**Waste and Material Footprints in prospective LCA: a study of 1600+ activities from 2020-2050**

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# ****Abstract (~400 words)****

#### ****Purpose****

Advancing a circular economy requires **direct, system-wide quantification** of the waste and material flows attributable to human activity. Yet Waste and Material Footprints (WMFs) remain **under-reported in standard LCA** and only sparsely integrated into **prospective** assessments. We quantify WMFs across the ecoinvent database and examine their evolution under contrasting socio-economic pathways to: (i) reveal sectoral and supply-chain hotspots (including hazardous waste); (ii) position WMFs alongside conventional LCIA endpoints; and (iii) assess how scenario-aligned backgrounds modify footprint magnitudes and interpretation.

#### ****Methods****

We constructed prospective LCI databases with ***premise*** (based on **ecoinvent 3.9.1**), aligned to two divergent ***REMIND*** Integrated Assessment Model (IAM) pathways—**SSP1-PkBudg500** and **SSP5-PkBudg500**—for **2020–2050**. We then applied **T-reX** to enable tracking of **50+ categories** of waste and material flows and computed WMFs for **>1,600 market activities**. In parallel, we calculated **ReCiPe 2016 endpoint** indicators (human health, ecosystems, resources) to benchmark WMFs against established damage metrics. Activities were grouped into sectors to identify hotspots and explore temporal and scenario contrasts. Because the underlying inventories use **economic allocation**, we explicitly discuss interpretive limits for mass-based inference and report sensitivity diagnostics to isolate allocation-driven effects.

#### ****Results and discussion****

Sectorally, **mining, metals, and chemicals** dominate both **total** and **hazardous** waste footprints, mirroring patterns in ReCiPe endpoints and reinforcing WMFs’ **decision relevance** for risk, circularity, and prevention strategies. WMFs show **statistically meaningful correlations** with human-health and ecosystem damage indicators at activity and sector aggregation. Across **2020–2050**, we observe **modest WMF reductions** in both pathways, with **SSP1** yielding the larger decline. However, the magnitude of change is **smaller than expected** given policy narratives on waste prevention, improved collection/sorting, higher recycling yields and qualities, and expanded secondary-material markets. This gap likely reflects **limited representation of waste-system transformations** in IAM-linked pLCIs and highlights where circularity dynamics (e.g., substitution ratios, contamination losses, hazardous fractions) are **under-specified**. Interpretation of absolute WMF levels is also **allocation-sensitive**: price-based allocation can amplify high-value co-products and attenuate low-value by-products, decoupling WMFs from physical mass balances.

#### ****Conclusions and recommendations****

WMFs complement LCIA endpoints in **prospective LCA** by making **material throughput and waste generation** explicit, revealing hotspots that standard impact profiles can obscure. To approach **mass-consistent** interpretation, future work should test **physical/flow-based allocation**, explore **consequential** databases, and embed **explicit waste-sector trajectories** in prospective LCIs (collection and sorting rates, recycling yields/qualities, secondary-material substitution, hazardous-waste management). Our results indicate a **methodological gap**: without scenario-dependent circularity modules, IAM-aligned databases understate WMF dynamics over time. Integrating these transformations will improve the fidelity and policy usefulness of pLCAs intended to guide circular-economy strategies.

**Keywords**

Circular Economy, Waste and Resource Management, Secondary Raw Materials, Critical Raw Materials, Life Cycle Assessment, Prospective Life Cycle Assessment, Integrated Assessment Models

List of abbreviations

CE Circular Economy

CRM Critical Raw Material

CPC Cooperative Patent Classification

EoL End-of-Life

IAM Integrated Assessment Model

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

MF Material Footprint

REMIND

RCP Representative Concentration Pathway

ReCiPe A standard LCIA method set

re-X A broad set of circular economy strategies (“reduce”, “reuse”, “repair”, “recycle” etc.)

SSP Shared Socioeconomic Pathway

T-reX The Tool for analysing re-X in LCA

UNFC United Nations Framework Classification for Resources

WF Waste Footprint

WMF Waste and Material Footprint

# Introduction (1000 words)

#### ****Environmental context: why circularity and waste matter****

Human activities continue to exceed key planetary boundaries, intensifying climate change, biodiversity loss, and resource depletion. In response, the transition to a circular economy has become a central pillar of sustainability policy (European Commission, 2019, 2020; Government of the Netherlands, 2016, 2023; Pardo and Schweitzer, 2018; Ellen MacArthur Foundation, 2015). Circular strategies seek to decouple well-being from primary material extraction by reducing material demand and preventing waste across value chains through ‘re-X’ measures—refuse, rethink, repair, remanufacturing, and recycling (Reike et al., 2018; European Commission, 2022; Alfieri et al., 2022; Parker et al., 2015). Recent geopolitical tensions further underscore the vulnerability of globalised supply chains and the need for material efficiency and system resilience (Carrara et al., 2023; Hartley et al., 2024; Berry, 2023).

