Circular economy practices drive climate impacts across international supply chains

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The circular economy framework is posited as a transformative solution to decouple escalating global material demand from raw resource extraction with constrained natural resources. Central to this model is secondary production, which repurposes waste into critical resources, reducing reliance on primary inputs while addressing resource security. However, emerging evidence reveals a systemic paradox: the global supply chains enabling circularity may inadvertently exacerbate carbon emissions through energy-intensive upstream processes. Recycling, reprocessing, and cross-border transportationâ€”cornerstones of secondary productionâ€”often depend on fossil fuel-derived energy in regions with carbon-intensive power systems. As nations increasingly outsource these activities abroad, the climate benefits of circular systems risk being offset by transboundary emissionsâ€”a blind spot in current sustainability frameworks.

Here, we investigate how secondary production redistributes carbon emissions globally by analyzing five materials critical to economic development and climate change: plastic products, iron and steel, aluminum, copper, and other metals. Using a multi-region input-output (MRIO) model and the hypothetical extraction method (HEM), we map cradle-to-gate emissions from primary and secondary production for 160 economies worldwide, based on the Global Trade Analysis Project (GTAP) Circular Economy Data Base Version 11. We distinguish between domestic and imported carbon emissions to reveal the asymmetric impacts of secondary production on global supply chains. We explore in which sectors and regions these impacts take place to inform targeted policy design that fosters a circular and low-carbon future for all.

We find that global production of secondary iron and steel leads to 613.9 Mt embodied emissions, followed by aluminum (77.1 Mt), plastic products (70.5 Mt), other metals (62.4 Mt), and copper (45.7 Mt). High and upper-middle-income regions account for most embodied emissions from secondary production due to their significant production scale. A majority of global economies risk increasing at least one of domestic or imported emissions when substituting secondary for primary production, revealing the systemic trade-offs between circular economy strategies and climate mitigation. Over 50% of plastic products, iron and steel, and other metals producers and 40% of aluminum and copper producers create imported carbon trade-offs despite domestic synergies. High-income regions are most likely to drive these imported trade-offs by outsourcing energy-intensive recycling processes to upper-middle-income regions, exacerbating emissions in the latter's energy sectors. More than 20% of iron and steel and other metal producers lead to both domestic and imported emission increases. For example, Japan's secondary iron and steel production generates 33.6% more domestic emissions and 30% more imported emissions than primary production due to increased energy use. By contrast, upper-middle-income regions are most likely to achieve both domestic and imported emission reductions. For instance, China's secondary iron and steel production reduces carbon emissions from not only domestic material sectors but also foreign energy sectors.

By linking circular economy practices to transboundary carbon leakage, this study challenges the assumption that secondary production universally aligns with climate goals. It calls for redefining circularity through a lens of global equity, ensuring that emission reductions in one region do not exacerbate climate injustices elsewhere. Our findings provide actionable insights for policymakers navigating the dual imperatives of sustainable production (SDG 12) and climate action (SDG 13),

emphasizing the need for coordinated international strategies to harmonize circularity with decarbonization.