scenarios focused on enhancing socio-economic performance of the forest-based sector by increasing industrial wood supply for local industry and by enhancing the climate change mitigation effect through additional carbon storage in HWP. The scenarios mainly differed in forest harvesting levels (fellings), roundwood export levels, and wood use for long-life or short-life HWP (Table 2).

Table 2. Assumed wood use scenarios in Lithuania.

Scenario	Description	Model Adjustment		
		EFISCEN	Parameter	ToSIA
Baseline	Fellings will remain at the same level as in the past (average of the five years 2010–2015). However, restitution of private forests will gradually increase fellings by 10% from 2020 to 2035. The shares of semi-finished HWP will remain the same. The share of exports of roundwood will remain at the same level as in the past (average of the five years 2010–2015)	√	Fellings Flows Shares Export	√
Fellings +20	This scenario is similar to the "baseline", but assumes that fellings will gradually increase by an additional 20% from 2020 to 2040 (base year for increase is 2020).	√	Fellings Flows Shares Export	√
Long-life +20	This scenario is similar to the "Fellings +20", but assumes that industrial roundwood resulting from increased fellings will be utilised only for the long-life HWP (sawnwood, wood-based panels, and CLT). Wood use for short-life HWP (EURO pallets) will remain in absolute terms the same as in "Fellings +20".	√	Fellings Flows Shares Export	√ √
Exports −50	This scenario is similar to the "Long-life +20", but assumes that investments in wood industry will increase production capacity and exports of industrial roundwood will gradually decrease by 50% from 2020 to 2040.	√	Fellings Flows Shares Export	√ √ √

Legend: EFISCEN—European Forest Information Scenario Model. √—changes in the model compared to the reference year 2015. Model parameters: Fellings—changes in forest felling; Flows—changes in material flows; Shares—changes in shares between HWP groups; Export—changes in shares of roundwood export.

3. Results

3.1. Socio-Economic Impacts

Our indicator on annual gross value added (GVA) increased in all scenarios ranging from 11% to 43% in 2100, compared to the reference situation in 2015 (Figure 3). This is due to the increase in domestic wood flows, as assumed in all scenarios. In some cases, the changes in GVA do not always correlate directly with changes in wood flows; e.g., sawnwood production wood flows nearly double as compared to the production of wood-based panels (Supplementary Material B), but GVA was always higher for wood-based panels in our scenarios compared to the sawnwood. This can be explained by feedstock costs; one third of the feedstock of wood-based panels is made up of low-value industrial residues (sawdusts, chips, and particles) and the rest is low-quality industrial roundwood. The feedstock for sawnwood is higher quality roundwood only.

A similar situation is observed when GVA of CLT and EURO pallets was compared. In this case, differences in GVA appeared due to product price. The wood flows were significantly higher in the production of pallets. However, GVA was observed to be higher from CLT production, because the difference in feedstock price is relatively small compared with product price. The CLT price was significantly higher than the price of pallets. The GVA for forest fellings was the same in the three scenarios "Fellings +20", "Long-life +20", and "Export −50" according to the scenario assumption.

Employment opportunities increased in all scenarios, ranging from 10% to 38% in 2100, compared to the reference situation (Figure 4), which is again related to the assumed increase of domestic wood flows in all scenarios. The highest indicator value was observed under scenario "Export −50", in which there were 11,400 full-time equivalents; that is 2100 more jobs compared to the reference situation. In all scenarios, sawnwood production provided more jobs than the production of wood-based panels, despite production quantities being similar. This is mainly due to a different production efficiency. In Lithuania, more than half of sawnwood is produced in small- and medium-size sawmills. In some of these sawmills, efficiency is rather low, on average 350 m^3 of sawnwood per full time employee per year (results of material flow analysis). In contrast, production of wood-based panels is concentrated in large factories with rather high production efficiency. Another reason was that wood-based panels are, to a large extent, produced from industrial residues that are usually produced by the sawmilling industry, where a lot of the supply chain employment is located, also benefiting the panels industry. Employment for forest fellings was steady in "Fellings +20", "Long-life +20", and "Export −50" scenarios due to scenario assumption of stable fellings.