#### ****Waste and material footprints****

Footprints provide compact indicators of environmental pressure. The Ecological and Carbon Footprints initiated this “footprint family” (Wackernagel, 1994; Čuček et al., 2015), which has expanded without fully converging on a coherent framework (Giampietro and Saltelli, 2014; Vanham et al., 2019; Ridoutt and Pfister, 2013). The Material Footprint (MF)—the total supply-chain material use attributable to products, sectors, or economies—correlates strongly with damage to human health and biodiversity and is recognised by the United Nations for SDG monitoring (Wiedmann et al., 2013; Steinmann et al., 2017; Lenzen et al., 2021). By contrast, the Waste Footprint (WF)—the mass or volume of wastes generated along value chains, including hazardous fractions—remains less developed and is often overlooked, despite evidence that waste burdens are associated with environmental damage and social inequity (Laurenti et al., 2016; Laurenti et al., 2023; Doka, 2024; Ridoutt et al., 2010; Jiao et al., 2013; N. Pellow, 2023; Akese and Little, 2018). Considering WF alongside MF can reveal where material use translates into waste generation, where hazardous waste arises, and where interventions may yield the highest returns for circularity.

#### ****LCA: capability and gaps****

Life Cycle Assessment (LCA) is the prevailing method to quantify environmental impacts across product and service life cycles (Guinée et al., 2010). In standard practice, life cycle impact assessment (LCIA) methods (e.g., ReCiPe, CML) convert inventory flows—elementary exchanges between technosphere and biosphere—into indicator scores (Huijbregts et al., 2016; Guinée et al., 2002). Several LCIA frameworks address aspects of waste and material use (e.g., Swiss Eco-Factors, EDIP, EN15804; and the Crustal Scarcity Indicator) (Swiss Federal Office for the Environment (FOEN), 2021; Hauschild and Potting, 2004; CEN, 2019; Arvidsson et al., 2020), but they rarely provide flexible, transparent MF/WF accounting, and some rely on abstract units that complicate interpretation (e.g., Umweltbelastungspunkte) (Su, 2020). Moreover, because waste is typically modelled as a service (treatment), the magnitude and distribution of waste generation along supply chains can remain obscured, making upstream waste effectively “invisible” (Guinée and Heijungs, 2021; Laurenti et al., 2016; Beylot et al., 2018). As a result, hotspots of material use and waste generation—including hazardous waste—are not always apparent from standard impact profiles.

#### ****Future-oriented LCA and prospective background databases****

Emerging technologies required for deep decarbonisation will scale over coming decades, often after substantial learning and capital investment. Prospective LCA (pLCA)—also called ex-ante or anticipatory LCA—assesses likely environmental implications early enough to inform design and policy (van der Giesen et al., 2020; IPCC, 2021; IEA, 2021a). Robust pLCAs require background data that reflect plausible future economic, technological, and policy conditions. Prospective life cycle inventory (pLCI) databases therefore combine current LCI data (e.g., ecoinvent) with scenario information from integrated assessment models (IAMs) and other sources (NEEDS, 2009; Gibon et al., 2015; Hertwich et al., 2015; Cox et al., 2020; Mendoza Beltran et al., 2018; Sacchi et al., 2022; Wernet et al., 2016).

IAM scenario frameworks typically pair a shared socio-economic pathway (SSP)—a narrative of societal development from sustainability-oriented (SSP1) to fossil-intensive (SSP5)—with a representative concentration pathway (RCP) that specifies a climate outcome via radiative forcing, corresponding to temperature goals such as 1.5–2 °C (O’Neill et al., 2014; van Vuuren et al., 2011; Liao et al., 2023; Lechtenberg et al., 2024). Implemented in IAMs, SSP×RCP pairings generate region- and sector-specific trajectories for technology deployment and emissions (Cucurachi et al., 2022; Sacchi et al., 2022). These scenarios are bounded by resource availability, infrastructure lock-in, and policy constraints such as carbon pricing, which shape feasible transitions (Pauliuk et al., 2017).

#### ****premise, REMIND, and sectoral transformations****

The premise workflow connects IAM projections (notably REMIND and IMAGE) to ecoinvent, producing pLCIs that regionalise markets and update process and supply-chain parameters for selected sectors (Sacchi et al., 2022; Sacchi et al., 2023). Current transformation domains include electricity generation and markets (with storage), cement (clinker ratio, kiln efficiency, optional CCS), iron and steel (process efficiency and CCS), fuels (refining, synthetic and biofuels, hydrogen), road freight (powertrain shares and fleet relinking), batteries (mass/energy-density scaling and market composition), heat supply (CO₂ factors), air-pollutant factors, and biomass markets distinguishing purpose-grown from residual feedstocks. By design, waste management is not yet a dedicated transformation domain; waste-to-energy appears indirectly via electricity markets, and other waste-sector inventories remain largely as in the base database (Sacchi et al., 2022; Sacchi et al., 2023; Bisinella et al., 2024). This gap motivates complementary tools that can expose material and waste footprints within prospective backgrounds.

