Policy is Essential to Curb Plastic Pollution

THE EXAMPLE OF CALIFORNIA'S SENATE BILL 54

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CONTENTS

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SECTION

1 EXECUTIVE SUMMARY

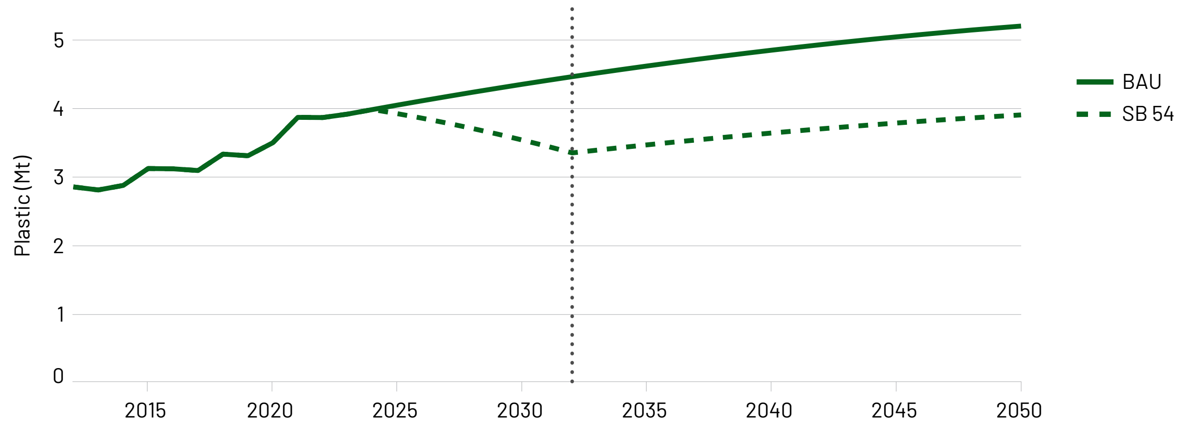
Plastic pollution represents a growing environmental and public health challenge, with California contributing disproportionately as the largest generator of landfilled plastic waste in the United States. Despite this, comprehensive data on plastic consumption and waste management within the state has been lacking. This report addresses that gap by presenting the first state-level, time-dependent material flow analysis (MFA) of plastics in California, spanning the period 1950 to 2050. The analysis quantifies plastic consumption, waste generation, and end-of-life management across all major use sectors and evaluates the projected impacts of key policy interventions, including California's landmark Plastic Pollution Prevention and Packaging Producer Responsibility Act, Senate Bill 54 (SB 54).

Key findings include:

- Between 2012 and 2020, California's plastic consumption increased from 7.2 to 8.8 million metric tons (Mt), with packaging consistently accounting for ~40% of total use.
- Over the same period, plastic waste generation rose from 5.3 to 6.9 Mt, with approximately 90% of waste landfilled and less than 9% collected for recycling.
- Under a business as usual (BAU) scenario, plastic consumption is projected to reach 13.1 Mt by 2050—a nearly 50% increase relative to 2020—with waste generation expected to rise to 11.8 Mt. Landfilling will remain the dominant disposal pathway in the absence of policy change.

Three classes of policy interventions are evaluated—source reduction, recycling rate, and recycled content mandates—for their potential to reduce plastic production, waste disposal, and associated greenhouse gas (GHG) emissions (measured in Mt carbon dioxide equivalent, CO_2e). Senate Bill 54, which mandates a 25% reduction in plastic packaging and a 65% recycling rate by 2032, is projected to reduce cumulative plastic production and disposal by 55.8 Mt and GHG emissions by 164.0 Mt CO_2e by 2050 relative to BAU (Figure 1). Over the next ten years, each year of delay in SB 54 implementation beyond the 2032 target is estimated to result in over 1.5 Mt of additional virgin plastic production and landfilling annually, along with 6.3–6.6 Mt CO_2e in excess GHG emissions. Adding a 40% recycled content mandate to SB 54 would further increase benefits to 69.3 Mt and 183.9 Mt CO_2e, respectively. However, interactions between interventions mean that combined effects are not strictly additive.

This analysis highlights the critical importance of integrated, multi-faceted policy strategies to effectively address plastic pollution. Source reduction yields the greatest environmental benefit, particularly in terms of GHG mitigation, while recycled content mandates offer systemic leverage by stimulating both in-state and out-of-state recycling markets. These findings reinforce the urgency of timely SB 54 implementation and provide a replicable framework for other states seeking to develop data-driven, impactful plastic pollution mitigation policies.



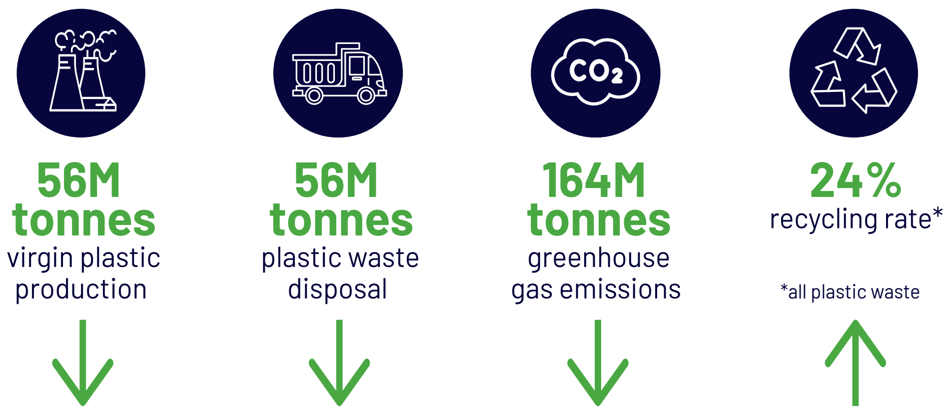


FIGURE 1: Impact of California Senate Bill 54 | (A) Projected plastic consumption (million metric tons, Mt) in the packaging sector from 2012 to 2050 under business as usual and with the implementation of SB 54. (B) The cumulative impact of SB 54 from 2025-2050 relative to BAU on plastic production (Mt), greenhouse gas emissions (CO_2e), and the total recycling rate in California.

SECTION

2 INTRODUCTION

Plastic production is accelerating rapidly, with increased reliance on plastics across nearly all sectors of the global economy. In 2020, annual global plastic consumption reached 547 Mt, of which 86% was virgin and 14% was recycled plastic (Pottinger et al., 2024). Derived largely from fossil fuels and produced via fossil fuel intensive processes, the life cycle of plastic production, consumption, and disposal is a growing source of greenhouse gas emissions (Nicholson et al., 2021). Mismanagement of plastic waste has widespread impacts on both people and nature. In ocean and freshwater systems, plastics are readily ingested by wildlife and impair reproductive health, feeding behavior, and growth (Azevedo-Santos et al., 2021; Beaumont et al., 2019). On land, plastics degrade soil quality and compromise sustainable food production systems (Tiwari and Sistla, 2024; Zhang et al., 2020; Zhu et al., 2025). Plastic production, use, and disposal also pose numerous risks to human health, and are associated with increased rates of cardiovascular, pulmonary, renal diseases, and cancers (Landrigan et al., 2023; Verma et al., 2016). The adverse effects of plastics and plastic pollution disproportionately affect socioeconomically disadvantaged and marginalized communities (Landrigan et al., 2023; Stoett, 2022).

California plays an outsized role in plastic waste generation: the United States is the largest producer of plastic waste globally (Law et al., 2020), and as its most populous state, California produces the largest amount of landfilled plastic waste in the country each year (Milbrandt et al., 2022). Yet, despite California's prominent role in plastic waste generation, robust information about the consumption and fate of plastics in the state is lacking. We do not know plastic consumption patterns in California—including use and discard rate through time and by use sector. We also lack critical information about the fate of plastic products consumed in the state, raising equity and environmental justice concerns for communities most burdened by deleterious impacts from plastic pollution. This report presents the first comprehensive, state-level plastic material flow analysis (MFA) for California, quantifying plastic consumption, waste generation, and end-of-life management across all major use sectors from 1950 to 2050. We use these findings to explore the impact of existing and plausible policy interventions aimed at reducing plastic pollution. This work is particularly timely given delays in the implementation and potential revision of California's landmark legislation to reduce single-use plastics: Senate Bill 54 (SB 54).

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SECTION

3 METHODS

The principal method used in this study is time-dependent material flow analysis (MFA), with a time increment of one year and a time coverage of 1950 to 2050 to track plastic consumption, waste generation, and end-of-life waste management in the state of California, USA (Figure 2).

3.1 Plastic consumption

Traditional MFA approaches calculate apparent consumption as material production plus net trade (imports minus exports). However, California lacks trade data required for this approach and instead we use a novel method combining economic input-output (IO) models with plastic intensities to estimate plastic consumption by use sector. While IO models have been used for life cycle assessments for over 25 years, their use for MFA is still in the early stages. The existence of state-level IO models presents a unique opportunity to advance MFA theory and an alternative way to estimate annual plastic consumption when trade data are not available.