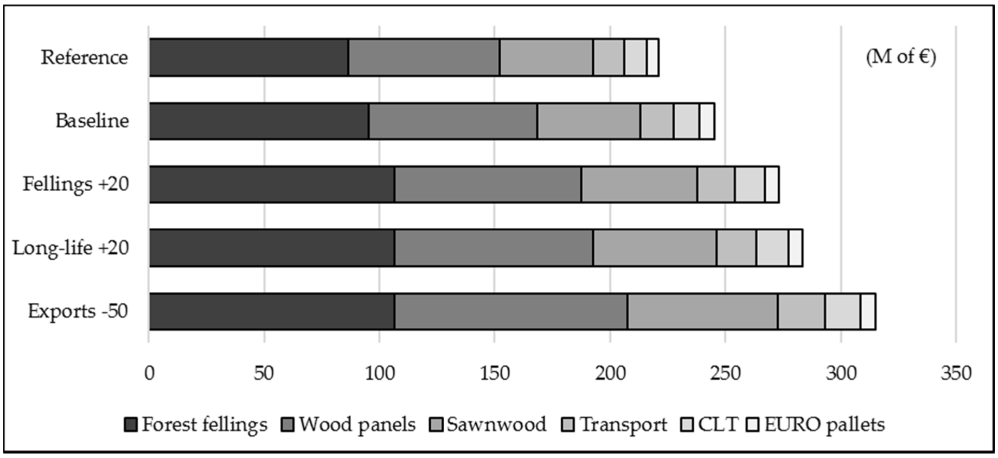


Figure 3. Annual gross value added in Lithuania under different wood use scenarios (year 2100). Reference represents current situation (year 2015). The values in the figure reflect GVA related to domestic wood flows only, starting from forest harvest until production of semi-finished HWP.

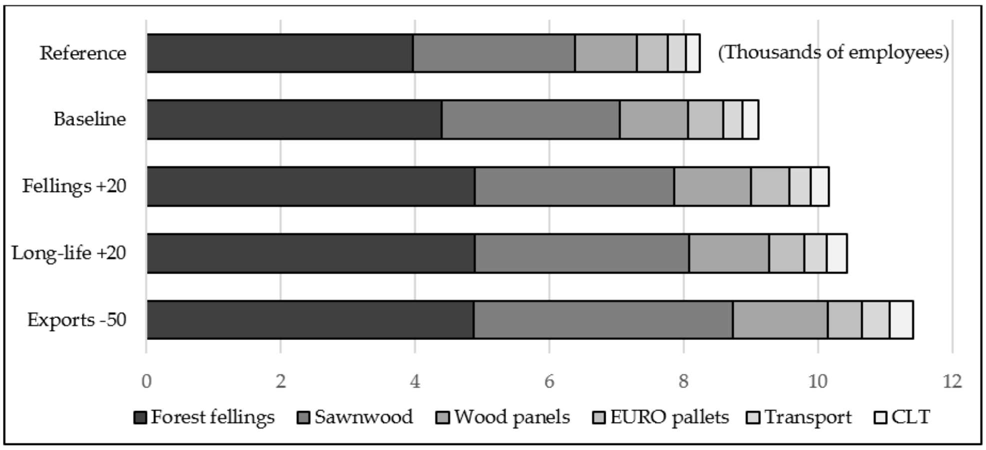


Figure 4. Annual employment under different wood use scenarios in Lithuania (year 2100). Reference represents current situation (year 2015). Values in the figure reflect employment related to domestic wood flows only starting from forest harvest until production of semi-finished HWP.

3.2. Environmental Impacts

In a similar way to the socio-economic impacts, GHG emissions increased in all scenarios, ranging from 11% to 45% in 2100, compared to the reference situation (Figure 5). On average, the amount of annual GHG emissions is 0.47 million tons of CO_2-eq—that equals 0.13 million tons of carbon when one ton of carbon equals 3.67 tons of CO_2. The effect of GHG emissions over the study period, on average, is −10.4 mill tons of carbon, which corresponds to −1.9% of the total climate change mitigation effect. The production of wood-based panels represented the largest contribution to GHG emissions compared to other processes. This is mainly due to the large quantities of energy used in the production process of wood-based panels. For example, manufacturing one cubic meter of particle board emits up to 392 kg of CO_2-eq [35].