#### ****Waste in LCA and circularity indicators****

Waste is often defined as material with negative economic value, but its practical significance extends well beyond treatment emissions (Guinée et al., 2004; Laurenti et al., 2023). Modelling waste as a service can hide the magnitude and locus of waste generation, including upstream burdens (Guinée and Heijungs, 2021; Laurenti et al., 2016). Empirical work shows associations between waste burdens and environmental damage, with disproportionate impacts on vulnerable communities (Doka, 2024; Ridoutt et al., 2010; Jiao et al., 2013; N. Pellow, 2023; Akese and Little, 2018). Reporting WF and MF alongside LCIA results helps reveal trade-offs and prioritise circular actions.

#### ****Prospective backgrounds: scope and limitations****

Prospective analyses depend on the availability and consistency of pLCIs. Neither IAM scenarios nor LCI databases currently provide full, high-resolution coverage across all sectors and regions. IAMs are detailed for electricity but sparser for agriculture, chemicals, and material cycles; standard LCIs prioritise current technologies, leaving emerging options under-represented (Pauliuk et al., 2017; Wernet et al., 2016). Hybridising IAM-based pLCIs with additional sources can close gaps but may introduce inconsistencies (Mendoza Beltran et al., 2018; Sacchi et al., 2022). Moreover, most pLCIs are atemporal snapshots: life-cycle stages are co-located in a reference year, so use-phase dynamics (e.g., evolving electricity mixes) are approximated (Beloin-Saint-Pierre et al., 2014; Levasseur et al., 2010). Practical workarounds include assembling analyses across multiple reference years or using temporal-average datasets, but further methodological development is needed (Beloin-Saint-Pierre et al., 2017; Cardellini et al., 2018; Pinsonnault et al., 2014).

#### ****Aim of this study****

This paper applies a workflow—T-reX integrated within Brightway and compatible with premise-based pLCIs—to explore and quantify waste generation (including hazardous waste) and material consumption across activities and sectors. Our objectives are to: (i) compute waste and material footprints at multiple levels of aggregation, (ii) identify hotspots along supply chains under present and prospective background conditions, and (iii) illustrate how results support circular-economy strategies and supply-chain risk management. We do not develop a new LCIA method or a new prospective database; rather, we demonstrate how targeted footprint accounting complements standard impact indicators in LCA and pLCA settings.

#### ****This paper’s contribution****

We implement T-reX within Brightway to compute WF and MF across products and sectors under both current and premise-based prospective backgrounds. We report total waste and hazardous-waste generation and total material consumption, highlight process- and sector-level hotspots, and discuss implications for circular-economy strategies (e.g., prevention, design for repair and remanufacturing, targeted recycling) and for risk management related to critical materials. Our analysis shows how footprint accounting complements LCIA indicators, clarifies where conventional models obscure waste generation, and provides actionable insights for policy and practice.

# Methodology (1500 words)

### Product Selection and Life Cycle Scope

### Prospective database selection and creation

### T-reX

### Waste and Resource Footprints

### Damage Footprints

### Regression Modeling

We used multiple linear regression (least-squares fitting) to relate the damage footprints to the resource footprints.

# Results (2500 words)

# Discussion (1500 words)

#### What this study adds

#### Strengths of the approach

#### Limitations and caveats

#### Outlook and use

# Conclusions (500 words)

# Supplementary Material

The supplementary material supplied in the appendices of this manuscript contain the following sections:

# Data availability

All publicly available data related to the development of the scenarios and the composition of this manuscript is available in online repositories hosted by Zenodo (https://doi.org/10.5281/zenodo.16995460) and Github (<https://github.com/Stew-McD/T-reX_LCA-MacroStudy>)

# Acknowledgements

This research project was financially supported by the European Union’s Horizon 2020 research and innovation programme under the grant agreement No. 101058522 (project FutuRaM — [futuram.eu](https://futuram.eu/)). The authors would like to thank the reviewers for their valuable comments and suggestions.

# CRediT authorship contribution statement

**Stewart Charles McDowall:** Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualisation, Writing: original draft, Writing: review & editing, Visualisation.

**Carlos Felipe Blanco:** Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

**Stefano Cucurachi:** Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

Figure 1: CRediT authorship visualisation

# Declarations

**Competing interests**

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

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**Use of artificial intelligence**

The authors declare that no generative artificial intelligence tools were used in the generation of the research data or results reported in this paper. Generative AI was used solely to assist in the editing and refinement of the manuscript text, with all content reviewed and approved by the authors.

# References

Tables

# Supplementary material