An IO model is a linear sector-by-sector representation of an economy that captures the trade of goods and services between economic sectors. The California Environmentally-Extended Input-Output (EEIO) model was developed by the federal Environmental Protection Agency (EPA). The EPA has developed and published state-level, multi-regional EEIO models for all U.S. states (Ingwersen et al., 2024). These models are called 'environmentally-extended' because they convert economic input-output data into environmental indicators such as climate change, acidification, and ecotoxicity. The EEIO models are available for the years 2012-2020 and account for the entire economy of a state by dividing it into 73

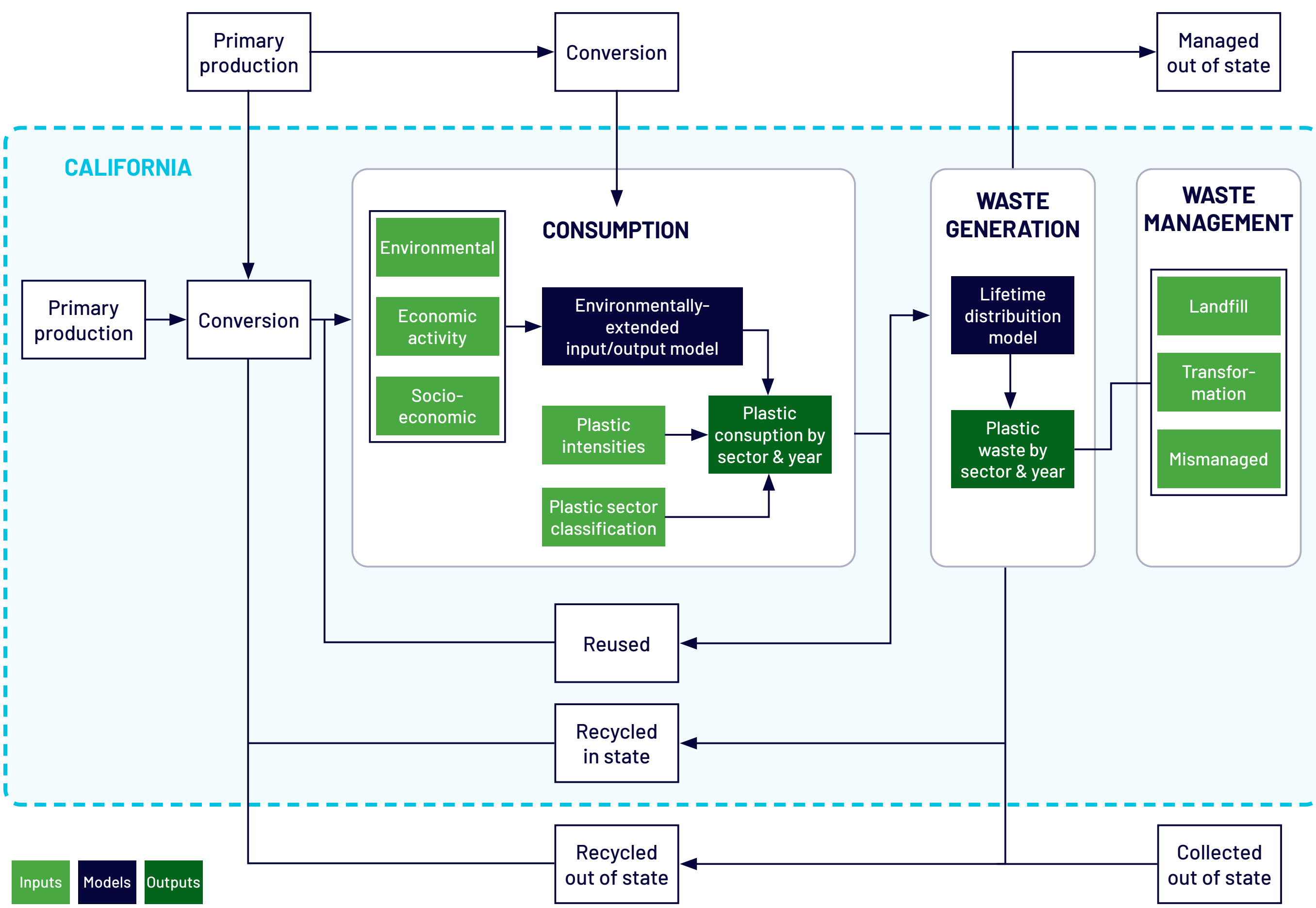

FIGURE 2. Material Flow Analysis. | A diagram of the relevant plastic flows, plastic transformation processes and model parameters included in the material flow analysis (MFA).

distinct commodities. These commodities are defined based on the 2012 Bureau of Economic Analysis (BEA) summary-level industry classification (US BEA, 2019). The BEA classification includes 71 summary-level industries, for example "326" represents plastics and rubber products manufacturing, as well as "Used" and "Other". The "Used" code represents used goods of any type and "Other" are goods that are generally imported and no equivalent goods are made in the U.S. (Ingwersen et al., 2024). The California EEIO model connects annual final demand of goods and services in California (in dollars and by industry) to the direct and total inputs (in dollars and by industry) required to produce this final demand. It distinguishes between inputs produced in California, in the rest of the U.S., and abroad. This industry-level approach allows us to trace inputs from the plastic industry (326 plastic and rubber products) through the other 72 industries in the economy via the Leontief matrix, which serves as a representation of the economy's industry relationships by showing how the output of one industry is used as an input by other industries and vice versa. The EEIO data (e.g., direct and total inputs) are converted into plastic mass flows using a plastic intensity which quantifies the relationship between plastic consumption and economic activity (i.e., the plastic intensity relates the economic value of purchased commodities to their average plastic content).

3.1.1 Present: 2012-2020

For the years 2012 to 2020, annual total plastic consumption in California is calculated as follows:

$$C_{total}^{t} = \frac{m_{326}^{2017}}{\rho_{326}^{t}} \cdot \sum_{i=1}^{73} \left(l_{326,i}^{t} \cdot f_i^t \right)$$

In the above formula, f_i^t is final consumption in California (from households, businesses, and government) of output from industry *i* in year *t* (in current $) and $l_{326,i}^{t}$ are the total requirements of industry *i* from *326* (plastics and rubber products) (i.e., element *236,i* of the Leontief matrix of year *t*, in current $). The $\frac{m_{326}^{2017}}{\rho_{326}^{t}}$ term is the inflated/deflated plastic intensity for year *t* (metric ton/2017 $), where m_{326}^{2017} is the mass-to-value ratio of industry *326* in the U.S. for year 2017, and ρ_{326}^{t} is the time value of money adjustment between years *t* and 2017 specific to sector *326* (Ingwersen et al., 2024). m_{326}^{2017} was calculated by dividing the total mass of the output of the U.S. plastic sector in 2017 by the total economic value of this output and is equal to 51,244,144 metric tons/89,816,940,606 2017$ (Ingwersen et al., 2022; American Chemistry Council 2025). C_{total}^{t} is the resulting estimate of total plastic consumption (in metric ton) in California in the year *t*.

Plastic consumption by industry is calculated based on purchasing from the plastics sector $(a_{326,i}^{t})$, rather than the industry that final consumers purchase from $l_{326,i}^{t}$. This is achieved by using the power series approximation of the Leontief matrix:

$$L = 1 + A + A^2 + A^3 + A^4 + A^5 + \cdots \approx 1 + A + A^2 + A^3 + A^4 + A^5$$

$$C_i^t = \frac{m_{326}^{2017}}{\rho_{326}^{t}} \left[f_{326}^{t} + a_{326,i}^{t} [f_i^t + (AF)_i + (A^2F)_i + (A^3F)_i + (A^4F)_i] \right]$$

For each of the nine years, the fifth degree polynomial is used which accounts for over 99% of total plastic consumption. The fraction plastic consumed by industry *i* is calculated as $\frac{C_i^t}{\sum_{i=1}^{73} C_i^t}$.

Lastly, the 73 industries of the California IO model are mapped onto 11 aggregated plastic use sectors: agriculture, commercial/institutional, building & construction, electrical/electronic, healthcare, household/leisure/sports, packaging, textiles, and other (Figure 3). The BEA economic industry groups encompass a wide range of activities, especially at the aggregated sector-level used in the California IO model. To improve classification, we started with the comprehensive 402 detailed BEA industry codes, which represent the highest-resolution classification available. For each code, a main plastic sector and secondary plastic sector were identified with an associated proportion reflecting the relative distribution of plastic use within that industry to the primary and secondary plastic use sectors (e.g., industry group 1111A0 oilseed farming [sector 111CA] = 95% agriculture and 5% packaging). The allocations were based on the specific descriptions of each industry group (US BEA, 2017) and expert input on the type of plastic(s) that are used by that industry. Proportions for primary and secondary plastic use sectors were derived for each of the 71 BEA summary industries by averaging across all detailed industry codes within each summary industry (e.g., sector 111CA farms = 93% agriculture and 7% packaging). The remaining two industries, "Used" and "Other", were both classified into the "Other" plastic sector. Finally, these proportions were applied to the total plastic consumption from each of the 73 industries in the California IO model to allocate plastic consumption into relevant plastic use sectors (e.g., sector 111CA farms = 81,998 tons; 76,258 tons of agricultural plastic and 5,740 tons of packaging plastic).

