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Wood and paper as alternatives to single-use plastics: supply chain considerations for North America

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ABSTRACT

Governments are increasingly adopting policies to reduce plastic and packaging waste, with single-use plastics (SUPs) among the main targets. Where reuse is not adopted, wood- and paper-based products are often proposed as alternative materials. This study examines the potential supply chain and environmental implications of replacing selected SUPs with wood- and paper-based alternatives across Canada and the USA, where large single-use product markets coexist with major forest-products industries. We map relevant forest-product supply chains, assess resource availability and processing capacity, and examine indicative land-use and waste implications. For the items assessed, replacing SUPs with wood- and paper-based alternatives could substantially increase the total mass of material used and was estimated to require an additional 13.68 million m^3 of wood across the USA and Canada. The associated harvested area is estimated at 84,202 hectares in 2030, equivalent to approximately a 1.6% increase in harvested area in Canada and 0.38% of planted forest area in the southern USA. Paper production capacity emerges as a key supply-chain constraint: meeting the additional demand would require an estimated 18.7 Mt increase in paper and paperboard production, approximately 25% above 2022 levels, or increased reliance on imports. Scenario analysis further shows that reuse and demand reduction can substantially reduce fibre demand. These findings demonstrate that the scale and configuration of behavioural and supply-chain responses are critical when designing material-specific SUP policies.

1. Introduction

Single-use plastics (SUPs) have become an often essential and unavoidable part of everyday life. Their prevalence has been driven primarily by utility, versatility, convenience and low cost, but in recent years, they have been subjected to increased scrutiny due to the problematic quantities of mismanaged plastic waste seen across the world – an issue which may worsen if current trends persist (Geyer et al., 2017; SYSTEMIQ, and The Pew Charitable Trusts, 2020).

To address rising quantities of plastic waste generation, governments across the world have begun to take regulatory action (WWF Mediterranean Marine Initiative, 2018; European Commission, 2018; Department for Environment Food, and Rural Affairs, 2024; Simantiris, 2024). For example, in 2022 the Canadian Government introduced the Single-Use Plastics Prohibition Regulations (SUPPR) (Plastics Regulatory Affairs Division, 2023), a ban on SUPs, meaning that from December 2022 the manufacture, import, and sale of single use shopping bags, cutlery, foodservice ware, ring carriers, stirrer sticks and straws were prohibited. Despite court cases and rulings overturning the ban, the regulations remain on the books subject to revival. A revived ban has the potential to induce changes in the manufacturing and consumer sectors in Canada.

SUPs are not solely confined to consumer-focused products. SUP packaging plays an important role in global supply chains and in the retail and food sectors, helping to deliver and protect perishable or damageable goods during transport (White and Lockyer, 2020; Avery et al., 2025). Plastic-based packaging is also particularly beneficial due to its light weight, which can lead to lower potential environmental impacts when items are transported over long distances (Avery et al., 2025). Mishandling of waste SUP packaging is often seen as a major

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driver of litter and plastic pollution, and regulatory action similar to Canada's SUPPR has been taken by multiple governments. Key examples of this include Extended Producer Responsibility (EPR) legislation, introduced in multiple US states and the European Union, and the European Union's packaging and packaging waste regulation (PPWR) (Tumu et al., 2023; European Commission, 2024). These regulations aim to address packaging waste through different approaches or mechanisms, in some cases limit or ban the use of SUP products, and may be linked to perceived emission (e.g., greenhouse gas) and resource use (e.g., fossil fuel and water) reductions, or mandatory targets. Some of the regulations aim to drive reductions in SUP use through mechanisms that may increase their purchasing costs or by introducing requirements for manufacturers to take responsibility for end-of-life treatment costs.

SUP restrictions can result in a range of market and behavioural responses, including elimination of products, adoption of reusable systems, and substitution with alternative single-use materials. Where the single-use nature of a product remains important, some businesses are making or considering switching from plastics to paper and wood-based options, primarily due to their biodegradability and perceived environmental benefits (SYSTEMIQ, and The Pew Charitable Trusts, 2020; Simantiris, 2024; Meng et al., 2024). However, substitution between materials can also change product mass, feedstock demand, production infrastructure, and supply-chain geography.

Previous work has studied the effectiveness of bans (Muposhi et al., 2022; Macintosh et al., 2020) and consumer attitudes to replacement products (Nuojua et al.,). This work considers the implications of SUP bans and regulations by studying the impact of some of the products used to replace SUPs over a wider scope than previously considered, including life cycle stages from growth and harvest to use and investigating whether the required raw materials are available and local production is feasible. These studies provide important insight into environmental impacts and consumer response, but relatively little work has quantified how substitution of high-volume SUP applications translates into regional-scale demand for wood fibre, harvested area, and paper production capacity. This distinction is important because material substitution may be technically possible at product level but constrained when aggregated across very large product markets. The purpose of this study is not to determine whether plastic or fibre-based products have lower overall environmental impacts. A full comparative environmental assessment would require a functionally equivalent life cycle assessment incorporating production, use, end-of-life, and biogenic carbon accounting. Instead, it addresses a narrower but currently underexplored question: what are the material-demand and supply-chain implications of large-scale substitution of selected SUP items with single-use wood- and paper-based alternatives?

Canada and the USA provide a particularly relevant regional case because large single-use product markets coexist with major domestic forestry, pulp, and paper industries. This allows the upstream resource and production implications of substitution to be examined within an established forest-products supply system. This study therefore aims to evaluate the feasibility (in scale and material production terms) and implications of replacing SUP products with single-use paper and wood-based alternatives across Canada and the USA. The manufacturing processes and supply chains of these alternatives are considered, and the availability of raw materials and processing capacity is examined. This work is based on a set of sample alternative products so does not represent the entire suite of alternative products, and considers only alternative single-use products, rather than replacement with reusable or other systems. The work is likely to be relevant to policymakers, product manufacturers, and users of single-use products.

2. Methodology

The methodology applied in this study was to first consider a range of single-use plastic (SUP) products, including one set of products banned by SUPPR, and another set based on previous studies in the field. For each of these combined sets of products, a paper or wood-based alternative product was identified. For some products, the likely reduction in overall demand was considered, though in most cases it was assumed that the absolute number of products required would be the same as in the SUP case. Using product data and based on the functional unit, the mass of material required to replace SUPs using paper or wood-based products was therefore calculated. From this, using United Nations data (United Nations Food and Agriculture Organisation, 2023), the required land use was estimated, and ultimately, the demand for additional paper production was calculated, allowing the potential greenhouse gas emissions impact of the change to be considered. A cradle to end-of-life (EoL) approach was followed by considering different life cycle phases of the products and materials from raw material extraction (for plastics) or plant growth (for paper or wood-based materials) to manufacturing of the items and to EoL. The analysis assumes functional replacement on a unit basis unless otherwise specified in the replacement scenarios. Differences in breakage, leakage, product loss, or the number of alternative items required to provide an equivalent function were excluded because consistent data were unavailable across the selected products. For disposal, different EoL dispositions characteristic of the material and regional waste management practices were considered.

The region covered is North America, focusing on Canada and the USA. The analysis is designed as a material-demand and supply-chain assessment rather than a comparative life cycle assessment. It therefore quantifies changes in product mass, forest-product demand, indicative harvested area, and production requirements, but does not determine the net environmental preference of plastic or fibre-based products.

To improve transparency and reproducibility, the calculation steps are stated explicitly here. For each selected product i, annual material demand was calculated as:

$$M_i = N_i \times m_i$$

where M_i is the annual mass demand for product i (t y^{-1}), N_i is the annual number of units consumed, and m_i is the mass per unit.

