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Evaluating decoupling Evidence: Examining Timeframes, geographic Scales, and planetary boundaries

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A B S T R A C T

Plans for green growth require that economies can decouple from material resource use. Previous research into this issue using Material Footprint has found some evidence of absolute decoupling. But the data used were limited, as were the geographical and historical frames within which change was assessed. This study systematically examines methodological biases that may inflate perceived "green growth" success and evaluates decoupling evidence across multiple analytical dimensions to determine whether economic growth can detach from material resource demands.

We analysed Material Footprint data from 105 countries (1970–2022) using a three-stage approach: (1) second-degree-polynomial, nonparametric-kernel, and neural-network models to identify apparent decoupling patterns; (2) panel regressions comparing national trajectories with lower-income nations and sustainability-limit scenarios; and (3) historical reconstruction analysis extending the UK's Material Footprint back to 1875 to examine long-term trends.

Stage 1 identified 25 countries demonstrating apparent GDP-material use decoupling during 1970–2022. However, Stage 2 panel analysis revealed that focusing on individual countries in isolation systematically overstates decoupling achievements when trajectories are compared against sustainability-limit scenarios and international benchmarks. Year-by-year regressions consistently showed positive quadratic coefficients indicating accelerating resource use at higher income levels throughout the entire period. Stage 3 demonstrated that the UK's recent apparent decoupling represents temporary fluctuations rather than structural change, with 147 years of data showing persistent long-term growth in resource consumption relative to GDP.

This study demonstrates that methodological choices—particularly short timeframes, geographic isolation, and absence of sustainability-limits—create systematic biases that misrepresent unsustainable change as progress. Our findings challenge green growth narratives by showing that apparent decoupling success recede when examined more critically. Our findings mean that, longer historical perspectives and explicit integration of sustainability limits are required to evaluate economic-environmental relationships.

1. Introduction

The challenge of our times is how to restructure economies so that they are no longer dependent upon resource extraction and its attendant environmental degradation (Georgescu-Roegen, 1971; Georgescu-Roegen, 1977; Fischer-Kowalski & Haberl,1997, 2015; Dudka and Adriano, 1997; Oberle et al., 2019). The feasibility of green growth hinges on whether economies can decouple from resource use.

Previous research examining decoupling has yielded ambiguous findings. Consumption-based metrics like Material Footprints have consistently found either no decoupling or only relative decoupling of economic growth from resource use (Wiedmann et al., 2015; Haberl et al., 2020; Charlier & Fizaine, 2023; Krausmann et al., 2017; Pothen and Welsch, 2019; Requena-i-Mora & Brockington, 2021; Sahoo et al, 2021; Cibulka and Giljum, 2020; Wu et al., 2017). Alonso-Fernández & Regueiro-Ferreira (2024) show that in high-income countries, decoupling occurs exclusively during low-growth periods. Belda & Requena-i-Mora (2025) found that recent signs of decoupling in a set of high-income countries was primarily a temporary phenomenon linked to the housing boom-bust cycle, rather than a persistent structural

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transition toward sustainable growth. Studies employing production-based indicators (see for instance Steinberger et al 2013 or Giljum et al 2014) have occasionally identified absolute reductions in material flows.

The decoupling results found using Material Footprint data are significant because this consumption-based indicator comprehensively accounts for both domestic extraction and the resource use embedded in a country's net trade flows (imports minus exports in raw material equivalents). In contrast, reductions in production-based material flow indicators typically coincide with periods of economic stagnation or contraction within individual countries, tempering the interpretation of positive decoupling results from such measures. These patterns reflect temporary economic downturns rather than structural change (Steinberger et al., 2010, 2011; Giljum et al., 2014; Shao et al., 2017; Wu et al., 2019). Fischer-Kowalski and Haberl (1997, 2015), observed decoupling as limited and insufficient to address the fundamental biophysical constraints of economic activity. They argue that apparent decoupling in high-income countries often results from outsourcing resource-intensive processes through international trade, creating an illusion of domestic decoupling while masking continued global increases in resource use. Their analysis of long-term global data shows no evidence of absolute decoupling at the global level and dependencies between economic activity and material flows that conventional economic analyses often overlook. Similarly, Bithas & Kalimeris (2018) using Domestic Material Consumption (DMC), found that resources consumed per unit of income increased by 60% globally (1900–2009), 49% for the USA (1870–2005), and 76.8% for Japan (1878–2005), directly contradicting traditional decoupling narratives in the long run. Requena-i-Mora (2024), provides additional evidence from Spain's historical material footprint analysis, showing that material consumption rose from 3.4 tons per capita in 1861 to 13.4 tons in 2019, with exponential growth during economic modernization periods (1960–1975).