The carbon stock in HWP increased in all scenarios, ranging from 42% to 122% in 2100 compared to the reference situation (Figure 6). Compared with other indicator values, this indicator showed the highest increase. There are two reasons for this: (i) the assumption of increased domestic wood flows especially in scenario "Export −50"; and (ii) the carbon accounting method. Carbon stock in HWP is a result of carbon inflow and emissions over time (from 4 to 90 years depending on the product life-time). However, historical FAOSTAT (Food and Agriculture Organization Corporate Statistical Database) data on HWP for Lithuania are available only from 1992. To estimate carbon stock, we applied an exponential decay function with initial carbon inflow based on the average of inflows during the first five years for which data are available (average of 1992–1996), as proposed by IPCC guidelines. In the case of Lithuania, production of HWP in 1992–1996 was small compared to production in the scenarios. Therefore, the carbon stock at the beginning of the accounting period is rather low compared with the carbon stock at the end of the accounting period.

The carbon stock in forests (living biomass and soil) increased in all scenarios between 20% and 25% in 2100 compared to the reference situation (Figure 7). However, compared to the baseline, the other scenarios show carbon stock reductions by 4%. This is due to the increased forest fellings in "Fellings +20", "Long-life +20", and "Export −50" scenarios.

Total climate change mitigation effect is presented in Figure 9, combining carbon stock in HWP, forests, and substitution effect of wood use (Figure 8).

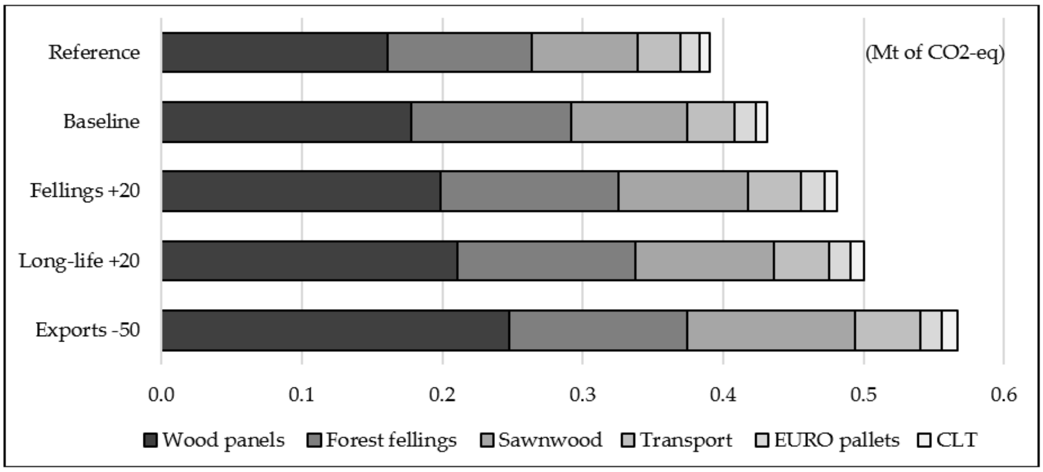


Figure 5. Annual greenhouse gas emissions under different wood use scenarios in Lithuania (year 2100). Reference represents current situation (year 2015). Values in the figure reflect GHG emissions related to domestic wood flows only, starting from forest harvest until production of semi-finished HWP.