For products subject to partial replacement scenarios, the annual mass demand for the wood- or paper-based alternative was calculated as:

$$M_{i,\mathrm{alt}} = N_i \times r_i \times m_{i,\mathrm{alt}}$$

where r_i is the proportion of the original SUP item replaced by the wood- or paper-based alternative under the specified scenario, and $m_{i,\mathrm{alt}}$ is the mass per alternative unit.

For products assumed to be fully replaced, $r_i = 1$. Category totals were then calculated by summing across all products assigned to each relevant UN FAO material category:

$$M_c = \sum_{i \in c} M_{i,\mathrm{alt}}$$

where M_c is the total annual mass demand for material category c. These category totals were then linked to forest product supply-chain data to estimate corresponding wood fibre demand and broader implications for harvest, land use, and paper production capacity.

2.1. Selected plastic items

To gain an insight into the feasibility of replacing SUPs with wood and paper-based alternatives, two groups of specific products were chosen for analysis. The first group (group A) represented consumer-focused SUP products, with each of the selected products fitting within one of the six SUP product categories covered by Canada's SUPPR. The second group (group B) contained eight SUP items used in packaging applications as highlighted in a previous work (Avery et al., 2025), all of which are typically made with polyethylene (PE), which

is a common type of plastic resin used in packaging applications (ACC, 2023). Although the selection of products covered by these two groups does not comprehensively cover all SUP items that could be impacted, it is a representative cross-section of the items that can serve as a basis for case studies for exploring the potential trade-offs of alternative material-focused policies and regulations, versus more science-based and material-neutral approaches.

The items chosen are displayed in Table 1, along with their estimated usage levels in North America (Grand View Research, 2023), their typical plastic and wood-based materials, and their typical mass per unit. It should be noted that a range of wood-based alternative products exists in most cases, particularly in group A, which may have differing mass or material type. The products selected were based on an informal assessment of the most common product in each type, and market data. Whilst a median product mass could have been selected, it was considered more valuable to identify specific real products for comparative purposes. However, different wood-based products could lead to differences in study results. Further details of selection for each group A product are given in the Supplementary Information (Section 1).

In the specific case of the clamshell, a kraft cardboard product of sufficient thickness to contain hot food was selected rather than lower-mass products designed primarily for cold-food applications. This choice was made to maintain functional comparability with the EPS clamshell assessed in the study. The selected hot-food-capable product has an estimated mass of 30 g, whereas lighter market alternatives of approximately 16 g were also identified for cold food applications. To illustrate the influence of product mass and lightweighting, an additional sensitivity case using a 16 g clamshell is presented in the Supplementary Information. The lighter product is not assumed to provide identical hot-food functionality but is included as a lower-mass market case.

Further information, including the definitions of functional units and specific material breakdowns for the multi-materials in group B, is available in the supplementary information. The mass of products shown represents the total mass. In some cases, products such as pouches or cartons may contain thin plastic or metallic barrier layers in addition to the main plastic or cellulosic component. In some packaging formats, these non-cellulosic layers may remain below approximately 5% of total packaging mass (ACC, 2023), which is sometimes used as a practical threshold when discussing predominantly fibre-based or "monomaterial" packaging, but this is not universally the case and can be exceeded in applications such as beverage cartons. In the present study, these minor non-cellulosic layers were excluded, and the total packaging mass was assigned to the principal SUP or wood-based replacement material for simplicity.

Composition and recycled content in wood-based products were assumed to reflect typical North American market conditions, as summarised in the Supplementary Information (Figure S3). Recycled content was assumed to reflect current North American market conditions and was held constant throughout the analysis. Future changes in paper recovery rates, recycling yields, secondary fibre availability, and circular economy policies could affect virgin wood demand. This dynamic feedback was not modelled and represents an important direction for future work.

2.2. Realistic levels of replacement

As Table 1 shows, clamshell containers and shopping bags are key contributors to the total use numbers in the consumer-focused group A. Combined, these items account for 93.5% of the total mass of the group in the SUP case, and 96.9% in the wood-based alternatives case. Varying the levels of replacement for these two items would therefore have a significant effect on the demand for resources and processing capacity.

Although other alternatives are outside the scope of this study, restrictions on the use of SUP group A products could, in addition to the adoption of wood-based single-use products, lead to increased use of reusable and non-wood-based single-use items. A reduction in overall demand in group A could be expected. Although alternatives to SUPs and wood-based materials may be adopted for some of the packaging items in group B, it is difficult to imagine significant reductions in usage or any widespread adoption of reusables without drastic changes to product design and supply chains. Scenario analysis, therefore, focused on group A.

The impact of bans was illustrated by a study (Banko and Bhanot, 2023) of a ban on the distribution of SUP shopping bags by retail outlets implemented by Philadelphia City Council in 2021. Prior to Philadelphia's plastic bag ban, customers used an average of 2.01 SUP shopping bags per shopping trip (Banko and Bhanot, 2023). Banko and Bhanot (2023) found that this figure fell to an average of 0.08 SUP bags

Table 1
Group A and B – consumer focused single-use plastic (Group A) and PE based packaging (Group B) replacements.

	Item	Units per Year+ (Millions)	Plastic		Wood-Based	
			Material	Mass per unit (g)	Material	Mass per unit (g)
Group A	Shopping bag	135,000	HDPE	8.0 (Shameer, 2024)	Paper	55.0 (Shameer, 2024)
	Fork	3,600	PP	3.0 (WebstaurantStore, 2026)	Wood	2.7 (T.Quality, 2024)
	Clamshell	232,000	EPS	4.0 (Packnwood, 2024)	Kraft Cardboard	30.0 (Pattersons, 2024)
	6-pack ring carrier	2,000	LDPE	3.2	Moulded Plant Fibre	16.0 (BioPack, 2024)
	Stirrer stick	8,000	PS	0.3 (Department for Environment Food and Rural Affairs, 2018)	Wood	1.1 (Department for Environment Food and Rural Affairs, 2018)
	Straw	400,000	PP	0.3 (Buzz Catering, 2024)	Paper	1.0 (Nisbets Limited Catering Equipment Supplies, 2024)
Group B	Water Bottle Multipack Shrink Wrap	20,766	PE Shrink Film	7.5	Folding Boxboard	69.9
	Bodywash Multipack Shrink Wrap	5,035	PE Shrink Film	28.7	Corrugated Board	308.0
	Pallet Stretch Wrap	6,701	PE Stretch Film	152.6	Paper Pallet Wrap	1023.9
	Dog Food Heavy Duty Sack	890	Multi-material Plastic Sack	151.6	Multi-material Paper Sack	226.9
	Cement Heavy Duty Sack	2,725	PE Sack	55.4	Multi-material Paper Sack	75.3
	Flexible Juice Pouch	9,766	Multi-material Plastic Pouch	4.5	Multi-material Paper Carton	10.8
	Flexible Candy Pouch	24,083	PE Pillow Pouch	3.5	Paperboard Box	15.3
	Flexible Spices Pouch	11,623	PE Pillow Pouch	4.8	Paper Pouch	4.4

+Number of units consumed per year across the USA and Canada.

per customer per trip after the ban was implemented, with 49.3% of use eliminated, 28.4% replaced by paper bags and 18.4% by reusable bags. The overall average number of shopping bags used per customer per trip fell to 1.02 (shown in more detail in Supplementary material). Similar US studies also suggest similar trends in replacement (Taylor and Villas-Boas, 2016). This suggests that it may be unrealistic to assume full replacement of SUP products with alternative products, since if a SUP ban were to have similar consequences to the Philadelphia shopping bag ban, demand for paper-based alternatives is likely to be much lower.