Here we make two contributions to this debate. First, following Alonso-Fernández & Regueiro-Ferreira (2024) and Belda & Requena-i-Mora (2025) we show that updated Material Footprint data from the UN International Resource Panel indicate that some countries do demonstrate absolute decoupling. This is potentially important: absolute decoupling derived from a consumption based environmental metric differs from previous empirical findings. But second, we show that these findings have to be interpreted with caution. When examined within comprehensive global, geographical, and historical frameworks these trends do not, necessarily, represent the improvement that we need.

To examine decoupling trends in consumption-based measures, we employ Material Footprint data from the GLORIA database (1970–2024) (Lenzen et al., 2022). These data identify a subset of countries that demonstrate continued economic growth alongside decreasing material consumption. To examine the implications of these trends, and to contextualize these trends, we interpret these changes as a manifestation of Environmental Kuznets Curve hypothesis—an inverted-U relationship between environmental degradation and economic development (Fig. 1). This model, first proposed by Grossman and Krueger (1991, 1995), suggests that environmental pressure initially increases with economic growth but eventually declines after reaching an income turning point. The concept derives from Kuznets' (1955) hypothesis which proposed that inequality first rises then falls with economic growth. The Environmental Kuznets Curve has become central to green growth narratives by suggesting that continued economic expansion will ultimately reduce resource use, thereby justifying the postponement of immediate environmental action. To contextualise the Environmental Kuznets Curves in the GLORIA database we take three steps. First, using the UK as an example (because it is often championed as a model of sustainability, see for instance Dhakal, et al. (2022)) we show that national success stories of apparent decoupling often mask continued ecological overshoot when measured against the resource use thresholds each country needs to strive to meet. The progress shown is not yet sufficient. This constitutes spatial cherry-picking: spotlighting a single

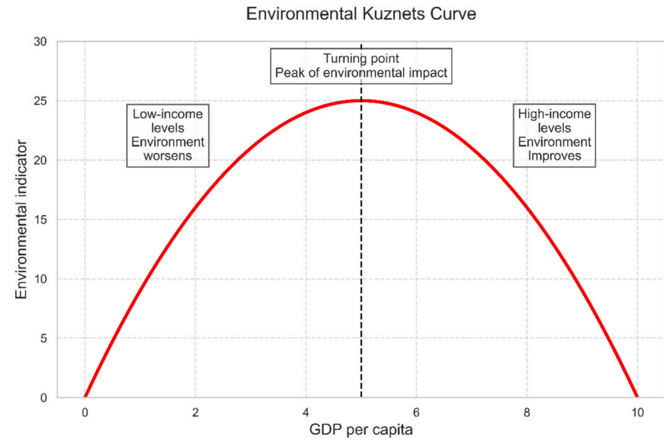

Fig. 1. Environmental Kuznets Curve.

apparent success while its MF per capita remains above sustainability-limit scenarios.

Second, we show that when all countries are considered together, no Environmental Kuznets Curve is apparent. Individual successes are not yet making the collective difference required. This is aggregation cherry-picking in two guises—temporal/trend cherry-picking (brief Material Footprint dips being read as structural change) and overshoot-level cherry-picking (claiming decoupling at very high Material Footprint per capita)—which together mis-state the panel result.

Third, we show that analyses of Environmental Kuznets Curves using only recent data may be using the wrong time frame. Again, for the UK, we extend the analysis back to 1875, providing unprecedented time series for evaluating its apparent decoupling. This long-term perspective reveals how short-term fluctuations in resource use may be mistaken for structural transitions, while longer-term coupling between economic growth and material consumption remains intact. This is temporal cherry-picking—i.e., trend cherry-picking by windowing—where endpoint truncation turns short-term dips into apparent structural breaks.