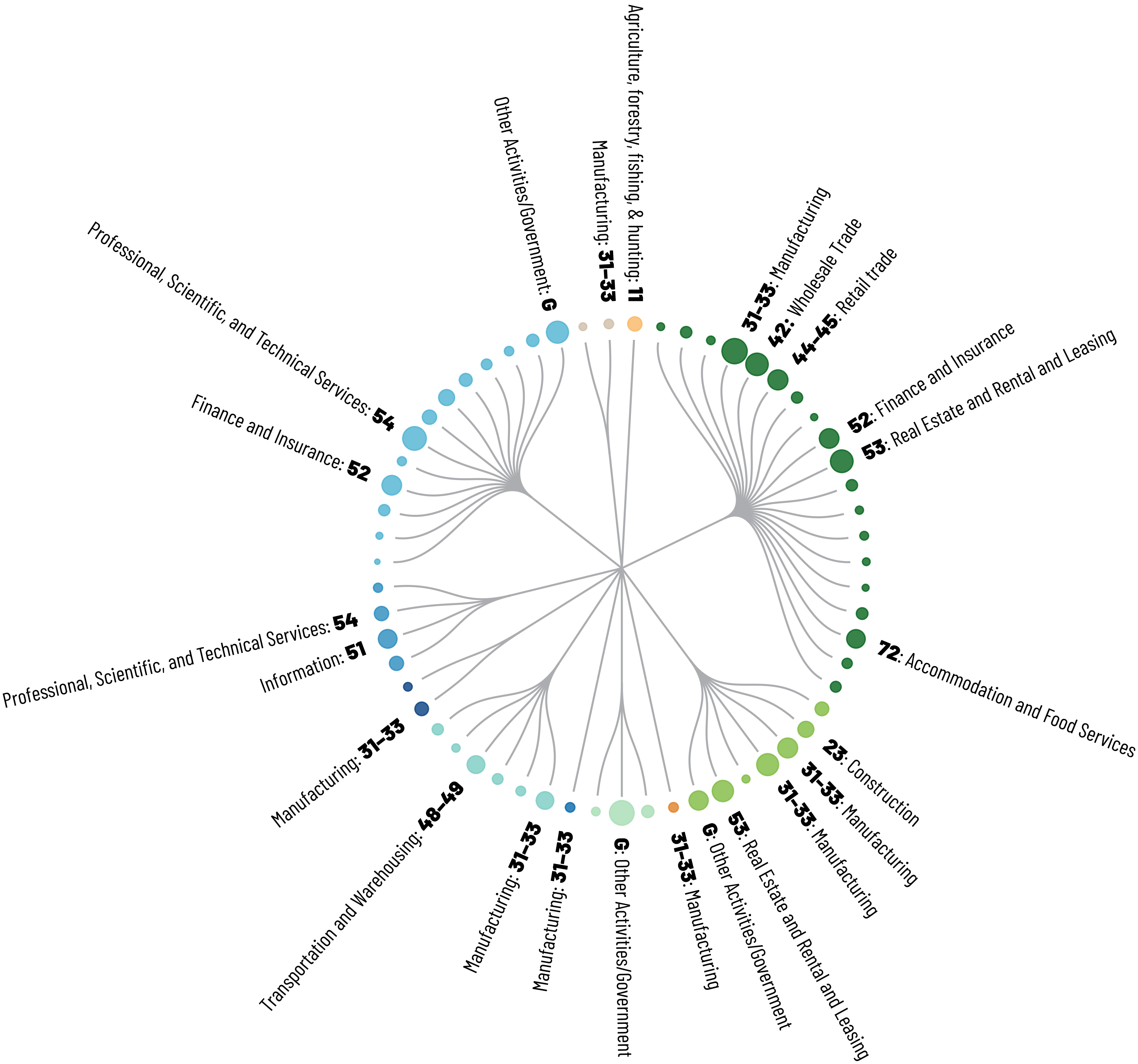

FIGURE 3: Economic to plastic sector classification. | Each circle represents a Bureau of Economic Analysis (BEA) sector-level industry classification (21 industries) with the circle size reflecting the amount of plastic from that industry sector. Larger circles indicate economic industry classes that contribute higher volumes of plastic within each plastic use sector. The primary contributors within each plastic use sector are labeled. Colors correspond to the 11 plastic use sectors.

3.1.2 Forecast: 2021-2050

The business as usual (BAU) projection is based on linear trend projections of the historical data for the California gross state product (GSP^t in 2017 USD) and the plastic intensity of GSP. m_{GSP}^t relates California plastic consumption to California GSP; it is distinct from m_{326}^t, which converts purchases from sector 326 from an economic value into mass of plastic. Historical California GSP data is available for 1997-2023. Historical data for $m_{GSP}^t = \frac{C_{total}^t}{GSP^t}$ can be calculated for 2012-2020. After extending both time series to 2050 via linear extrapolation, annual California plastic consumption projections for 2021-2050 are calculated as:

$$C_{total}^t = m_{GSP}^t \cdot GSP^t$$

3.1.3 Hindcast: 1950-2011

California plastic consumption estimates prior to 2012 are developed in order to facilitate the lifetime distribution approach to modeling plastic waste generation, in particular for sectors with long product lifetimes, such as building and construction. This was done by using California plastic consumption estimates derived from North American (NA) plastic consumption data published in Pottinger et al., (2024) and available for the years 1950-2020. Two California plastic consumption estimates were generated; one by scaling the NA data by California's population share, and one by scaling it by California's GDP share. The input-output based California plastic consumption data was then extended backwards in time by keeping it at a fixed relative distance between the two NA-based estimates.

3.2 Plastic waste generation

California plastic waste generation estimates are derived by modeling the time delay between plastic entering and leaving the use phase as discretized lognormal distributions, LTD_i^j, which denotes the fraction of plastics in industrial use sector *i* used for *j* years. Plastic waste generated in California in year *t* is then calculated as

$$W_i^t = \sum_{j=1}^{70} \left(C_i^{(t-j)} \cdot LTD_i^j \right)$$

3.3 Plastic waste management

In this study, all plastic waste generated in California is assumed to eventually enter the formal solid waste management system, where it is either landfilled, collected for recycling, or incinerated with energy recovery (also called transformation). The annual percentages of California plastic waste going to these three fates are derived from data collected and made publicly available by California's Department of Resources Recycling and Recovery (CalRecycle). State-level landfill, collection for recycling, and transformation data are available on CalRecycle's Recycling and Disposal Reporting System (RDRS) for the period 2019 to 2023 (CalRecycle, 2025). Five simplifying and conservative assumptions are made: (i) all plastic waste reported in the RDRS as collected, separated, and baled for recycling is from the packaging sector, (ii) this reported plastic collected, separated, and baled for recycling is equivalent to the recycling rate post yield loss, for which we adopt the widely used assumption (iii) that plastic recycling yield is 70% (e.g., Geyer et al., 2017; Plastics Europe, 2024; Pottinger et al., 2024). Landfill and transformation data are also available for earlier years and with higher spatial resolution. The data from CalRecycle are augmented with historical capacity data of the three incinerators in California, the last of which ceases operation in 2026. The California plastic waste recycling rate is modeled as an S-curve, with zero as the starting asymptote and the current value as the ending asymptote. In other words, (iv) in the BAU projection the California recycling rate of plastic waste is assumed to remain flat, while the plastic waste incineration rate will be zero after 2026. Every year, the plastic waste landfill rate is calculated as one minus the other two rates, and (v)all recycling waste (i.e., yield loss) is assumed to be landfilled.

3.4 Policy interventions

We assess the impact of three general classes of policy interventions to reduce plastic pollution following methods reported in Pottinger et al., (2024): (1) source reduction, (2) recycling rate mandates, and (3) recycled content mandates, with each intervention class targeted at the packaging use sector specifically. These are all interventions at the material flow level, allowing for mechanistic modeling without the need for additional economic data or modeling frameworks. Policy interventions are simulated as gradual annual changes in key parameters which, in turn, change the annual quantities of plastic consumption, waste generation, and end-of-life waste management in California. The source reduction and recycling rate targets are modelled following regulations specified in SB 54. Although SB 54 does not include a recycled content mandate, we model this as a plausible complementary intervention following an identical timeline. All targets within SB 54 must be achieved by 2032. Accordingly, all interventions are assumed to begin ramping up in 2025 in order to reach their target values by 2032, after which parameters remain constant.

Policy interventions and scenarios are modeled as deviations from the BAU projection. Three indicators are used to measure the impact of the interventions: change in primary plastic production in Mt, change in plastic disposal in Mt (effectively landfill, since we assume no incineration after 2026), and change in associated greenhouse gas (GHG) emissions in Mt carbon dioxide equivalent (CO_2e) as the cumulative impact between 2025-2050 relative to BAU. Since the only way to reduce material disposal is to reduce primary material production, those two indicators always have the same value (Zink and Geyer, 2017). Associated GHG emissions are calculated for primary resin production, resin conversion, as well as plastic waste landfill, incineration, and recycling. GHG intensity data for these processes are from Zheng and Suh (2019).

We present results in three ways: (1) the impact of each policy intervention independently; (2) the combined impact of source reduction and recycling rate mandates under SB 54, and (3) the overall impact of a comprehensive plastic packaging policy, incorporating SB 54 measures and recycled content requirements. It is useful to consider each intervention both independently and in combination, because source reduction interacts with both recycling rate and recycled content targets that are set as a fixed percent.

3.4.1 Source reduction

In waste management, the term source reduction means to reduce the source of waste, which typically means to reduce consumption of the considered products, materials, or substances. The downstream effect of this intervention is an equal reduction in waste generation. The upstream effect is typically assumed to be an equal reduction in production, even though this is a market-mediated rather than a simple physical relationship (Zink and Geyer, 2017). California's SB 54 mandates a reduction target of 25% by 2032 for plastic in single use packaging and food service ware. In the presented MFA, this is modeled as a linear decrease in consumption in the packaging sector between 2025 and 2032, when the source reduction target has been reached. The source reduction target is modeled as an absolute 25% source reduction with a fixed endpoint of 75% of the 2023 consumption baseline value, as stipulated in the regulation, which is modeled as a fixed total consumption by the packaging sector between 2032-2050.

3.4.2 Recycling rate mandate

Recycling rates are often established as minimum fixed targets. California's SB 54 includes a minimum recycling rate target of 65% by 2032 for plastic in single-use packaging and food service ware. In this MFA, the recycling mandate is modeled as a linear increase in the recycling rate in the packaging sector between 2025 and 2032, when the recycling rate target has been reached. Interim targets (30% by 2028 and 40% by 2030) are not explicitly modeled because they do not affect the interpretation of results. The recycling rate for the packaging sector is held constant at 65% between 2032-2050, establishing a lower bound estimate of impact. In both SB 54 and in this MFA, the recycling rate is defined as "the weight of covered material that is recycled divided by the sum of the total weight of covered material disposed of" (State of California 2022). This policy intervention has no upstream effect, but increased recycling is assumed to lead to increased availability of secondary plastic, which in turn decreases primary plastic production, use, and landfill. As this is a market-mediated process, the effect is difficult to quantify precisely. The baseline assumption is an 80% displacement rate between secondary and primary plastic (i.e., every 1 kg of recycled plastic displaces 0.8 kg of virgin resin).

3.4.3 Recycled content

Recycled content mandates are a relatively new but increasingly popular policy tool. While recycling rate mandates are supply-side interventions, recycled content mandates stimulate demand for recycled material. Although SB 54 does not include a recycled content requirement, this study models a 40% post-consumer recycled content (PCR) mandate for the packaging sector by 2032 as a plausible complementary intervention. The mandate is modeled as a linear increase in PCR in the packaging sector between 2025 and 2032, after which the recycled content share is held constant at 40%. Because the secondary material can originate from within or outside California, the baseline assumption is a 50:50 split between in-state and out-of-state sources. It is further assumed that out-of-state recycled plastic increases total plastic waste collection and recycling by an equivalent amount, while in-state recycled plastic only increases plastic waste collection and recycling to the extent that it exceeds the BAU projection.