It could be argued that similar trends may be observed in other group A products in a post-ban scenario. However, different products would be expected to have a different balance of levels of elimination, replacement with single-use products and replacement with reusable products. A key difference between shopping bags and clamshell containers (the other major contributor by mass to group A) is the retailer's food processing /consumer functional necessity, as well as important brand experiences. Unlike shopping bags, which are not always essential for the consumer, it is perhaps difficult to imagine a future where the use of takeaway containers is eliminated without a reduction in consumer brand experience and reduced takeaway food sales, since an effective and convenient means of transporting the food is intrinsic to the activity of takeaway food. If not replaced with other single-use containers, it is much more likely that SUP takeaway containers would need to be replaced with either consumer-owned refillable containers or with returnable containers (Greenwood et al., 2021). Such behavioural trends can make a significant difference to the quantity of resources and processing capacity required to facilitate the switch from SUPs to wood-based alternatives. Taking this into consideration, three scenarios were defined with varied levels of adoption of alternatives to SUPs for shopping bags and clamshell containers. For shopping bags, in all scenarios, 4% of the items remained SUP. Adoption of alternatives (single-use items made from wood or paper, single-use items made from bio-based plastics and other materials, or reusable items) was then varied between three different scenarios. The 'middle' scenario reflects the results of the study by Banko and Bhanot (Banko and Bhanot, 2023), with others reflecting higher and lower replacement with wood or paper single-use products and different levels of reuse and elimination. The scenarios are summarised in Table 2.

These scenarios were applied only to the shopping bag and clamshell, for reasons discussed previously of replacement likelihood and the significance of their contribution to total mass. Due to the nature of the product and packaging systems used, it was also assumed that group B items would only be replaced by full replacement of the product. Due to the pre-sealed nature of flexible juice pouches, for example, for tamper-proof food safety and best-before/use-by shelf-life attributes, these products are unlikely to be fully replaced by reusable products. All group B products were therefore assumed to be initially 100% SUP and subsequently replaced with 100% paper products, with 0% other single-use, reuse, or elimination. This should be interpreted as a bounding material-substitution case rather than a prediction of actual packaging-sector transition. In practice, future responses may include lightweighting, partial elimination, packaging redesign, reusable systems, or substitution with non-fibre materials. These responses were not modelled here and could affect the fibre demand estimated under the full-replacement case. This is a limitation of the present study. Further understanding of likely rates of replacement, adoption of reuse, or elimination would allow a more refined assessment to be undertaken.

Results based on the Middle scenario are presented throughout this study, with results from High and Low scenarios (Table S2) available in the supplementary information. Following the identification of products and suitable replacement scenarios, a three-step methodology to estimate supply chain impacts due to the replacement of selected SUP products was applied. This methodology is illustrated in Fig. 1.

2.3. Data on the forest products industry

The forest products industry is of global importance, serving a broad range of end users with products of varied value. The structure of the

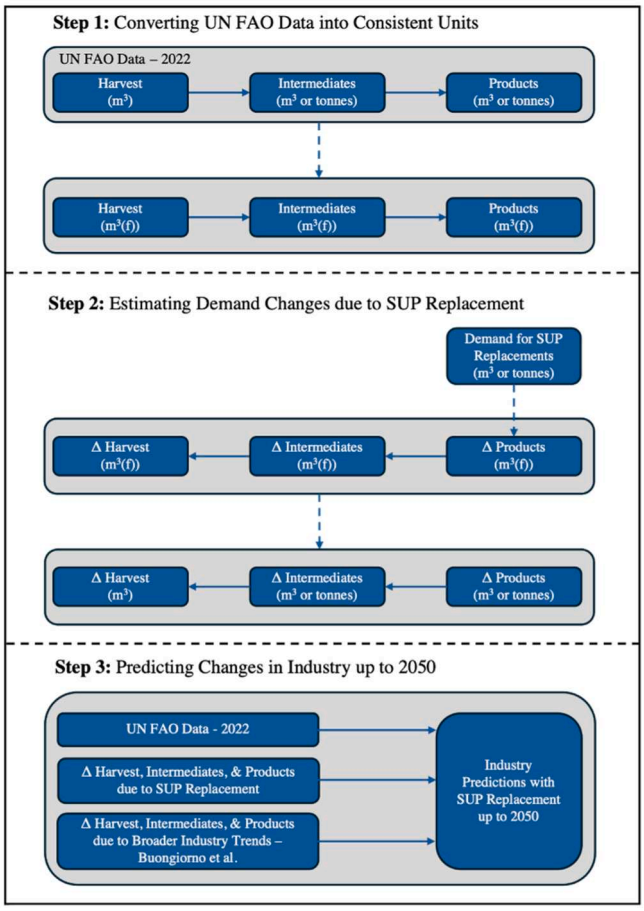


Fig. 1. Methods used to estimate supply chain impacts due to Selected SUP replacements.

Table 2
Scenarios for adoption of alternatives to SUP shopping bags and clamshells.

Scenario	Item	Proportion of SUP Items Replaced by Alternatives				
		Wood/Paper	Other Single Use	Reusable	Elimination	Remaining SUPs
High	Clamshell	66.0%	5.0%	25.0%	0.0%	4.0%
	Shopping Bag	38.4%	0.0%	13.4%	44.3%	4.0%
Middle	Clamshell	56.0%	10.0%	30.0%	0.0%	4.0%
	Shopping Bag	28.4%	0.0%	18.4%	49.3%	4.0%
Low	Clamshell	46.0%	15.0%	35.0%	0.0%	4.0%
	Shopping Bag	13.4%	5.0%	23.4%	54.3%	4.0%
All	All other cases	100%	0%	0%	0%	0%

industry is complex and at times highly integrated: for example, wood chips and sawdust produced as a by-product by a sawlog mill may be purchased by a pulping mill and used as a feedstock or energy source. There is also a high degree of variability in the industry, with processes adapted to the specific qualities desired for a given product. For instance, two paper mills may have considerably different processes depending on the type of feedstock or paper features they intend to make and supply. Graphic papers and printable packaging cardboard for consumer CPG brands often require bleaching, optical coating and finishing stages, whereas unbleached, lower quality kraft paper and cardboards may not.

There are relatively few data sources that cover the whole forest products industry across multiple countries, but one source that fulfils these requirements is the United Nations Food and Agriculture Organisation (UN FAO) (United Nations Food and Agriculture Organisation, 2020). The UN FAO annually publishes data for UN member states, providing statistics on annual production and trade for intermediate and final products. Data is standardised into defined product categories and can easily be compared. The data structure of the UN FAO is provided in the Supplementary material. Of particular importance to this study is the 'Paper & Paperboard' category. Since the units of the reported statistics vary between mass and volume depending on the product category in question, it is difficult to follow the flow of wood from the harvest stage through to a given final product, since pulp used in paper production may contain significant quantities of water and chemicals, whereas a tonne of dried industrial roundwood is likely to consist almost entirely of the wood fibre.

To track the flow of wood through the industry supply chain, the UN FAO data was, as proposed by multiple previous studies (Bösch et al., 2015; Jochem et al., 2021; Bösch et al., 2023), converted into a single consistent unit, volume of wood fibre equivalent, or m^3(f). This unit "the equivalent volume of wood fibres" contained in a specific product and excludes the volume of water and other non-wood components from forest products.

Conversion factors between metric tonnes and m^3 were sourced from the UN FAO Joint Forestry Sector Questionnaire and accompanying documents (United Nations Economic Commission for Europe, 2024; United Nations Food and Agriculture Organisation, 2020), while conversion factors to m^3(f) were sourced from the literature (Jochem et al., 2021; Bösch et al., 2023) and are displayed in the supplementary information. After converting the latest available UN FAO data for the Canadian and US forest products industries to the common unit of m^3(f), the flow of wood through the supply chain could be mapped.

The results of this mapping are shown in Sankey diagram form in Figure S3 in Supplementary material. With the flow of wood through the forest products industry established, this data was used to model the impacts of increased demand for wood-based alternatives to SUPs. Table 3 shows how the SUP items selected for this study across groups A and B were fitted within the UN FAO supply chain structure. Masses in each case correspond to full replacement of SUP products with alternatives.