By integrating long-term historical analysis of the UK (1875–2024), cross-country comparison across 105 countries, and assessment relative to sustainability-limit scenarios, we provide a more comprehensive framework for evaluating claims about green growth and decoupling. Our three-stage methodological approach reveals how conventional Environmental Kuznets Curve analyses systematically filter out contradictory evidence, creating a misleading portrait of compatibility between continued economic expansion and environmental sustainability. These methodological choices constitute systematic cherry-picking – spatially and temporally — choosing where, when, and which limits to consider so Material Footprint appears compatible with growth despite contradictory evidence.

These methodological challenges are particularly evident in recent attempts to define criteria for what constitutes “genuine green growth.” Stoknes & Rockström (2018) propose a boundary-consistent productivity test: growth is “genuine” only if the annual improvement in resource productivity—operationalized for climate as $\Delta\ln(GDP/CO_2)$ meets or exceeds the rate implied by Paris-consistent budgets; under territorial accounting, some Nordic cases appear to pass a ≈5%/yr 2 °C threshold. Tilsted, Bjørn, Majeau-Bettez & Lund (2021) show that such verdicts are highly sensitive to scope choices—emissions accounting (territorial vs production- vs consumption-based, with bunkers), target stringency (2 °C vs 1.5 °C), numerator (GDP vs GNE), gas coverage (CO_2 vs CO_2e), baselines/time windows, and equity (totals vs per-capita)—arguing that “genuine” claims are fragile to those decisions. Together, these studies motivate our use of explicit limits and transparent scoping.

This study makes three key contributions that advance decoupling research beyond existing studies. First, methodologically, we integrate multiple analytical approaches—cross-country comparisons, panel data analysis, and historical reconstruction—systematically to explore how temporal, geographic, and methodological choices create systematic biases in decoupling assessments. While previous studies have identified limited decoupling using consumption-based metrics, our approach reveals that apparent successes recede when subjected to comprehensive analytical scrutiny. Second, empirically, we extend the temporal scope of decoupling analysis through historical reconstruction (demonstrated via UK data back to 1875) and explicitly integrate sustainability limits into cross-country comparisons, showing that individual country "successes" may be insufficient when measured against planetary boundaries and global resource allocation requirements. Third, conceptually, we introduce a framework for identifying "cherry-picking" biases—spatially (spotlighting individual countries), temporally (emphasizing short-term fluctuations), and overshoot-level (claiming success at unsustainable consumption levels)—that systematically inflate perceived green growth achievements. These contributions are crucial for policy because they demonstrate that current decoupling evidence, while methodologically sound within narrow analytical windows, may provide false confidence in green growth strategies. Our findings show the urgent need is for rapid, absolute reductions in material use remains.We proceed as follows. First, we introduce the equations used in our analysis and describe the Material Footprint and GDP data, including the construction of our country panel. Second, we compare the benchmark quadratic specification with more flexible methods—kernel regression and a regularised neural-network estimator—to identify turning points and assess the robustness of apparent decoupling. Third, we estimate panel and year-by-year regressions to examine how the Environmental Kuznets Curve parameters evolve across time frames and country groups. Finally, we summarise the main patterns emerging from these exercises and discuss their implications for the interpretation of decoupling evidence.

2. Methods

In general terms, the proposed model for the Environmental Kuznets Curve is a quadratic polynomial function of the following type:

$$EnvironmentalPreassureIndicator_t = a + \beta_1 GDP_t + \beta_2 GDP_t^2 + \mu_t \tag{1}$$

Wheret denotes the year of observation, and Environmental Pressure Indicator_t represents the indicator of environmental degradation in year t. The term GDPpc_t captures the level of economic development in year t, measured as per capita Gross Domestic Product, and corresponds to the variable X_t in the general formulation. The parameter a is the intercept, reflecting the baseline level of the Environmental Pressure Indicator when $\text{GDP}_t = 0$. The coefficient β_1 measures the linear effect of economic development on environmental pressure, while β_2 captures the non-linear (quadratic) effect, allowing for patterns such as a U-shaped or inverted-U-shaped relationship between GDP per capita and environmental degradation. Finally, μ_t is an error term that aggregates all other factors affecting the Environmental Pressure Indicator in year t that are not explicitly included in the model.