3.5 Model validation and benchmarking

To validate and benchmark results, we compare the plastic consumption estimated by the IO-based MFA with scaled versions of an existing MFA developed for a broader but overlapping geographic region. Pottinger et al., (2024) present a plastic consumption dataset for North America (Canada, the U.S., and Mexico; NA) that is closest in scope and therefore best suited for benchmarking relative to other larger scale plastics MFAs (e.g., Di et al., 2021; Heller et al., 2020). Plastic consumption for NA and the years 1950-2050 was extracted from Pottinger et al., (2024) and scaled to California by the state's population and GSP. Between 2012 and 2020, California's share of NA's gross domestic product increased from 10.6% to 12.1%, while California's share of NA's population decreased from 8.2% to 8.0%.

We further validate the IO-MFA results by comparing sector-level shares between both the Pottinger et al., (2024) NA model and an additional sector-level plastics consumption model presented in 2020 by the EU plus Switzerland, Norway, and the United Kingdom (called EU27+3; Plastics Europe, 2021). It is important to note that comparisons between the California IO-based MFA and the NA apparent consumption model are limited, as the California model excludes polymer fibers and includes three additional sectors. However, the EU27+3 model also excludes textiles, making it suitable for inclusion in the sector share benchmarking exercise.

Finally, we validate plastic waste generation estimates using three sources of information from CalRecycle: plastic disposal and recycling data from the RDRS (CalRecycle, 2025), the *Proposed Regulations for the Plastic Pollution Prevention and Packaging Producer Responsibility Act: Standardized Regulatory Impact Assessment* (SRIA; CalRecycle, 2023), and the *Source Reduction Baseline Technical Report: A Plastic Pollution Prevention and Packaging Producer Responsibility Act Needs Assessment Report* (CalRecycle, 2024). Reported values from each CalRecycle source are directly compared to the plastic waste generation estimates produced by the IO-based MFA.

SECTION

4 RESULTS

Input-output data for California are available for the years 2012 to 2020. During this nine year period, California plastic consumption increased from 7.2 to 8.8 million metric tons (Mt). The share of packaging was consistently around 40% (increasing from 2.9 to 3.5 Mt over the study period), followed by building/construction, the share of which is estimated to have grown slightly from 18% to 20% (increasing from 1.4 to 1.7 Mt; Figure 4). Other major sources of plastic consumption are transportation (9.5-11.5%; 0.75-0.92 Mt), healthcare (9-10%; 0.68-0.84 Mt), and commercial/institutional (8-9.5%; 0.63-0.78 Mt). Together, these sectors account for 86-90% of total plastic consumption in California (Figure 5). The estimate for the textiles sector is low (~1%), because the model only accounts for plastic resins and thus excludes polymer fibers.

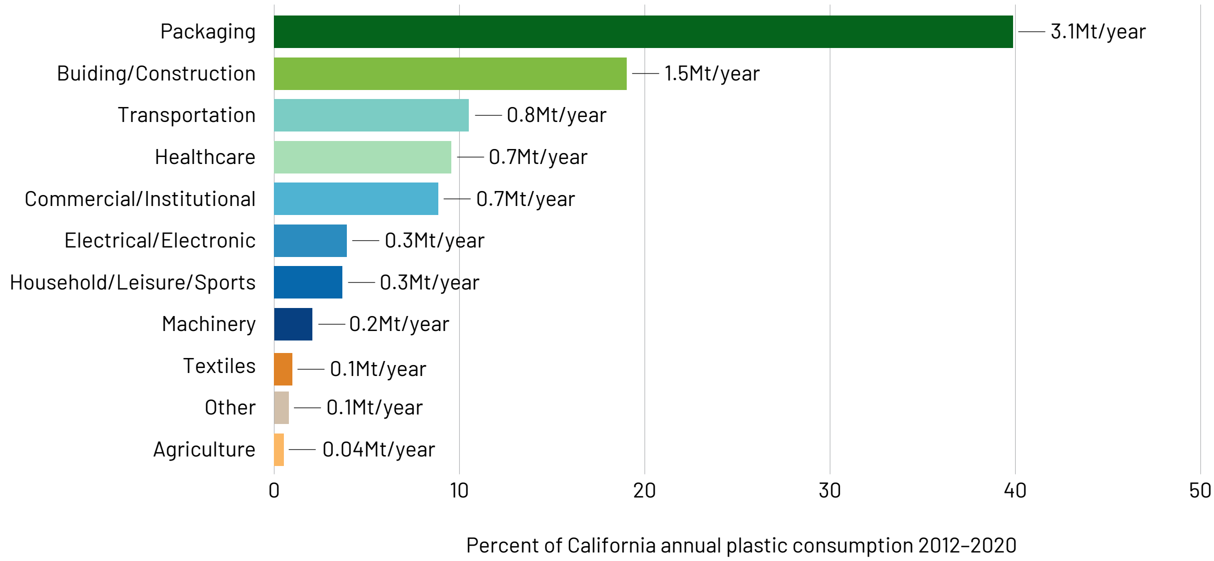

FIGURE 4: Sector-level plastic consumption. | Percent of annual plastic consumption 2012-2020 by plastic use sector, with average annual plastic consumption in million metric tons (Mt).

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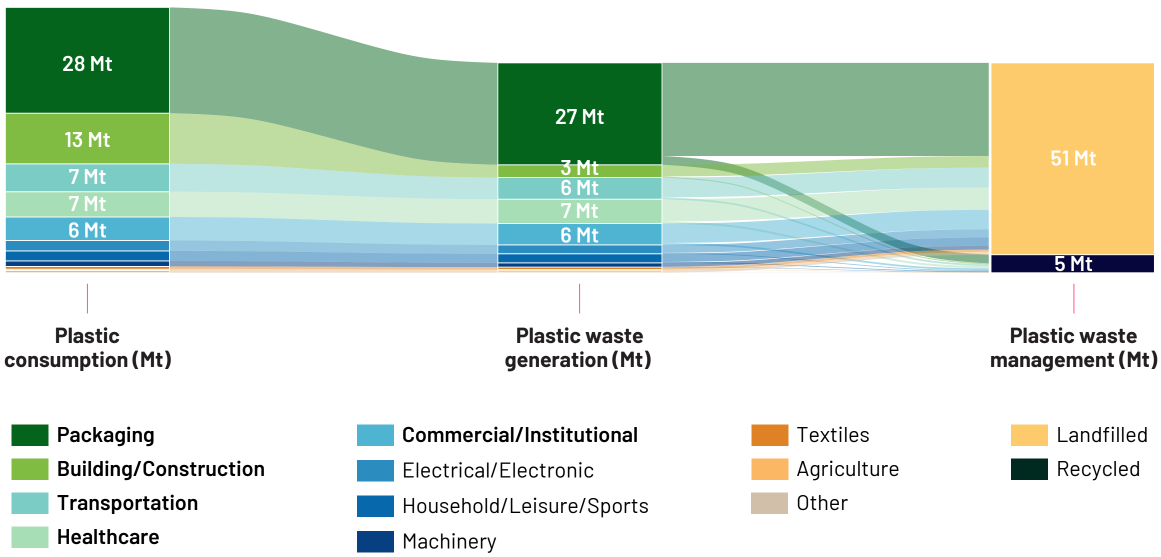

FIGURE 5: Plastic flows 2012-2020 | Flows of cumulative sector-level plastic consumption (left), to sector-level waste generation (middle), and end-of-life waste management (right). All mass values are cumulative from 2012-2020 and displayed in million metric tons (Mt).

Between 2012 and 2020, plastic waste generation in California grew from 5.3 to 6.9 Mt. The mass difference between consumption and waste generation reflects the time delay between plastic entering and leaving the use phase (Figure 5). Due to its short lifetime, plastic packaging's share in plastic waste is higher than in plastic consumption and ranges from 47-49%. For building/construction plastics, the very long lifetimes reduce its share in plastic waste generation relative to consumption to 5-7% (Figure 6).

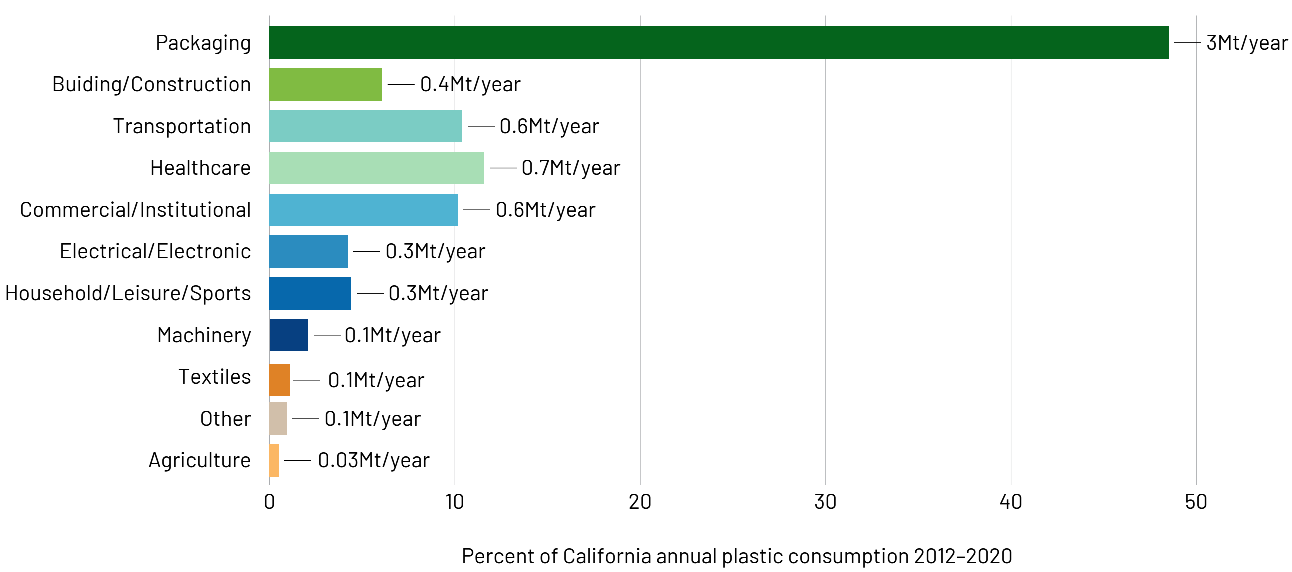

FIGURE 6: Sector-level plastic waste generation. | Percent of annual plastic waste generation 2012-2020 by plastic use sector, with average annual plastic waste generation in million metric tons (Mt).