2.4. Modelling future demand

Many previous studies have examined future trends in the forest products sector using economic and sectoral modelling approaches. Although such models do not directly estimate the impacts of the additional demand (see Table 3) associated with the specific SUP replacements considered here, they can provide useful background on how baseline production, consumption, and trade may evolve over time.

Buongiorno et al. (Buongiorno et al., 2003; Buongiorno, 2015) developed the Global Forest Products Model (GFPMX), one of the most comprehensive models of this kind. GFPMX does not resolve the specific product categories assessed in the present study, but instead represents broader forest product classes such as paper and paperboard.

Further work in 2021[38] used the GFPMX to generate predictions for future trends in production, trade, and consumption of forest products, based on the structure used by the UN FAO. In the present study, these projections were used only to provide baseline sector context for the USA and Canada. The additional material requirements associated with replacement of selected SUP items were calculated independently in this study from product-level consumption and mass data. The GFPMX-based projections are used only to provide an external baseline for broader forest-sector trends. The additional replacement demand estimated in this study is not fed back into GFPMX, and the analysis therefore does not model endogenous price responses, trade shifts, demand regulation, or technological adaptation. The projected scenarios should consequently be interpreted as material-demand illustrations rather than market-equilibrium forecasts.

This distinction is important. The present study does not model endogenous market reactions, price effects, trade shifts, or technological adaptation arising from additional demand for wood- and paper-based alternatives. Instead, it combines a bottom-up estimate of material substitution requirements with externally derived sectoral baseline projections to provide a high-level assessment of potential supply-chain implications.

A full breakdown of the mass of material per item is available in the Supplementary Information. GDP, population growth, GDP deflator, and other macroeconomic inputs used in the GFPMX-based projections were taken from the World Bank Development Indicators database (WBI).

Using this work alongside the equivalent masses calculated in the Methodology section, this work estimates the mass of material required to replace SUP items at the levels in the scenarios shown in Table 2. This enables the estimation of land use requirements and initial discussion on paper production capacity and waste. In all cases, estimates and assumptions are used, but the work undertaken here can provide a basis for further detailed scenario development following a life cycle assessment (LCA) approach.

Table 3
Material Requirements for SUP Replacement Items – UN FAO Categories. It reports the annual mass of wood- or paper-based material required if the selected SUP items were replaced by the corresponding alternatives shown in Table 1. For each item, this mass was calculated as annual units consumed multiplied by the mass per replacement unit, and then aggregated by the relevant UN FAO material category.

	Material (UN FAO Category)	Applied products	Mass for Total Replacement (tonnes)
Group A	Wrapping papers	Shopping Bag, Straw	8,587,500
	Cartonboard	Clamshell	6,960,000
	Sawnwood	Fork, Stirrer Stick	21,172
	Other Fibreboard	Ring Carrier	35,360
Group B	Wrapping Papers	Pallet wrap, Dog Food sack, Cement sack, Spices pouch	7,278,069
	Cartonboard	Water bottle multipack wrap, Juice pouch, Candy pouch	1,894,356
	Case Materials	Bodywash multipack wrap	1,550,680

3. Results & discussion

3.1. Mass of materials required

The clear initial conclusion when comparing the selected items and their alternatives is the significant increase in mass required for single-use wood-based products compared to SUP equivalents (Table 1 and Fig. 2). This is common to both groups A and B, but is most pronounced for shopping bags and clamshell containers in group A, which become 1.9 and 4.2 times heavier, respectively in the Middle scenario, and in group B for collation shrink wraps for water bottles and body wash,

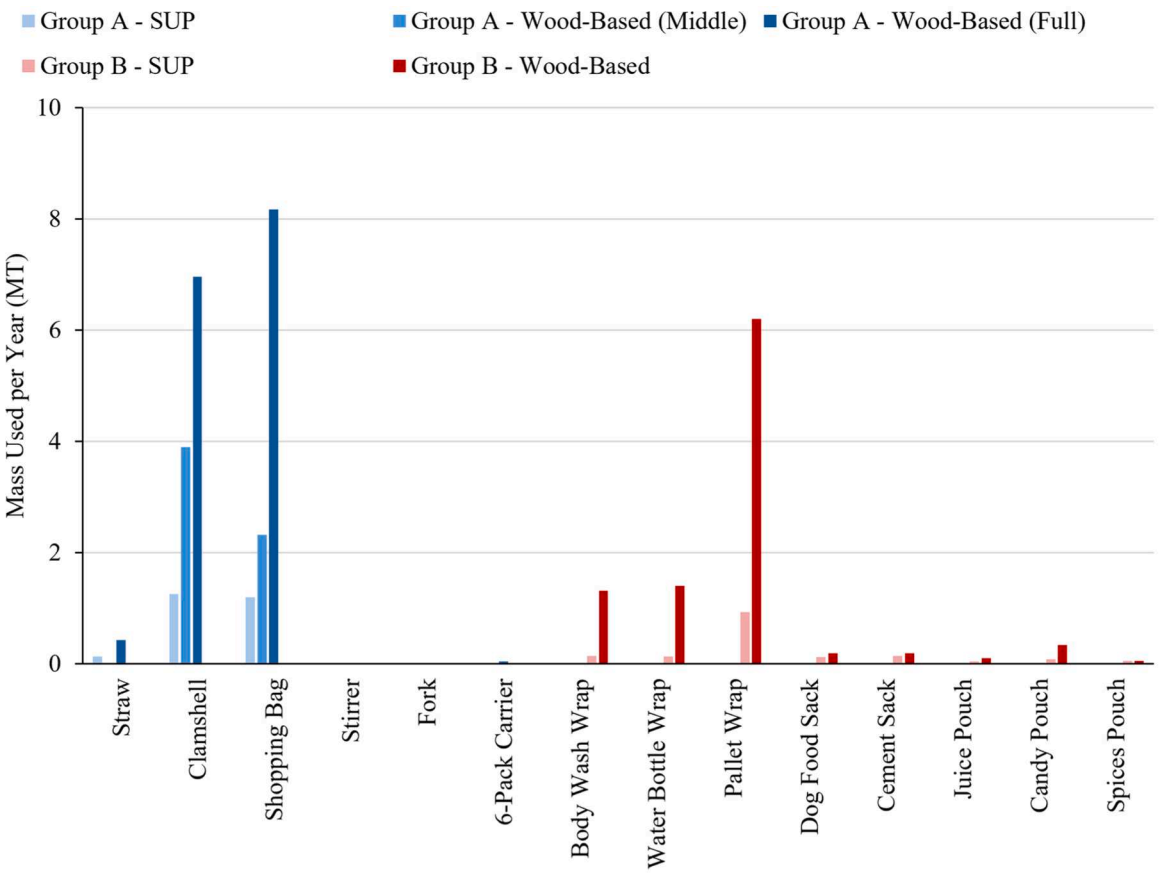


Fig. 2. Annual mass of selected SUP products and their wood- and paper-based alternatives across the USA and Canada under the full-replacement and Middle scenarios. Values are based on the representative product masses and replacement assumptions described in Sections 2.1 and 2.2.

which become 10.7 and 9.3 times heavier, respectively.