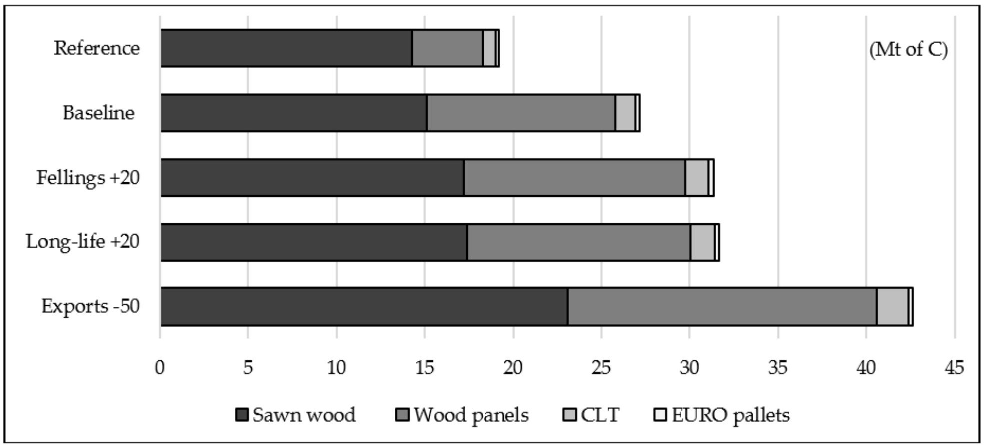


Figure 6. Carbon stock in HWP under different wood use scenarios in Lithuania (year 2100). Reference represents the current situation (year 2015). Values in the figure reflect carbon stock related to domestic wood flows only, starting from forest harvest until production of semi-finished HWP.

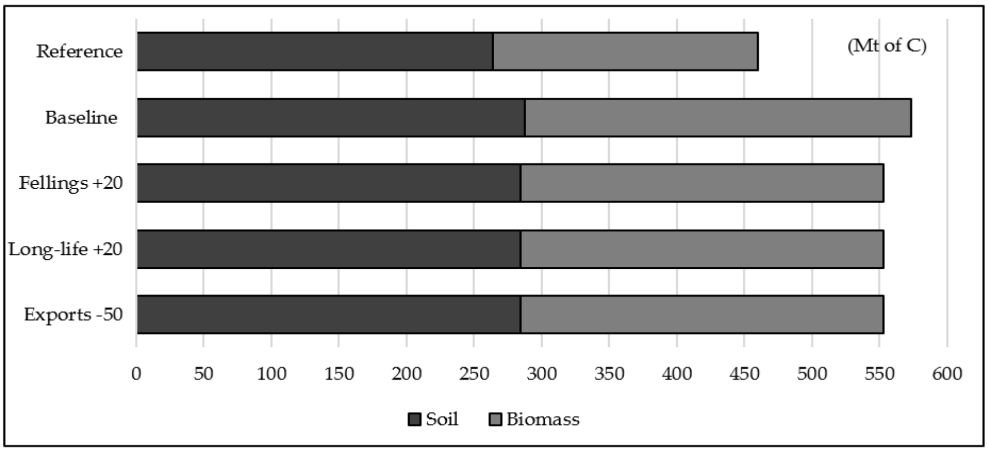


Figure 7. Carbon stock in forest (living biomass and soil) under different wood use scenarios in Lithuania (year 2100). Reference represents the current situation (year 2015). For carbon stock and harvest level changes over the entire study period please see Supplementary Material B.

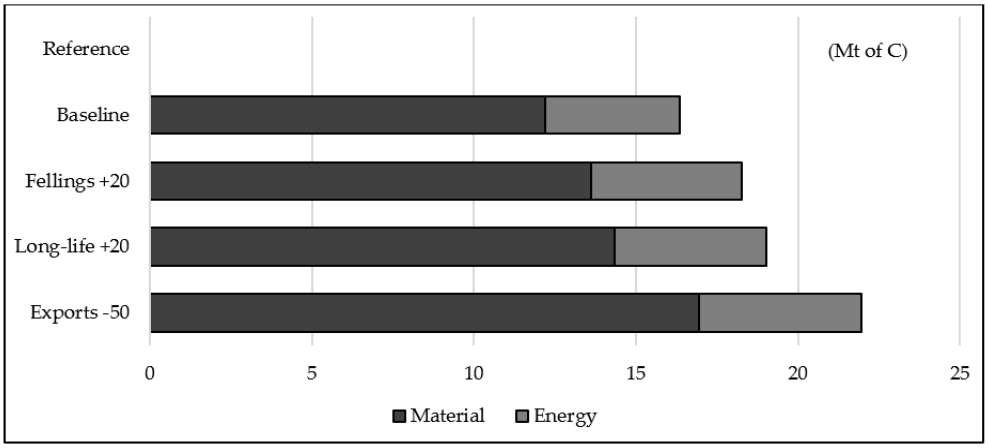
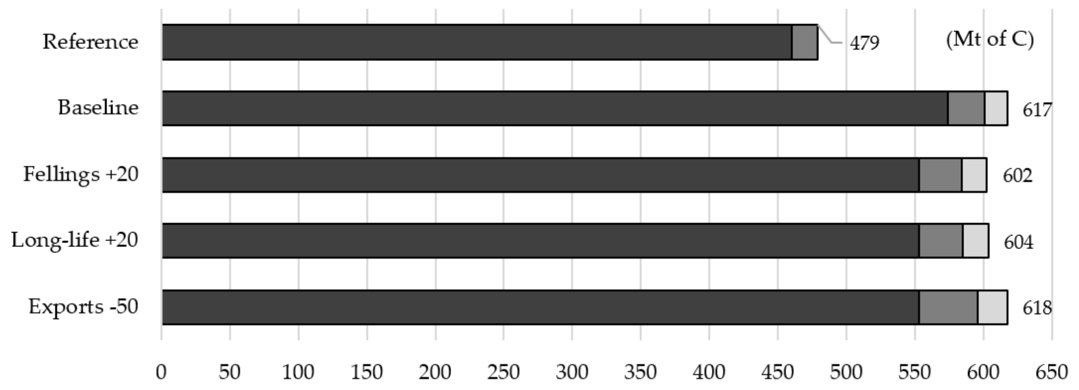