There were no significant changes in plastic waste management in California during the nine year period. The rate of plastic waste collected for recycling was between 8.4% and 8.9%, while the incineration rate decreased slightly from 1.7% to 1.1% due to the closure of one of California's three waste incinerators. As a result, around 90% of plastic waste generated in California was landfilled between 2012 and 2020 (Figure 5). Accounting for a 70% plastic recycling yield and assuming that all recycling waste (yield loss) is landfilled increases the landfill rate of California's plastic waste to 93%.

4.1 Business as usual

In the business as usual (BAU) projection (2021-2050), California plastic consumption is projected to grow, albeit at a declining rate, reaching 13.1 Mt by 2050 (Figure 7A). The input-output data provide sector-level plastic consumption data for nine years (2012-2020). During this period, some sector shares exhibit a growing (e.g. building/construction) or declining (e.g. electrical/electronic) trend, while others remain constant (e.g. packaging) or show significant variability. Due to the short length of the time series and the significant variability in some sectors, constant average sector shares were used for the projection. This means that, by definition, all sectors grow at the rate of total consumption.

Growth in plastic consumption leads to growth in plastic waste generation, which is projected to reach 11.8 Mt in 2050 (Figure 7B). Due to the slowing rate of growth in plastic consumption, the packaging share of California plastic waste generation is projected to decrease to 44%, while the building/construction share will grow to 13%.

The recent closure of California's remaining two waste-to-energy plants leaves the state without incineration capacity. Since the recycling rate is projected to remain constant without additional interventions, the landfill rate of California plastic waste, including recycling yield losses, is 94% throughout the projection period (Figure 7C).

4.2 Source reduction mandate

Between 2025 and 2050 and considered in isolation, a 25% source reduction mandate (relative to 2023 consumption) will generate cumulative plastic reductions of 42.5 Mt relative to BAU (Figure 8A). The direct GHG reductions due to decreased plastic production are estimated to be 143.5 Mt CO_2e (Figure 8B). Reductions in plastic production and GHGs represent a 12% and 13% decrease from BAU, respectively (Figure 9). All other things being equal, source reduction also leads to reductions in recycling and displaced primary plastic production. The reduction in plastic recycling is estimated to lead to a cumulative increase in primary plastic production of 4.3 Mt, which, in turn, generates a GHG increase of 1.9 Mt CO_2e.

4.3 Recycling rate mandate

Between 2025 and 2050, and relative to BAU, a 65% recycling rate target by 2032 would increase secondary plastic production by 34.4 Mt, and is thus estimated to decrease primary plastic production and thus plastic waste disposal by 27.5 Mt (Figure 8A) representing a 9% decrease from BAU (Figure 9). This would generate cumulative net GHG reductions of 34.9 Mt CO_2e (Figure 8B), a 3% decrease from BAU (Figure 9).

4.4 Recycled content mandate

Between 2025 and 2050, the cumulative upstream effect of this intervention is the use of 43.1 Mt of secondary plastics in packaging production. Under the baseline assumption regarding plastic origin, the intervention would lead to a cumulative increase in secondary plastic production of 28.2 Mt above BAU and an equal-sized decrease in primary plastic production (Figure 8A), representing a 9% decline relative to BAU (Figure 9). This would result in cumulative net GHG emission reductions of 41.5 Mt CO_2e (Figure 8B), a 3% decrease from BAU (Figure 9).

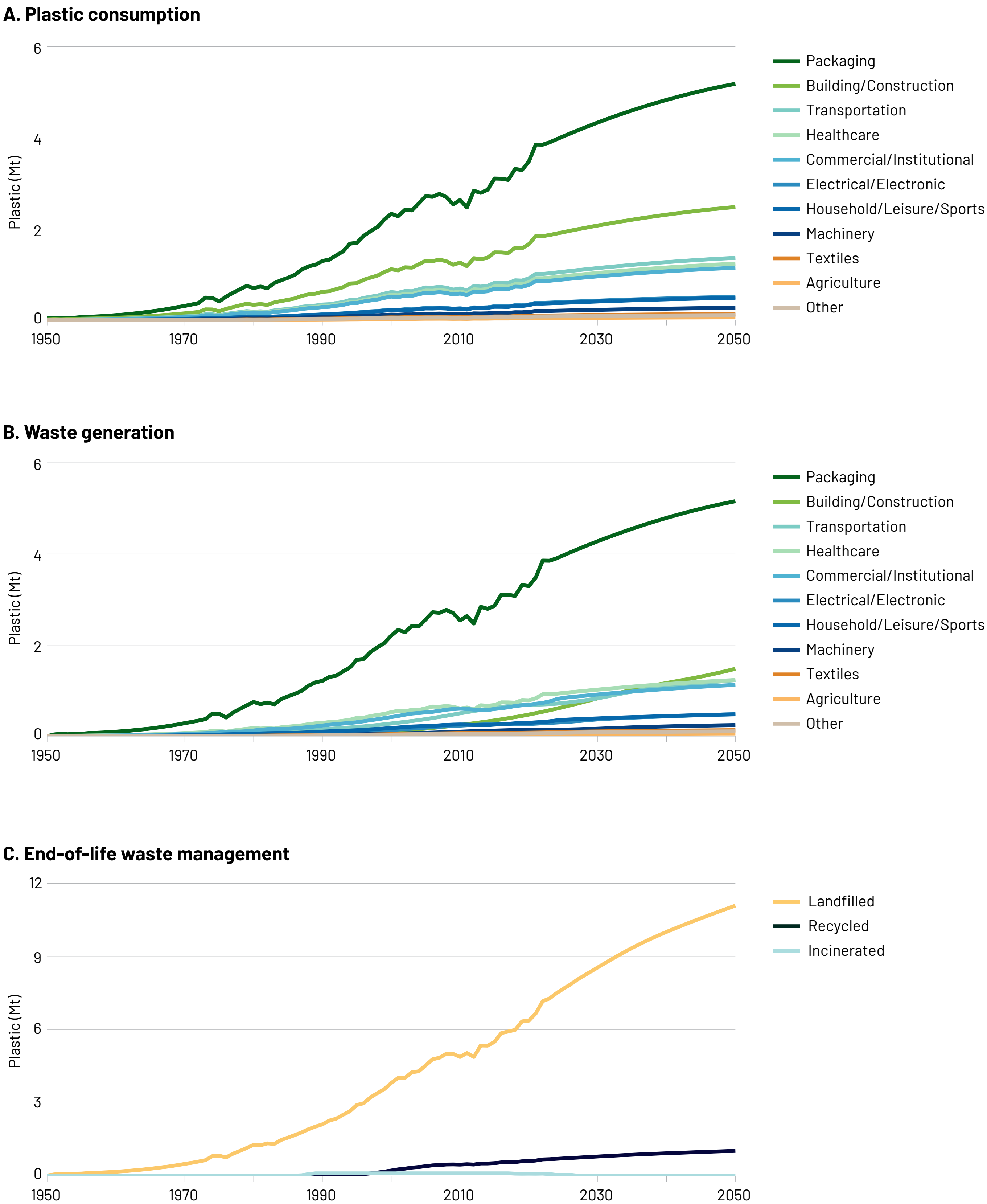

FIGURE 7: Plastic flows under business as usual (BAU) 1950-2050 | BAU projection for California (A) plastic consumption, (B) waste generation, and (C) end-of-life waste management. All amounts are in million metric tons (Mt). Plastic consumption and waste generation are colored by plastic use sector. End-of-life waste management is aggregated across all sectors.