However, this disparity in mass-per-unit is not the only driver of wood demand for a given category of product; usage levels also play a part. Shopping bags and clamshell containers both show high usage

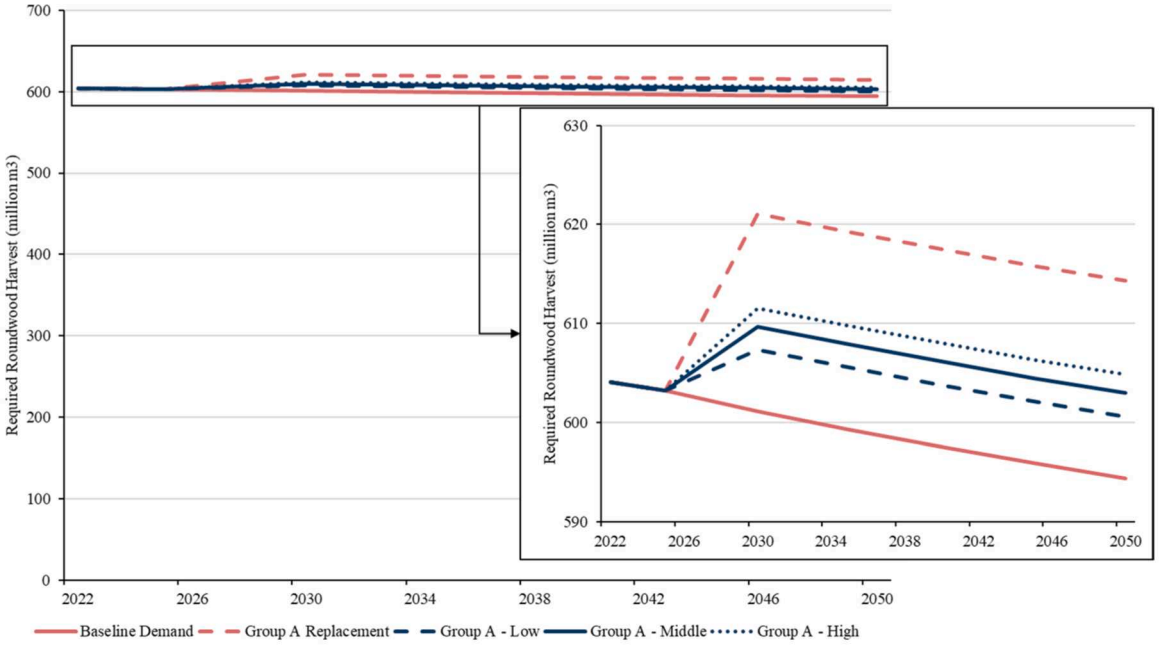


Fig. 3. Estimated additional wood demand associated with Group A replacement scenarios, shown relative to the projected baseline trend for the USA and Canada. The replacement requirements are calculated in this study from product-level mass and consumption data, while the baseline trend is derived from the GFPMX-based projections reported in (Buongiorno, 2021).

levels and large mass increases and were shown to be the most important items in group A, collectively accounting for more than 92% of the mass of the group in the SUP scenario. Three items are shown to be dominant in group B (Fig. 2), with the collation shrink wraps and pallet wrap items combined accounting for 91% of the total mass of wood-based alternatives for this group.

Despite the varying contributions and breakdowns of the two groups selected for analysis, both exhibit a similar overall increase in mass required when comparing SUPs to their wood-based alternatives. The consumer-focused items in group A had an estimated total mass of around 2.6 million tonnes when made from SUPs, increasing to around 8.25 million tonnes when using the Middle scenario, and 18 million tonnes if 100% of SUPs are replaced with single-use paper or wood products. Because the clamshell is a major contributor to Group A material demand, a lower-mass sensitivity case using a 16 g clamshell was also assessed. The results, presented in the Supplementary Information, show how product lightweighting affects the aggregate material and production requirements.

The packaging items in group B had an estimated total mass of around 1.8 million tonnes when made from SUPs, increasing to around 10.8 million tonnes when replaced completely with wood-based alternatives (a 6-fold increase).

Annual demand for wood across North America is expected to fall by over 9.6 million m^3 (1.6%) by 2050 (Fig. 4, Baseline Demand). Taking this as a baseline figure, the changes in demand based on partial and full replacement are shown in Figs. 3 and 4, based on the 2021 GFPMX data (Buongiorno, 2021) introduced above.

Assuming that the wood-based materials required for groups A and B are produced in the USA and Canada using domestically sourced wood, and assuming that the production, imports, and exports of other wood-based products remain unchanged, based on the Middle scenario an additional 8.79 million m^3 of wood (1.5% increase in 2030) would need to be harvested across the USA and Canada to facilitate the replacement of the items in group A, and an additional 12,153,818 m^3 (2% increase in 2030) required for group B.

The impact of these three Group A adoption scenarios on the total USA and Canada harvest requirement is also shown in Fig. 3 (Group B results are shown in Fig. 4). The 'middle' scenario shows that with reported levels of adoption for paper shopping bags (28.4%) (Banko and Bhanot, 2023) and an adoption rate of 56% for clamshell containers, the additional wood harvest required falls by approximately 10.9 million m^3 relative to the full replacement scenario, reaching a level 55.9% lower than that scenario.

Changes in demand based on group B only and group A and B combined scenarios are shown in Fig. 4. Under the 'Group A & B Replacement' scenario (which assumes that the selected replacements of SUPs in both groups will begin in 2025 and be complete by 2050) demand is expected to rise between 2025 and 2030, peaking at roughly 633 million m^3 before beginning to fall once again (solid purple line). With the Middle scenario (dashed purple line), the peak is 622 million m^3.

In this scenario, the additional wood required by 2030 is approximately 20 million m^3 compared to 2022 (a 3.3% increase). After 2030, this figure falls, again based on the model. The increased demand from SUP replacement, driven by regulation, is offset by decreased demand elsewhere in the forest products industry.

Using inputs from the GFPMX, previous work (Buongiorno, 2021) and the calculations above, Fig. 5 shows how much of the wood demand created by groups A and B can be offset by this broader fall in demand across the sector. By 2050, over 79% of the SUP replacements for group B can be implemented with no overall change in wood demand, or all group A requirements can be met (based on the Middle scenario), or 44% of combined demand if both groups were replaced simultaneously. If the full replacement group A scenario is assumed instead, 48% of group A demand or 30% of combined group A and B demand can be met by 2050.

The following sections interpret these estimated material-demand changes in relation to raw material availability, indicative land requirements, paper production capacity, and process waste streams. These sections combine direct outputs of the present calculations with contextual sectoral statistics and literature in order to assess broader supply-chain implications.

3.2. *Raw material availability*

Total wood volume in Canada was estimated to be around 50,199 million m^3 in 2021, with just over half of this located in areas managed for commercial forestry (Natural Resources Canada, 2023). Of this