Figure 8. Material and energy substitution effect when wood replaces more energy-intense materials under different wood use scenarios in Lithuania (year 2100). Reference represents the current situation (year 2015). Values in the figure reflect substitution effects related to domestic wood use only.



	Exports -50	Long-life +20	Fellings +20	Baseline	Reference
Forest carbon	553	553	553	574	460
HWP carbon	43	32	31	27	19
Substitution	22	19	18	16	0

Figure 9. Total climate change mitigation effect under different wood use scenarios in Lithuania (year 2100). Reference represents the current situation (year 2015). Values in the figure (carbon stock in HWP, forest (living biomass and soil), and emissions avoided due to substitution) reflect climate change mitigation effects related to domestic wood flows only. Values at the end of the bars show the sum of different effects. The effect of GHG emissions is −10.4 mill tons of carbon, which corresponds to −1.9% of the total climate change mitigation effect.

3.3. Comparing Impacts of Different Scenarios

Our results showed that in all scenarios, compared to the baseline, the socio-economic indicators on GVA and employment would significantly increase. However, the indicator on GHG emissions showed negative impacts, with increased emissions in all scenarios compared to the baseline. The total climate change mitigation effect was positive only in the "Export −50" scenario (Figure 9), because in other scenarios forest carbon saturated so much that carbon storage in HWP and substitution could not compensate carbon losses in forests compared to the baseline. Overall, the "Export −50" scenario showed the highest values on most indicators, except forest carbon (Figure 10).

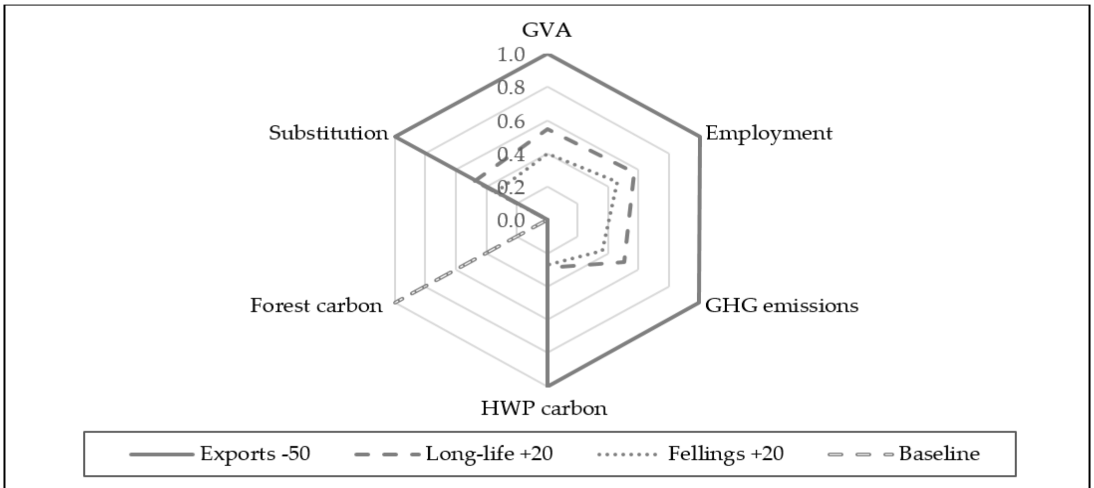


Figure 10. Indicator results representing socio-economic and environmental impacts under different wood use scenarios in Lithuania (year 2100).