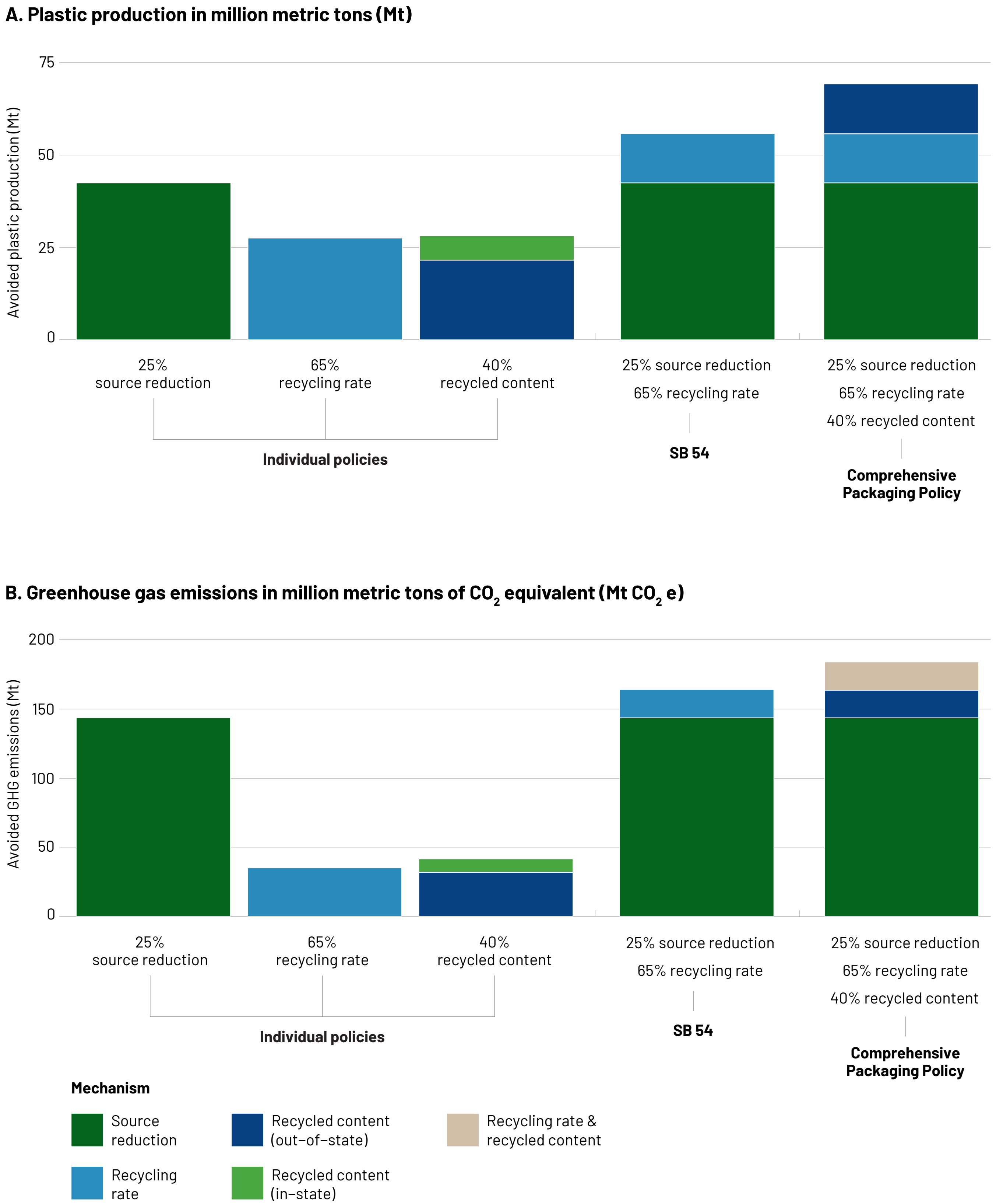

FIGURE 8: Plastic packaging policy net impact | Cumulative impacts relative to business as usual (BAU) of individual policy interventions, SB 54, and a comprehensive plastic packaging policy from 2025-2050 on (A) plastic production in million metric tons (Mt), and (B) greenhouse gas emissions in million metric tons of CO_2 equivalent (Mt CO_2e). Colors reflect the contribution of each individual component of the policy to the overall impact. In the comprehensive plastic packaging policy, the out-of-state effects of recycling rate and recycled content mandates are shown together because they cannot be meaningfully disentangled.

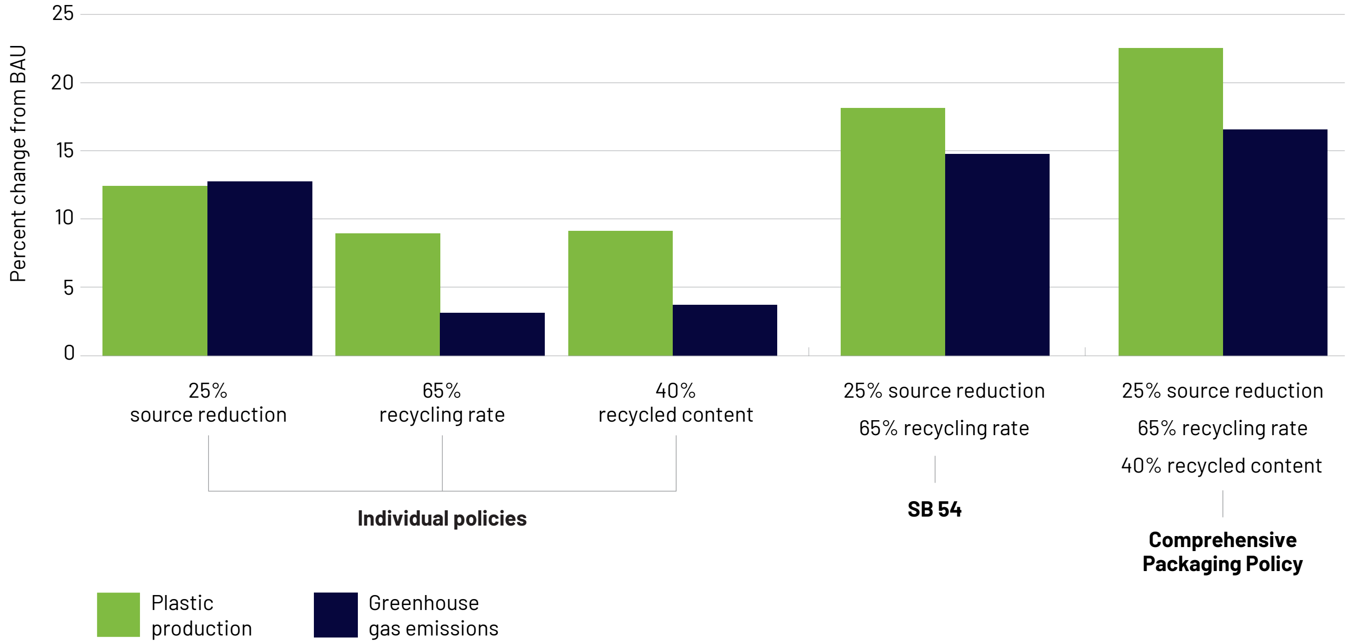

FIGURE 9: Plastic packaging policy relative impact. | The overall percent change in plastic production and greenhouse gas emissions from the cumulative reductions (2025-2050) of each of the five policy interventions relative to business as usual (BAU).

4.5 SB 54 Impact: combining source reduction and recycling rate mandates

As a midstream intervention targeting plastic consumption, the effect of the source reduction component of SB 54 is the same as if it were implemented in isolation: the source reduction target decreases plastic production and disposal by 42.5 Mt and related GHG emissions by 143.5 Mt CO_2e by 2050 relative to BAU.

However, midstream interventions like source reduction targets also interact with downstream interventions, including recycling rate targets. Specifically, source reduction decreases plastic consumption and waste generation (Figure 10), and thus reduces the impact of recycling rate targets formulated as percentages, i.e., in relative terms. In combination with a source reduction intervention, a 65% recycling rate target by 2032 for packaging has reduced effectiveness compared to implementation in isolation. The larger the source reduction target, the larger its impact on a recycling target formulated as a percentage. Subject to the 25% source reduction target, the 65% recycling rate intervention is estimated to reduce primary plastic production and disposal by 13.3 Mt and associated GHG emissions by 20.4 Mt CO_2e by 2050 (compared to a decrease in primary plastic production and disposal by 27.5 Mt and associated GHG emissions by 34.9 Mt CO_2e if considered in isolation).

Nevertheless, combining the two interventions, as done in SB 54, has a significantly larger impact than each intervention on its own: the combination of the 25% source reduction with the 65% recycling rate target decreases primary plastic production and disposal by 55.8 Mt and associated GHG emissions by 164.0 Mt CO_2e (Figure 8), representing a 18% and 15% reduction in plastic production and GHGs, respectively, relative to BAU (Figure 9). Over the next ten years, each year that SB 54 implementation is delayed beyond the 2032 target will result in 1.5-1.8 Mt yr^{-1} of additional virgin plastic production and plastic waste disposal and 6.3-6.6 Mt CO_2e yr^{-1} more than a scenario in which SB 54 is implemented as planned.

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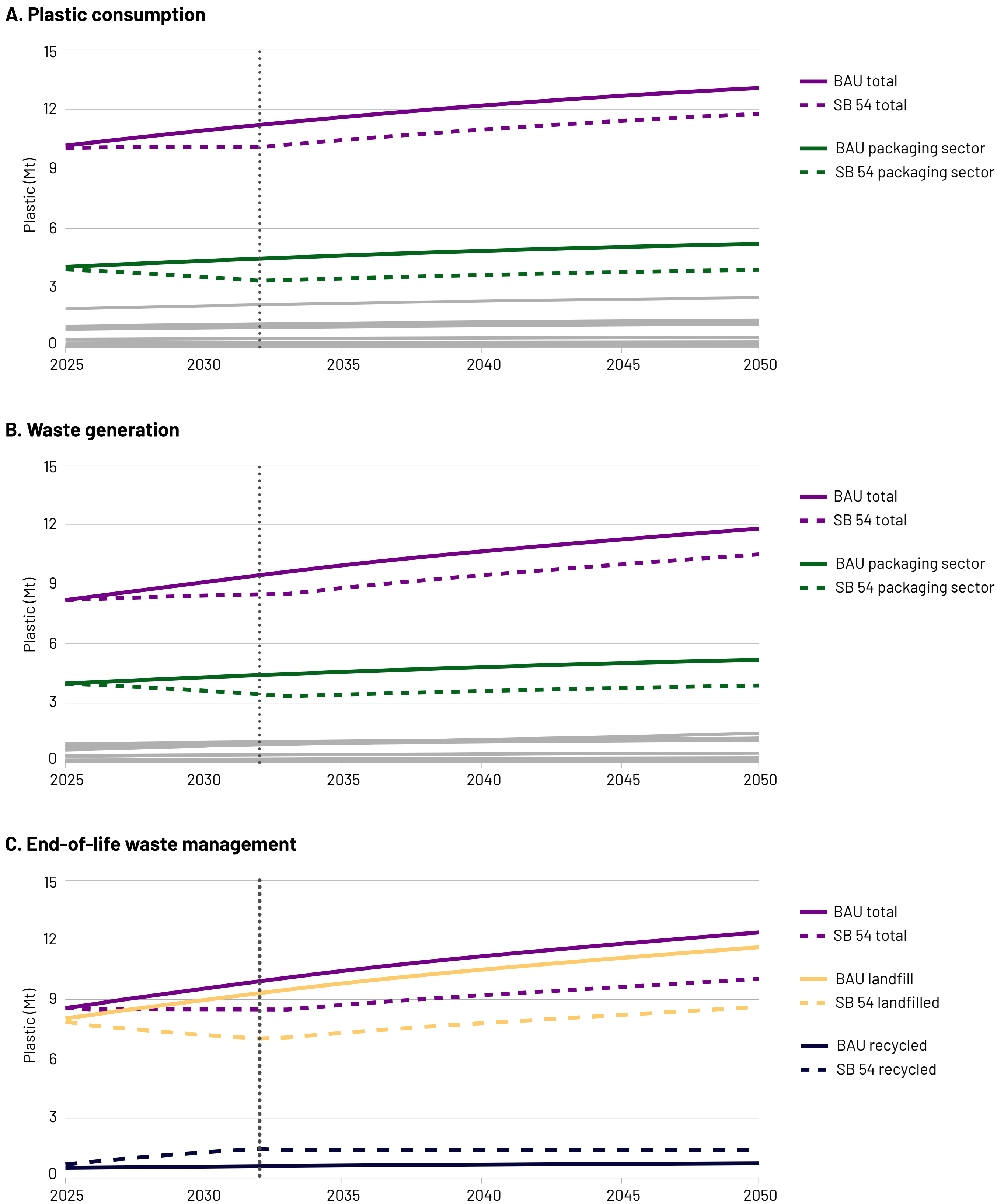


FIGURE 10. Effect of California's Senate Bill 54 on plastic consumption, waste generation, and end-of-life waste management. | Comparison of (A) plastic consumption, (B) waste generation, and (C) end-of-life waste management under BAU and with Senate Bill 54 implementation from 2025-2050. Changes are shown for both the total amount of plastic and plastic packaging (all in million metric tons, Mt). All other plastic use sectors have no change under SB 54 and are displayed in gray.