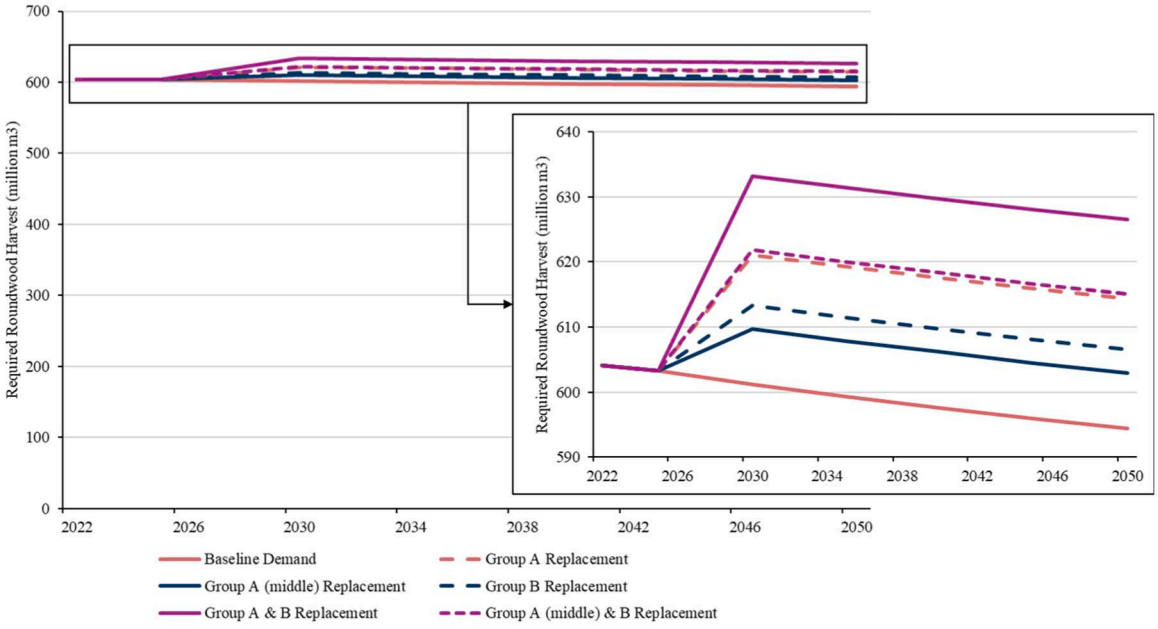


Fig. 4. Projected baseline wood demand for the USA and Canada (no SUP replacement), together with the estimated additional demand associated with replacement of Group A, Group B, and Groups A and B combined. Baseline demand is based on (Buongiorno, 2021); replacement demands are calculated in this study.

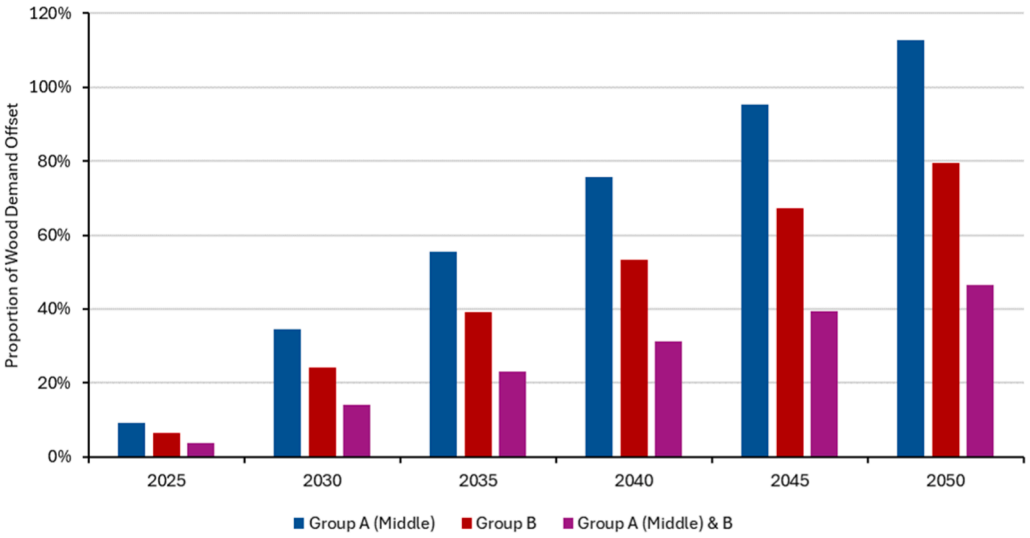


Fig. 5. Proportion of wood demand offset by falling baseline demand.

volume, a proportion is designated available for harvest each year, with the exact proportion changing annually depending on what is deemed 'sustainable forestry' (Natural Resources Canada, 2023) following provincial forest management objectives. This 'sustainable supply' level was 215 million m^3 in 2021 (Fig. 6a), with only around 68% (147.3 million m^3) of this actually harvested (Natural Resources Canada, 2023; Government of Canada, 2024). Canada's forest resources are primarily located in four territories: British Columbia, Quebec, Alberta, and Ontario. In 2022, across these four territories alone, it was reported that wood harvests were 65.6 million m^3 below sustainable supply limits, suggesting that there may be headroom for increased forestry within current sustainable definitions (Canadian Council of Forest Ministers, 2023). The US government does not publish a nationwide sustainable supply level but instead aims to meet a target of annual growth exceeding removals and mortality to prevent unsustainable levels of forestry (Oswalt, 2021). Much of the USA's commercial forestry is concentrated in the 'wood basket' southern states (Fig. 6b), which in 2017 accounted for 60% of all US wood removals (Oswalt et al., 2019). The southern US is able to produce this amount of wood due to the prevalence of planted forests, with 71% of US forestry plantations located in this region (Oswalt et al., 2019). Planted timberland is often much more productive than natural forest, with southern plantations producing 3.3 times as much growth and less than half the mortality per unit area compared to national averages (Oswalt et al., 2019). Recent work predicts that nearly all potential for growth in the US forest products sector resides in the southern US (Wear and Coulston, 2024), and that recent demand increases have been met in this region (McGinley et al., 2023).

3.3. Land use

There is considerable variability in forest productivity depending on land ownership, geographical location, and whether the forest is natural or planted (Wear and Coulston, 2024; Karimi et al., 2025). The land-use estimates presented here are therefore illustrative approximations rather than precise predictions. To provide an order-of-magnitude estimate, Canadian government annual statistics were used to estimate the average wood volume harvested per unit area, and therefore, estimate the land required to facilitate a given increase in wood harvest. In 2021, the Canadian government reported that 698,025 hectares of forest land had been harvested, yielding a harvest of 147.3 million m^3 (Government of Canada, 2024). This suggests an average yield of 211 m^3 per hectare of forest harvested. Using this average, to satisfy demand for groups A (Middle scenario) and B would require an additional 40,574 and 43,628 hectares of harvest, respectively, when wood demand peaks in 2030, split across the USA and Canada. If full replacement of group A is

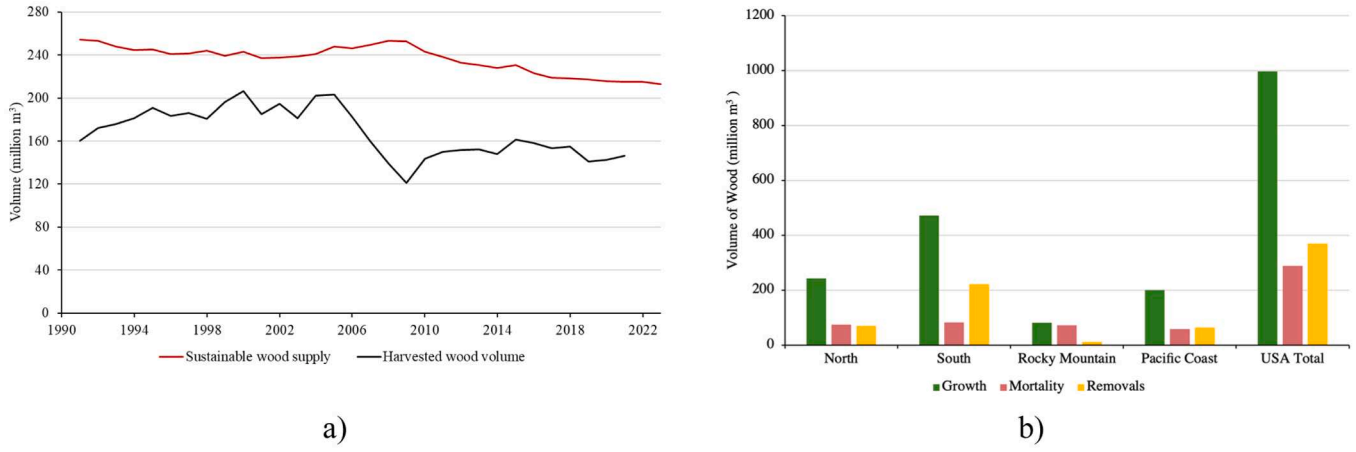


Fig. 6. a) Canada's 1990-2022 sustainable supply level (Natural Resources Canada, 2023) and harvested; b) Forest Resources of the US Regions 2017[44] wood volume (Government of Canada, 2024).

assumed, this increases to 80,461 and 43,628 hectares of harvest, respectively.