4. Discussion

4.1. Scenario Trade-Offs

In this study, we analysed impacts of increased domestic wood utilisation in Lithuania on three sustainability aspects: (i) employment; (ii) economic performance; and (iii) carbon storage in the forest-based sector. We studied wood use alternatives that might support the bioeconomy and at the same time mitigate climate change through increased carbon storage in HWP and substitution effect of additional wood use. Few studies have attempted to determine trade-offs of other sustainability aspects that might be influenced by increased wood utilisation in the forest-based sector [32,36]. Our results revealed that increased wood use could lead to significant trade-offs, depending on the scenario analysed. The socio-economic indicators were positively affected by increased domestic wood utilisation, but the net carbon balance in the forest and HWP was found to be negative in all scenarios compared with the baseline. Increase in HWP carbon in most cases did not compensate for the carbon losses in the forest due to the additional fellings. Only in scenario "Export −50" when the substitution effect was added, did the total climate change mitigation effect reach the level of the baseline scenario.

Indicator values on GVA and employment increased differently under different scenarios. The highest increase in socio-economic values was observed in the scenario "Export −50" compared to the baseline. The smallest increase was observed when comparing the "Fellings +20" scenario with the "Long-life +20" scenario. Similar features were observed when comparing carbon stock in HWP under different scenarios. This means that replacing short-life products with long-life products in Lithuania will have a minor effect on employment, economic performance, and carbon storage, but increased domestic wood use by additional fellings and reduced export of roundwood might have positive effects on the country's bioeconomy and climate change mitigation efforts.

4.2. Effect of System Boundaries

In accordance with international greenhouse gas accounting and reporting principles, in this study we included wood (carbon) flows only from domestic harvest (Supplementary Material B) and we excluded carbon flows related to traded wood and wood originating from deforestation [25]. Adopting these system boundaries has a significant effect on the results, especially for roundwood exporting countries such as Lithuania. From the global perspective, carbon storage in HWP and the overall climate mitigation effect of Lithuanian wood use is larger than we show in our study results. The total effect for Lithuania would be shown if carbon in exported roundwood was also accounted for.

During recent years (2010–2014), the export of industrial roundwood from Lithuania amounted to almost 1.7 million m^3 on average [18]. This corresponds to 0.4 million tonnes of carbon. It is evident that huge amounts of domestic carbon are exported as industrial roundwood. This carbon could be accounted for in Lithuania; however, there are currently no proposed methodologies and reliable data available for estimating carbon flows (HWP produced from exported roundwood) and life-times of HWP that are associated with exported roundwood. If production data on HWP from exported roundwood were available, IPCC default half-life values could be used. We would need to assume average half-life values very roughly between very short and long half-life values. Values for pulp and paper could be used as first approximation, but with very high uncertainty. However, the ranking of scenario alternatives would only be affected in the unlikely case that exported wood is already utilized for products with long life times. In all other situations, the expansion of system boundaries with calculation of exported products would result in higher estimates without a change between scenario ranking.

Indicator values on GVA, employment, GHG emissions, and substitution effects would also be affected if wood flows could be tracked until the end of life of HWP and outside the country. At the moment reliable data on wood flows and indicator values are not available, but considering a growing amount of related studies [37–40], it would be worthwhile to use regional or European scale averages to estimate such effects. The ToSIA methodological framework could be used to estimate those effects, if robust enough data on wood flows were available. The estimate of substitution effects does not cover potential foregone effects on GVA and employment in other sectors. Evidence-based decision-making should ideally also include such cross-sectoral consequences, but benchmarking reference data to compare full sustainability impacts of alternative materials and fuels are generally lacking. The expansion of system boundaries would improve the realism of foresight studies and clearly increase the policy relevance at the national and international levels.