4.6 Comprehensive plastic packaging policy: combining source reduction, recycling rate, and recycled content mandates

As a thought experiment, the two interventions of SB 54—25% source reduction and 65% recycling rate target—are combined with the 40% recycled content mandate from Section 3.4. The three interventions interact in multiple ways. The source reduction acts directly on plastic consumption and is thus independent of the other two interventions. The recycled content mandate is impacted by source reduction and, in turn, influences recycling rate, both in-state and out-of-state. As described in Section 3.4, it is assumed that half of the recycled content is sourced from within California and the other half from out-of-state. It is also assumed that the PCR mandate only increases in-state plastic waste collection and recycling if it exceeds either the BAU projection or the recycling rate mandate. However, while a recycling rate mandate results in an 80% displacement between secondary and primary plastic production, the displacement effect of recycled content mandates is 1:1. The recycling rate intervention not only interacts with the recycled content intervention, but also with the source reduction intervention, since it reduces the amount of plastic waste available for recycling and thus the impact of a recycling rate target formulated as a percentage.

The combination of the three interventions is estimated to reduce primary plastic production and disposal by 69.3 Mt (23% decrease from BAU) and associated GHG emissions by 183.9 Mt CO_2e (17% decrease from BAU; Figure 8-9). The source reduction mandate accounts for 61% of the reductions in plastic production and disposal, with an additional 20% from the impact of the recycled content mandate on out-of-state recycling, and 19% from the recycling rate mandate. The recycled content mandate does not increase in-state recycling beyond the recycling rate intervention. Similarly, source reduction accounts for a majority of the GHG reductions (78%), with the remainder split evenly between increased in-state and out-of-state recycling (11% each). Although increased recycling leads to higher emissions relative to landfill, it reduces overall plastic production, resulting in a net reduction in GHG emissions. Table 1 contains the results of all five policy intervention scenarios. Combining interventions increases overall impact, even though interactions between them make their combined effect less than additive.

TABLE 1. Plastic packaging policy impacts. | Decreases in plastic production and disposal, and associated greenhouse gas emissions (GHG), relative to business as usual, for all five simulated policy interventions. All interventions are applied to the packaging sector only, modeled as linear increases from 2025 to 2032, and held constant thereafter. Results are presented in million metric tons (Mt) of plastic and million metric tons of CO_2 equivalent (Mt CO_2e) as the cumulative impact between 2025-2050 relative to business as usual.

Intervention	Decrease in plastic production and disposal (Mt)	Decrease in associated GHGs (Mt CO_2e)
Individual policies		
25% source reduction from 2023 baseline	38.2	141.7
65% recycling rate	27.5	34.9
40% post-consumer recycled content	28.2	41.5
SB 54		
25% source reduction & 65% recycling rate	55.8	164.0
Comprehensive packaging plastic policy		
25% source reduction, 65% recycling rate, & 40% post-consumer recycled content	69.3	183.9

4.7 Benchmarking results

A comparison of IO-based MFA consumption estimates to the population- and GSP- scaled NA model presented by Pottinger et al., (2024) reveals close alignment. The IO-based MFA estimates are consistently between the two benchmarks, with values closer to NA apparent consumption scaled by GSP (Figure 11). Given California's distinct demographic and economic profile relative to the broader NA region, it is reasonable to infer that population-based scaling may underestimate, while GSP-based scaling may overestimate, the state's plastic consumption. Across sector shares, despite differences in represented sectors, we found general alignment between all three models of plastic consumption: (1) the IO-based MFA presented here, (2) the NA model by Pottinger et al., (2024), and (3) the EU27+3 model from Plastics Europe (2021) (Table 2).

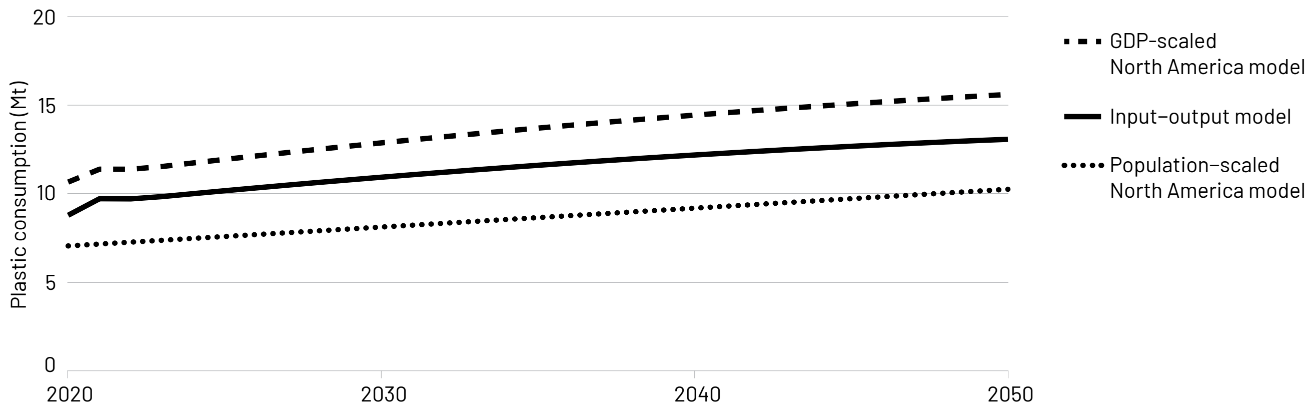
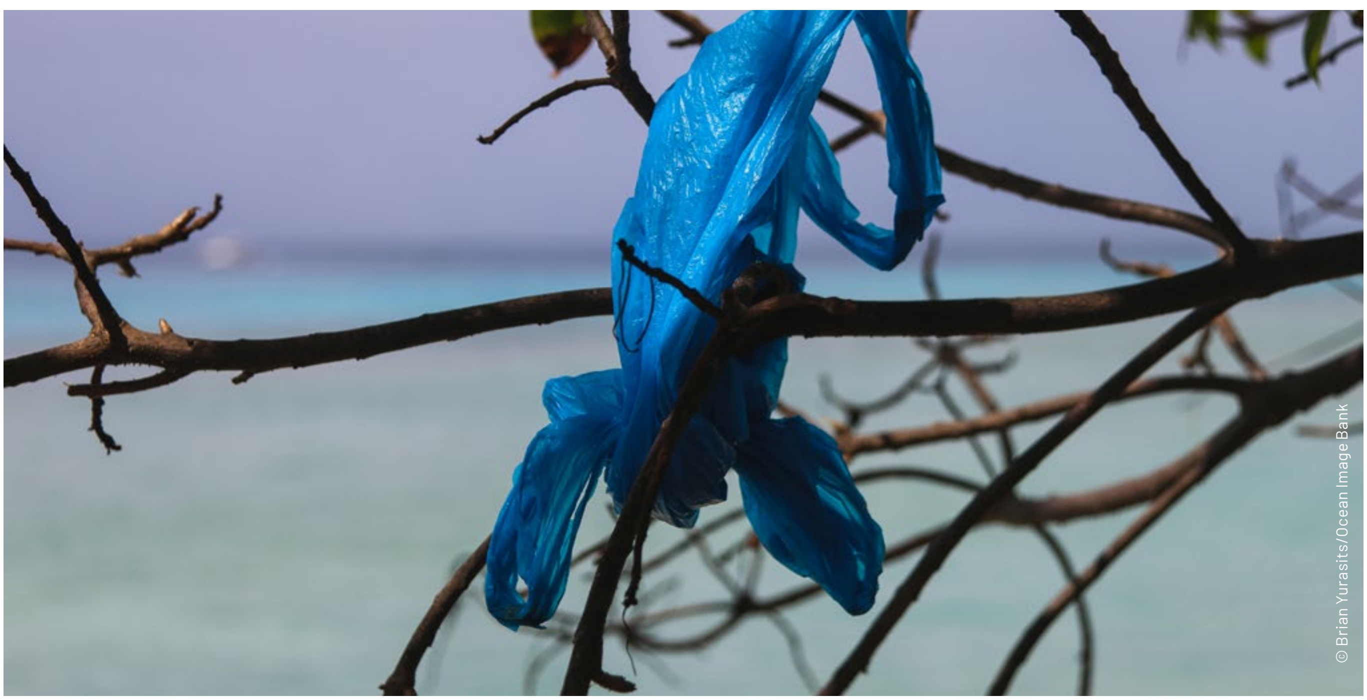


FIGURE 11. Benchmarking plastic consumption. | Plastic consumption (million metric tons, Mt) projected from 2020-2050 for the three different estimation methods: current input-output approach, gross domestic product (GDP)-scaled North American model, and population-scaled North America model.

For benchmarking plastic waste generation, combining plastic disposal and recycling data from CalRecycle's RDRS yields plastic waste generation estimates of 5.43 Mt in 2021 and 5.82 Mt in 2023 in California (CalRecycle, 2025). A separate 2021 baseline waste generation estimate for products covered under SB 54—single-use plastic packaging and food service ware—by CalRecycle's SRIA is 5.0 Mt (CalRecycle, 2023). This discrepancy suggests that the SRIA value is an overestimate and/or the RDRS data is heavily skewed towards packaging waste. Using an alternative methodology, the most recent SB 54 baseline study estimates that waste generation for covered plastic products in 2023 was 2.63 Mt (CalRecycle, 2024). In comparison, the IO-based MFA estimates for the packaging sector are 3.6 Mt in 2021 and 4.0 Mt in 2023, placing them between the divergent CalRecycle estimates for SB 54-covered plastic products.