According to Stern (2004), regressions that allow levels of indicators to become zero or negative are inappropriate. This restriction can be applied by using a natural logarithmic dependent variable. We also test for the presence of a quadratic term (corresponding to Environmental Kuznets Curve behaviour if it is negative), and for a simple time-related trend. Moreover, following Steinberger et.al (2013) to prevent colinearity between the linear and quadratic terms, we subtracted the mean value for GDP per capita in the quadratic term. Therefore, the equation used is as follows:

$$logenvironmentalindicator_t = a + \beta_1 logGDP_t + \beta_2 (logGDP_t - log\overline{GDP})^2 + u_t \tag{2}$$

In this specification, t denotes the year of observation, and environmental indicator_t represents the chosen indicator of environmental degradation in year t, expressed in per capita terms; $\log(\text{environmental indicator}_t)$ is its natural logarithm. The variable GDP_t denotes Gross Domestic Product in year t, and $\overline{GDP}$ is the sample mean of GDP over the period considered. The parameter a is the constant term, β_1 captures the linear association between the logarithm of GDP and the logarithm of the environmental indicator, and β_2 captures the non-linear component by modelling the squared deviation of $\log(\text{GDP}_t)$ from its mean value. Finally, u_t is the error term, which groups all other influences on the environmental indicator in year t that are not explicitly included in the model.

In order to correct for heteroscedasticity and autocorrelation, we used Newey-West standard errors.

In Environmental Kuznets Curve estimation, testing for and addressing cointegration is essential to ensure that our regression results reflect genuine long-term relationships rather than spurious correlations.. Cointegration confirms that the observed relationships between economic growth and resource use are genuine, rather than spurious. Spurious results can lead to false conclusions, suggesting relationships that are either non-existent or influenced by unaccounted-for variables (Stern,2004). We have conducted two different cointegration tests that are specifically good for testing polynomial relationships, which are different from the ones that only test cointegration in linear relationships. The Johansen Cointegration Test with a Vector Error Correction Model (VECM) is well-suited for identifying multiple cointegrating relationships involving polynomial terms. As a robustness check, we also employ the Gregory–Hansen test. This test allows for a structural break in the cointegrating relationship, which is crucial when dealing with long-run data that may span multiple economic regimes.[1]

When the different test fails to account for cointegration we included $\beta_3 time_t$ variable in the model. However, the inclusion of this time variable notably impacts the functional form of the relationship between income and environmental degradation, particularly altering the estimated peak of income at which resource use begins to decrease. Thus, to transparently assess the influence of this methodological adjustment, we present the results both with and without the time variable. This dual presentation allows us to delineate how the time correction may distort the conventional interpretation of the Environmental Kuznets Curve, potentially shifting the income peak. Such an analysis is essential for accurately evaluating the temporal dynamics in the income-environment relationship and ensuring the reliability of policy implications derived from our study.

For the panel regression, we applied the same process but included an additional term, 'i,' which represents a specific country, in Equation (2)

$$logenvironmentalindicator_{it} = a + \beta_1 logGDP_{it} + \beta_2 (logGDP_{it} - log\overline{GDP})^2 + u_{it} \tag{3}$$

Where t is the year and i is the country; environmental indicator_{it} represents the chosen indicator of environmental degradation per capita for country i in year t, and $\log(\text{environmental indicator}_{it})$ is its natural logarithm. The variable GDP_{it} denotes Gross Domestic Product per capita for country i in year t, while $\overline{\text{GDP}}$ is the sample mean of GDP per capita over all countries and years in the panel. The parameter a is the constant term, β_1 measures the linear association between the logarithm of GDP and the logarithm of the environmental indicator, and β_2

[1] In our implementation, we iterated over candidate break points (using a trimmed sample) and, for each candidate, estimated the cointegrating regression—either with or without an additional time trend—by including a dummy variable (D) that switches on at the candidate break date. An Augmented Dickey–Fuller (ADF) test was then applied to the residuals of each regression. The candidate break that yielded the most negative ADF statistic was selected as the optimal break date, thereby providing diagnostic evidence on the stability and robustness of the long-run relationship.

captures the non-linear component by modelling the squared deviation of $\log(\text{GDP}_{it})$ from its mean. Finally, u_{it} is the error term, which collects all other factors affecting the environmental indicator for country i in year t that are not explicitly included in the model.