To illustrate the possible geographical scale of this land requirement, a simple per-capita allocation was used to split the additional harvested area between Canada and the USA. This is a simplifying assumption adopted only because directly comparable national harvested-area statistics were not available for both countries. Under this assumption, the additional harvested area would correspond to approximately 12,619 hectares in Canada and 71,584 hectares in the USA at the 2030 peak. To put these figures into perspective, this would equate to a 1.6% increase in harvested forest area for Canada when compared to 2021 figures. It is not possible to make a similar comparison for the USA due to a lack of published information, but comparing instead to the area of planted timberland in the southern USA (likely to be the source of any increased harvests (McGinley et al., 2023)) 72,901 hectares represents about 0.38% of southern plantations, which were reported to have a total area of over 19,457,000 hectares in 2017[44]. However, the estimated land requirement should be interpreted as an illustrative order-of-magnitude calculation rather than a spatial prediction. The per-capita allocation between Canada and the USA was used only because directly comparable harvested-area data were unavailable. Actual additional harvest would be geographically uneven and influenced by forest productivity, ownership, mill location, timber prices, transport, and trade.

However, this calculation ignores factors such as the uneven spread of demand (privately owned planted forests would likely be quickest to respond to increased demand, and with their above-average productivity and harvest intensity (Riddle, 2021) such plantations would require much less land area than would be needed elsewhere) and assumes complete harvest (whereas in reality although a particular area of land may be recorded as 'harvested', many immature trees may be left intact to be felled at a later date).

3.4. Paper production capacity

Another important consideration is the availability of paper production capacity. As Fig. 7 shows, replacement of the selected SUP items following the Middle scenario by 2030 requires an increase in production of 8 Mt across Canada and the USA for group A, and 10.7 Mt for group B. Full group A replacement would increase this to 18 Mt which group B remains at 10.7 Mt.

Although partially offset by a small, predicted drop in production requirements for other paper products, such a rise would correspond to a 25% increase from 2022 levels (39% increase for full group A replacement) and would be almost entirely confined to the packaging papers sector. Overall paper production has not been at this level since 2008, with falling demand for graphic papers having fuelled a downward trend in production over the last 20 years. The decline in graphic paper demand, as well as increasing operating costs, has driven many mills in North America to curtailment and closure. However, some mills have adapted by converting from graphic paper production to the production of packaging papers and board (Berg and Lingqvist, 2019). The 2024 capacity utilisation rate, as provided by the American Forest & Paper Association, is 87.5% (65th Edition Paper Industry Annual Capacity and Fiber Consumption Survey, 2024).

3.5. Waste and By-products

The production of forest products produces a variety of waste products at different stages of the value chain. At the harvest and initial processing stage, sawdust is a common waste product. The bark is also an important byproduct at this stage and is typically used as fuel for biomass burners, agricultural mulch or a standalone consumer product. When burnt as fuel, bark and wood products produce large quantities of fly ash, which is often collected and sold to the cement industry. Increases in forest product use and production would increase the production of these additional products. The impact of increased availability of these products has not been studied in detail during this work, and would require analysis of the current market saturation and demand for these products.

For simple wood products such as sawnwood, relatively little processing of raw materials is required. The waste from these processes usually consists of wood chips, sawdust, and other offcuts. Wood chips and sawdust are often used by pulping mills to supplement their pulpwood feed, as well as in the production of wood-based panels, fibreboards, and wood pellets.

The pulping process produces more complex waste streams. Kraft pulping in particular, which is the dominant chemical pulping method in North America, produces significant quantities of inorganic, alkaline

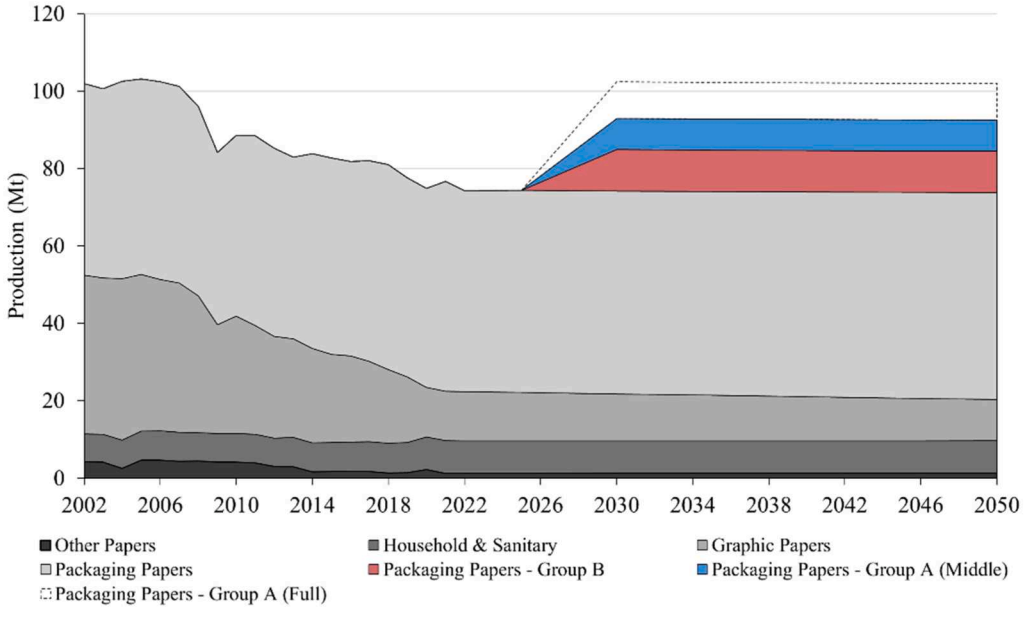


Fig. 7. North American paper production under the projected baseline trend and under the estimated additional demand associated with Group A and Group B replacement scenarios by 2030[16]. Baseline production trend is contextualised using (Buongiorno, 2021); replacement demand is calculated in this study.

waste products. The Kraft process essentially uses a mixture of sodium hydroxide and sodium sulfide to break down lignin, leaving the remaining cellulose to form a fibrous pulp. The chemicals and broken-down lignin, collectively known as 'black liquor', are then washed out of the pulp and sent to the recovery stage, where they undergo multiple processes to recover sodium hydroxide and sodium sulphide for reuse (Quina and Pinheiro, 2020; Tran and Vakkilainnen, 2016).

The chemical recovery stage produces multiple solid waste streams, including slaker grits, lime mud, and liquor dregs, all of which are typically alkaline (see Fig. 8) (Quina and Pinheiro, 2020; Tran and Vakkilainnen, 2016). Where bleached pulp is required, the bleaching stage is responsible for the majority of wastewater, with some studies suggesting the stage is responsible for up to 85% of the total wastewater produced by the process (Cabrera, 2017).

With the significant increases in wood harvest and paper production required to facilitate the switch from SUPs to wood-based alternatives, these waste products will also be produced in increased quantities. As has been outlined, many of the waste and by-products created in the forest products industry are used as feedstocks for other processes. However, it is unclear whether there would be sufficient demand for these products to handle increased levels of production, and alternative means of disposal may be required.

Waste not used in other processes (such as the chemical waste products produced by the kraft process and the wastewater created during bleaching) also pose challenges if production rates are increased. Wastewater treatment capabilities may need to be expanded, and the environmental impacts of increasing the quantities of solid waste sent to landfill or incineration would need to be considered and assessed.

The present study does not quantify individual process waste streams. Such estimates would require mill- and process-specific data on pulp grade, chemical recovery, bleaching configuration, water management, and waste treatment. The waste streams discussed here are therefore identified as potential production-capacity and infrastructure considerations associated with increased pulping activity rather than quantified environmental outcomes.