4.3. Scenario Assumptions

In the baseline a 10% increase in forest fellings was assumed compared to the current (2015) felling levels, due to restitution and restoration of regular forest management in the affected forests. In the scenarios "Fellings +20", "Long-life +20", and "Export −50" we projected a further increase in forest fellings by 20% compared to the baseline. A national scenario study [41] projected that by the end of the 21st century under an optimal management scenario, harvest levels should reach 10 million m^3 per year. In our study, we projected harvest levels that do not exceed 10 million m^3 per year (Supplementary Material B). Therefore, we postulate that it would be possible to increase forest fellings in Lithuania in a sustainable manner to support an expanded bioeconomy and climate change mitigation. Otherwise, unutilised forests will naturally decay and emit carbon without additional benefits.

In the scenario "Export −50", we assumed that exports of industrial roundwood would decrease by 50%. According to EU legislation, trade of goods cannot be restricted within the EU [42]. Nevertheless, local investments in the wood industry might foster domestic industrial wood utilisation. We assume that investments will gradually happen and from a national standpoint Lithuania could then account for the higher domestic carbon stock in HWP under currently existing carbon accounting and reporting rules. However, from a global standpoint, this does not affect climate change mitigation and consequently it would be more policy-relevant to develop methodologies to cover trade related imports and exports as well. While uncertainties would be higher compared to the national domestic budgets, this would nevertheless improve the relevance of the information to guide climate change mitigation strategies at the international level. The ToSIA methodology applied in this study offers a suitable methodological framework for such estimates.

4.4. Data and Tools

The value chains based on empirical data were integrated into the ToSIA tool to quantify carbon flows, and to assess other sustainability aspects related with carbon flows in the forest-based sector. Initially this tool was designed for sustainability impact assessment of forest wood chains [32]. Nevertheless, wood value chains are essential components to represent the forest-based sector and to track the carbon over the processes [43]. This tool is suitable for scenario analyses and already includes carbon-based material flows to quantify the carbon budgets in HWP. We have chosen this tool because material flows capture both carbon flows as well as other sustainability aspects in the forest-based sector.

The carbon flows in value chains were used as an inflow for estimating carbon stocks in HWP as an indicator. We considered HWP carbon storage through indicator calculations because ToSIA lacks a dynamic time dimension and the material flows refer to one reference year only. The forest wood chain reflects the current structure of the wood industry and does not include future changes. Therefore, for indicator calculations for different scenarios we projected wood removals by employing a large-scale forest resource model EFISCEN. The main driver impacting carbon stocks is wood removal [44], and we relate future flows to forest fellings in alternative scenarios. For the scenario analysis, it is unlikely that future flows could be projected without considerable uncertainties. Where substantial changes in circumstances are anticipated, the assumptions could be adjusted in the indicator calculation.

4.5. Comparison to Previous Studies

Pilli et al. recently highlighted that in the future, the current EU carbon sink in HWP will saturate, unless harvest levels were to increase by 20% compared to the average harvest of 2000–2012 [40]. Our results indicate that the carbon sink in Lithuania's HWP is expected to increase even under our baseline. Increased harvest rates by 20% would not only maintain, but significantly increase, the carbon sink in HWP. Other studies may have reached different conclusions because different system boundaries (EU and national) and data were used. In our study, we used country-specific empirical data instead of data reported by the national and international statistical offices. For estimating annual carbon inflow into the pool and life-time values of HWP, we used data from the wood industry in Lithuania (Supplementary Material B). The national statistical data on the use of wood can deviate significantly from empirical study results. In Germany, approximately 18% of wood flows is not reflected by the statistics, mainly due to the use of wood residues for the production of HWP [45]. Another study by Jochem et al. reported that 20% of wood removals in Germany are not reported by the statistics due to the amount of unregistered fellings [46]. A material flow analysis on the primary use of roundwood in Slovakia indicated that the real consumption of wood was 16% higher than the domestic wood consumption reported in statistics [47]. Therefore, we postulate that the use of empirical wood flow data is more reliable for building alternative wood value chains.