TABLE 2. Benchmarking plastic shares. | Sector shares of plastic consumption of different datasets used in the primary analysis and for benchmarking. CA IO model is the California Environmentally-Extended Input-Output (EEIO) model developed by the federal Environmental Protection Agency (Ingwersen et al., 2024); NA model is the North America model presented in Pottinger et al., (2024); EU 27+3 converter demand is a model of sector-level plastic consumption across the European Union plus Switzerland, Norway, and the United Kingdom (Plastics Europe, 2021). Percentages shown are sector shares only across these three datasets.

Sector	CA IO model (2012-20 avg.)	NA model (2005-20 avg.)	EU 27+3 converter demand (2020)
Packaging	39.9%	30.5%	40.5%
Building & Construction	19.1%	16.8%	20.4%
Transportation	10.5%	7.7%	8.8%
Healthcare	9.5%	–	–
Commercial/Institutional	8.8%	–	–
Electrical/Electronic	3.9%	6.5%	6.2%
Household/Leisure/Sports	3.8%	20.1%	4.3%
Machinery	2.1%	–	–
Textiles	1.0%	10.4%	–
Other	0.9%	7.4%	16.6%
Agriculture	0.5%	0.6%	3.2%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SECTION

5 MODEL LIMITATIONS

This study is the first to estimate state-level plastic material flows, and is also the first to conduct a plastics MFA using input-output data. As with any modeling exercise, there are key limitations and sources of uncertainty that should be considered when interpreting these results. We highlight six notable limitations and considerations here.

First, a critical barrier preventing the use of input-output models in material flow analysis is the necessity to convert monetary values of plastic transactions reported in IO data (USD) to volumes of plastic (i.e., value to mass conversion). We overcome this challenge by defining m_{326}^{2017} as the mass-to-value ratio of sector *326* in the U.S. for year 2017 (total mass of the output of the U.S. plastic sector in 2017 by the total economic value of this output; metric ton/2017 USD), which is then converted to a plastic mass by multiplying by the Leontief matrix (in USD). This mass-to-value ratio represents an average across all plastics consumed within the US, and is therefore neither resin nor use sector specific. In reality, the mass-to-value ratio varies depending on the individual plastic commodity and is therefore both resin and use sector specific; however, we lack data required to estimate plastic intensities with this level of precision. This constraint likely has a limited and conservative effect on our estimate of packaging volumes and related impacts from policy interventions

given the dominance of the packaging sector and because plastic packaging is a relatively inexpensive plastic commodity and is made from a variety of plastic resins (primarily PET, PP, HDPE, LDPE and PS) and is therefore likely well represented by an average. However, this simplification likely underestimates plastic volume for plastic commodities that are less expensive on average (e.g., PVC plastics used in the building/construction sector) and overestimates plastic volume for more expensive plastic commodities (e.g., PP-based products which may be overrepresented in the household/leisure/sport sector).

Second, we report results in aggregated plastic use sectors following the convention established by the field (e.g., Geyer et al., 2017; Plastics Europe, 2021; Pottinger et al., 2024). These plastic use sectors are not economic sectors and therefore do not directly align with the BEA industries reported in the IO model. The expert-informed process used to aggregate BEA industries into plastic use sectors relied on key assumptions about the proportion of plastic commodities likely to occur within each BEA industry. Although informed by published literature and expert input from the IO model developers, this aggregation process is inherently uncertain. We note that plastic volumes reported by use sector across existing plastic MFAs similarly rely on assumptions, because they use resin-level production data to infer plastic mass within use sectors (e.g., Geyer et al., 2017; Pottinger et al., 2024).

Third, and relatedly, the waste disposal data used in this analysis is not plastic use sector specific. We assume all plastic reported as collected and bailed for recycling in the CalRecycle RDRS data is from the packaging sector, thereby overestimating the contribution of that sector, and consequently underestimating the impact of SB 54's recycling rate mandate. CalRecycle RDRS data (CalRecycle, 2025) primarily tracks municipal solid waste, the plastic component of which is dominated by packaging. As such, these data are critically important for tracking SB 54's impact on waste disposal. However, if future California policies target other plastic use sectors—e.g., building/construction or textiles—these impacts will be more difficult to track, because plastic waste data is reported by "material type," which may not allow attribution to specific use sectors.

Fourth, there is some ambiguity about the extent to which the recycling rate should account for the significant amounts of contamination and yield losses that can occur during waste collection and recycling. SB 54 intends to distinguish between avoidable and unavoidable yield losses in its recycling rate calculations. Since this is currently impossible with available data, recycling rate is here measured at the bale level, i.e., after collection losses, but before reprocessing losses. This assumption underestimates the impacts of SB 54 as achieving a 65% recycling rate as defined under the regulations would require a 93% collection rate (given 70% yield).

Fifth, we assume that all mismanaged plastic waste (i.e., litter) is eventually collected by the formal solid waste management system. As a result, we do not formally account for mismanaged plastic waste, although we know it is non-zero in California. California cities, towns, and taxpayers spend nearly $500 million each year to combat and clean up litter (including but not limited to plastic litter), equating to between $10-$70 per capita across a range of communities (Monroe, 2013). California beaches are also a known hotspot of mismanaged plastic waste, with urban beaches averaging 133 pieces of plastic litter per square meter—roughly twice the amount on non-urban beaches (Heard, 2024). Although much of this plastic litter will eventually enter the state's formal waste management system, as is assumed by this analysis, some will not. This "escaped" plastic waste is not accounted for here.

Finally, we report three categories of impact resulting from plastic packaging policies—reductions to plastic production and consumption, landfilled plastic, and GHG emissions—but note that California residents are not the primary beneficiary of all improvements. Reductions in plastic consumption and landfilled plastic yield local benefits, whereas GHG emission reductions from decreased plastic production are global in nature. Plastic production accounts for 96% of the carbon footprint of plastics, largely due to increasing global reliance on coal-based production methods, while end-of-life stages (recycling, incineration and landfill) contribute a small fraction of overall GHG emissions (Cabernard et al., 2022). While changes to the demand for plastic in California affects global emissions, these emissions largely occur outside the state and country. In 2015, nearly 80% of the United States' plastics-specific carbon footprint was induced abroad, with one third occurring in China alone (Cabernard et al., 2022). Notably, increased recycling rates under SB 54 may lead to higher local GHG emissions, as recycling can be more emissions-intensive than landfilling (Zheng and Suh, 2019). Senate Bill 54 includes provisions to address the disproportionate impacts of plastic pollution on low-income and minority communities; therefore, potential increases in local air pollution from expanded recycling operations should be considered amongst this suite of expected impacts.

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6 CONCLUSION

The presented input-output based material flow analysis finds that plastic consumption and waste generation in California is large and projected to continue to increase, though the rate of growth is projected to slow over time. Plastic consumption is dominated by the packaging sector (40%), followed by building/construction (20%), and transportation, healthcare, and commercial/institutional sectors (10% each). Present-day plastic waste generation is dominated by packaging (49%), healthcare (12%), and commercial/institutional and transportation sectors (10% each). However, the building/construction sector's share of plastic waste generation is projected to increase from 7% in 2020 to 13% by 2050.

Plastic waste management has changed very little during the years for which complete data are available (2019-2023) and is projected to remain unchanged without major interventions such as SB 54. Currently, California's plastic waste recycling rate is comparable to the most recently reported national average of 8.7% in 2018 (US EPA, 2020). However, unlike many other states, California relies entirely on landfilling for its non-recycled plastic waste.

All modeled interventions are expected to significantly reduce plastic production, disposal, and associated GHG emissions. When implemented individually, a 65% recycling rate mandate and a 40% post-consumer recycled content mandate yield similar reductions in plastic production and disposal. In contrast, the 25% source reduction mandate results in a >35% larger reduction in production and disposal than either other strategies alone. The GHG reductions associated with source reduction are substantially greater than those from the other two interventions, because source reduction avoids GHG emissions from both primary resin production and conversion, whereas recycled content or end-of-life recycling only avoid GHG emissions from primary resin production while increasing GHG emissions from recycling processes. It is important to note that source reduction of one packaging material could lead to substitution with other materials, potentially increasing their associated GHG emissions. A 40% post-consumer recycled content mandate is expected to result in greater reductions in plastic production, disposal, and associated GHG emissions than a 65% recycling rate mandate, due to recycling yield losses and incomplete displacement of primary resin production. Under baseline assumptions of a 70% recycling yield and 80% displacement rate, a 65% recycling rate translates to a 36.4% displaced production rate (as a fraction of total waste generation).

When combined—as in SB 54—source reduction mandates reduce the marginal impact of percentage-based collection for recycling targets. The combined benefits are thus less than the sum of the individual benefits. However, the impact of a 25% source reduction mandate on a 65% recycling rate target is estimated to be moderate (Table 1). Notably, though not currently required under the SB 54 regulations, adding a post-consumer recycling content target to a combined source reduction and recycling rate policy (i.e., comprehensive plastic packaging policy presented in section 3.6) generates additional benefits, as the effects of recycled content and recycling rate mandates are not simply duplicative. In particular, state-level recycled content mandates can stimulate plastic waste recycling both within and beyond California and thus have a wider reach than state-level recycling rate mandates.

This analysis provides a critical foundation for evidence-based policymaking to address plastic pollution in California and beyond. By leveraging state-level input-output modeling and material flow analysis, it offers a replicable framework for quantifying plastic use, waste generation, and the impacts of targeted interventions that can be readily adopted by other states seeking to track plastic flows and implement effective plastic pollution policies. We demonstrate how plastic packaging policy—specifically California's SB 54—can significantly reduce plastic production, waste, and associated greenhouse gas emissions. While SB 54 represents a major step forward, its full potential will depend on timely implementation and robust enforcement. As other states and jurisdictions consider similar legislation, this report underscores the importance of integrated, data-driven approaches to designing plastic pollution policies that deliver both environmental and equity outcomes.

SECTION

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