3.6. Discussion

The results suggest that large-scale replacement of selected SUP items with single-use wood- and paper-based alternatives could create substantial additional demand for wood fibre and paper production capacity in North America. These changes may, in turn, have broader environmental and trade implications beyond the immediate substitution of one material for another.

Existing literature shows that pulping and papermaking can be associated with high energy use, steam demand, chemical recovery requirements, wastewater generation, and solid by-products, with important contributions to life cycle greenhouse gas emissions and other potential environmental impact categories, including acidification and eutrophication (Sun et al., 2018). Additional impacts may also arise from feedstock transport, bleaching, and the treatment or disposal of waste streams (Sun et al., 2018). At the same time, conventional fossil-based plastics also have associated impacts, including fossil resource use, greenhouse gas emissions, and waste-management challenges. But no comparison of absolute environmental performance between plastics and wood-based alternatives was undertaken in this study. The present study, therefore, does not imply that plastics are environmentally preferable, but rather that large-scale material substitution within the single-use model can shift burdens rather than eliminate them.

Land use and carbon stock impacts are also relevant contextual considerations. Increased harvesting reduces standing forest carbon stocks, although higher demand can, in some cases, lead to intensified forest management and reduced conversion to non-forest uses. These aspects were not assessed in the present study, but they provide important context for interpreting changes in forest product demand.

Biogenic carbon accounting represents an additional source of methodological uncertainty when comparing plastic and paper-based products. Multiple approaches exist and can yield divergent results (Nemecek et al., 2025; Waqas et al., 2025). A detailed evaluation of biogenic carbon was outside the scope of this study, but its influence on net GHG emissions underscores the need for a more comprehensive assessment in future work.

Overall, the findings support the view that replacing SUPs with single-use wood- and paper-based alternatives should not automatically be assumed to reduce environmental burdens. The outcome may depend on product design, replacement rates, recycled content, energy systems, production geography, end-of-life treatment, and behavioural responses. A comparative LCA was outside the scope of this study but would be helpful to evaluate potential environmental impact trade-offs robustly.

4. Conclusions

For both groups of items assessed in this study, switching from single-use plastic materials to single-use wood and paper alternatives would increase the total mass of products used, due to the difference in mass between existing SUP items and their wood-based equivalents. This increase was driven by three items in particular: shopping bags and clamshell containers in group A, and pallet wrap in group B. High usage levels compared to the other items in each group amplify the impact of these products. Shopping bags and clamshell containers were assumed to be replaced at rates suggested by previous studies, meaning that the required number of products in the single-use wood and paper cases was

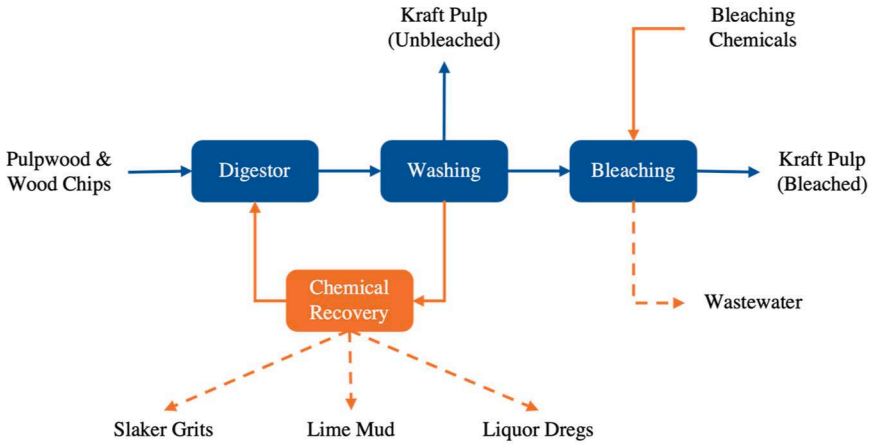


Fig. 8. Overview of the Kraft pulping process.

28.4% and 56% of those in the SUP cases, respectively (with the remainder either eliminated by reduced use or replaced by other products not considered in this study).

To facilitate the switch from SUPs to wood-based alternatives for the selected items was estimated to require an additional 13.68 million m^3 of wood across the USA and Canada (58% due to group A, 42% due to group B). Assuming such a switch would be implemented gradually from 2025 to 2030, and considering broader trends in the forest products industry, it was estimated that the total required harvest for the USA and Canada would peak at 3.3% above 2022 levels, with this additional demand being increasingly offset in the following years due to a broader decrease in wood demand elsewhere.

Despite the disparity in data availability in Canada and the USA, land use can be estimated. Extrapolating published Canadian average yield figures across both countries, an additional 84,202 hectares of forest land would need to be harvested to meet the estimated wood demand peak in 2030. Assuming an even demand split per capita, this would represent a 1.6% increase in land harvest in Canada and 0.38% of total planted forest land in the Southern USA.

Paper production capacity, by grade type, is a key bottleneck. For the domestic industry to satisfy the demand created by a total replacement of the selected items, paper production would need to increase by approximately 18.7 Mt (25%) across the USA and Canada from 2022 levels. Based on the previous 20-30 years of pulp and paper production consolidation globally, and reduced North American production specifically (FAO, 2025; Palmer and Cohen, 2020), it is unlikely this new demand would be met initially and even in the medium/long term by paper production from inside the USA or Canada. Pulping and papermaking stages can be key sources of environmental impacts and waste. Therefore, the projected large increases in production necessary to switch to wood-based alternatives would require an understanding of environmental trade-offs across a broad range of environmental issues, both locally and within the global supply chain.

It is unlikely that all SUPs would be replaced by wood-based alternatives in a like-for-like switch. The scenario considered for shopping bags and clamshell containers recognises that many SUPs may be replaced by a mixture of single-use and reusable alternatives; however, many further items in group A may be eliminated by reduced use. Even after applying this scenario, there remains significant doubt surrounding the environmental benefits of switching material type within the single-use model (Meng et al., 2024). Conventional fossil-based plastics also have potential environmental impacts, including fossil resource consumption, greenhouse gas emissions, and waste-management challenges. The results presented here should therefore not be interpreted as demonstrating that one material or product has an environmentally lower impact than the alternative. Instead, they show that material substitution may introduce additional upstream resource and production requirements that should be considered alongside the impacts of the incumbent plastic system.

Policy and regulation decisions can be better informed through material demand-driven and robust life cycle environmental and economic assessments in the early stages of development to avoid potential unforeseen and unintended consequences. This study aims to highlight the benefits of such life cycle approaches to help shape science-based and material-neutral policies and solutions to effectively address recognised issues, including waste and end-of-life scenarios. Further work should develop detailed, specific LCA studies, including use-phase performance, end-of-life pathways, and biogenic carbon accounting, to expand this work, taking into account the differences in scale between plastic product and wood-based alternative product manufacturing sectors. Recycled content, the development of recycling technology and forecasts for changes in secondary raw material availability can also be considered in future work.

Product design and mass are also important sources of uncertainty. The lower-mass clamshell sensitivity demonstrates that lightweighting could materially reduce fibre demand, although lighter products may not provide the same functionality as the baseline alternatives. Future work should therefore assess broader product mass ranges while maintaining consistent functional units.

CRediT authorship contribution statement

Joseph Greaves: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Rachael Rothman:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Jon McKechnie:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Experience I Nduagu:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Kirti Richa:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Timothee W Roux:** Writing – review & editing, Supervision, Conceptualization. **Fanran Meng:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Authors Experience I Nduagu, Kirti Richa, and Timothee W Roux are employed by ExxonMobil Technology and Engineering Company and/or its affiliates. The academic authors retained scientific independence in pursuing this work and no editorial control was exercised by the sponsor. F.M is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2026.200380.

Data availability

All data used can be found in the manuscript and SI.

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