Our study identified that the climate change mitigation effect was positive only in one scenario compared to the baseline. Previous studies on the climate change mitigation effect in the forest-based sector in Sweden drew more positive conclusions [48–50] because different system boundaries and assumptions were used. Those studies assumed a cumulative material substitution effect from all wood flows in the country. In our study, we estimated the climate mitigation effect only for domestic harvest and the substitution effect was accounted only from additional wood use. It means that the substitution effect in this study occurs only when wood from additional harvest is used for replacing fossil fuels or energy-intense materials. In our understanding, substitution effects have additional climate change mitigation effects only when wood products replace fossil-based alternative materials (cf. discussion on additionality in [51]). Thus, replacing wood buildings with other wood buildings does not create additional substitution effects, but replacing concrete buildings with wooden buildings will create additional substitution effects. Therefore, for the reference situation we did not calculate substitution effects. A study by Knauf estimated that material and energy substitution corresponds to 57% of the climate change mitigation effect of the German forest-based sector [52]. In our study, we estimated that the substitution effect in the forest-based sector would range from 3% to 3.5%, depending on the scenario. This means that results from other similar studies are barely comparable, with differences between the study results occurring mainly due to different assumptions and system boundaries. We argue that to guide policy making, comparisons with the reference situation are most meaningful, and that system boundaries relevant for international greenhouse gas reporting should be applied. It should be noted that material substitution effects are not reportable yet under the category LULUCF, but if UNFCCC parties were to decide to account for substitution effects, it is likely that a reference level would be defined.

4.6. Policy Implications

Our findings are a useful input to the discussion about how the intensified domestic wood utilisation in Lithuania would support the implementation of national and international policies influencing the forest-based sector. The national policy in Lithuania targets the increase and preservation of forest resources and, at the same time, the strengthening of socio-economic functions of the forest-based sector [23]. In line with the latter objective, the EU bioeconomy policy aims to tackle natural resource scarcity, fossil resource dependence, and climate change, while achieving sustainable economic growth [1], while global climate change mitigation policies aim to increase carbon sinks in the forest-based sector.

Our scenario analysis showed that from the national perspective the baseline would be in line with Lithuanian policy objectives. Under the baseline, the forest carbon stock was the largest and socio-economic values slightly increased. The other scenarios are in conflict with the national target of preservation of forest resources, as forest carbon stocks decreased due to intensified fellings. However, additional wood utilisation would significantly increase socio-economic values compared to the baseline.

From the EU bioeconomy perspective, the "Export −50" scenario would be the most beneficial, because socio-economic values increased significantly and the total climate change mitigation effect was found to be positive compared to other scenarios.

In the framework of climate change policies and existing carbon accounting and reporting rules, the baseline would be the most beneficial for Lithuania, because accountable carbon stocks (in forest and HWP) were highest in the baseline. Material substitution effects are not reported under the LULUCF category of UNFCCC, because they are captured in the national emissions of other sectors. The separation between land use and other sectors in the accounting can lead to short-sighted policy guidance. When substitution effects were considered and exports of roundwood were reduced, the total climate change mitigation effect from the country's perspective turned positive in the scenario "Export −50". This illustrates that considering only the LULUCF category in the UNFCCC reporting—ignoring substitution effects and applying only national boundaries in the HWP reporting—decreases the calculated climate change mitigation effect of national resource use strategies. Consequently, for roundwood exporting countries such as Lithuania the current accounting practices could lead the countries towards aiming to increase the national carbon budget. However, there would be no additional benefit from a climate change mitigation perspective, because they overlook the higher overall climate change mitigation potential that occurs in other sectors or outside of the national borders. In reality, the benefits of increased carbon storage in HWP and fossil fuel substitution on climate change mitigation has no country borders.

5. Conclusions

In this study, we analysed the impacts of alternative domestic wood utilisation scenarios for a Lithuanian bioeconomy and climate change mitigation in the forest-based sector, taking into account employment, economic performance of the sector, and carbon balances in forest biomass and soil and in HWP. Impacts on bioeconomy development and climate change mitigation (when existing carbon reporting rules are applied) are strongly affected by system boundaries and accounting practices. We conclude that: (i) increased wood utilisation might support Lithuania's bioeconomy through increased socio-economic benefits—however, positive climate change mitigation effects from the national perspectives could be gained only if substantial actions are taken to utilise more domestic wood for long-life HWP; (ii) under existing carbon reporting practices where substitution effects are not separately quantified and carbon storage in exported roundwood is often ignored, the EU bioeconomy development and climate change mitigation policy targets cannot be reconciled in wood exporting countries such as Lithuania; (iii) decision making affecting forest resource use should increasingly consider cross-sectoral effects of wood product use and net impacts on bioeconomy and global climate change mitigation beyond country borders.

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Data analysis	GJ, PJV
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