The Hausman and Larange Multiplier tests indicated the most efficient models. The model was corrected for heteroscedasticity, serial correlation, and cross-sectional dependence. The cointegration test indicated that the model is not cointegrated, just as we did for time series regression, we included $\beta_3 time_{ti}$ and run the test again.

Whether or not the detection of a quadratic term is a proof of delinking (inverted U) or relinking (U) depends on the statistical significance and the negative sign of the coefficient β_2. Moreover, the peak of income should be within the range of the incomes existing in the sample: otherwise, only one half of the inverted U (i.e., no inverted U at all) has been observed (Steinberger et.al 2013). In terms of the Environmental Kuznets Curve analysis, the peak income is given by:

$$\log peakofincome = log\overline{GDP} - \frac{\beta_1}{2\beta_2} \quad (4)$$

In this expression, $\log(\text{peak income})$ denotes the natural logarithm of the income level at which the Environmental Kuznets Curve reaches its turning point; $\overline{\text{GDP}}$ is the sample mean of income (typically GDP per capita) used to centre the quadratic term in the original regression; $\log(\overline{\text{GDP}})$ is therefore the logarithm of this mean income level; β_1 is the estimated coefficient on $\log(\text{GDP})$, capturing the linear component of the relationship between income and the (logged) environmental indicator; and β_2 is the estimated coefficient on the squared term, capturing the curvature of the relationship. When β_2 is negative and statistically significant, the implied curve is inverted U-shaped, and the corresponding $\log(\text{peak income})$ gives the income level at which environmental pressure stops rising and starts declining; for this turning point to provide evidence of “delinking,” the associated peak income must also lie within the observed range of incomes in the sample.

A decoupling situation is said to occur when both conditions i) a significance and negative β_2 and ii) the peak of income is a small number relative to the average per capita GDP levels are accomplished. These two conditions are necessary to draw the inverted U shape that characterize the Environmental Kuznets Curve, where resource uses first grow, then decrease with income, in the shape of an inverted-U.

Building on the significance of detecting a quadratic term for assessing the shape of the Environmental Kuznets Curve the role of the linear coefficient, β1, is equally pivotal. A positive β1 (β1>0) implies that environmental degradation increases with income in the early stages of economic growth. Conversely, a negative β1 (β1<0) indicates that environmental degradation decreases as income increases from the start. Thus, the sign of β1 helps elucidate the initial trajectory of resource use relative to economic growth, setting the stage for understanding whether environmental improvement is inherently linked to economic expansion or if it requires reaching a higher income threshold.

Criticism has often been levelled at the scant attention paid to robustness of this way of conducting the Environmental Kuznets Curve (e.g. Stern, 2004, 2017). More recently, several facets of robustness have been investigated by applying non-parametric methods (e.g. Bertinelli and Strobl, 2005; Luzzati et al., 2018). Our analysis utilized kernel regressions, which do not assume a specific functional form, providing a more flexible assessment of the relationship between GDP per capita and environmental degradation without imposing the constraints of a second-degree polynomial. The research presented here also incorporate a robustness exercise that involves both comparisons between parametric and non-parametric methods.

A part for testing the second-grade polynomial, we have conducted Kernel regressions. Which are non-parametric methods to estimate the conditional expectation of a random variable. In our context, it is used to estimate the relationship between log-transformed GDP per capita and log-transformed Material Footprint per capita without assuming a specific functional form, unlike polynomial regression. Kernel regression smooths the data points by averaging the neighbouring data points, with weights given by a kernel function. The kernel function determines how much weight each neighbouring point contributes based on its distance from the target point. The bandwidth parameter h controls the width of the neighbourhood over which the smoothing is performed.

$$\widehat{m}(\log GDP_t) = \frac{\sum_{s=1}^{n} k\left(\frac{\log GDP_t - \log GDP_s}{h}\right) \log environmentalindicator_s}{\sum_{s=1}^{n} k\left(\frac{\log GDP_t - \log GDP_s}{h}\right)} \quad (5)$$

In this equation, $\widehat{m}(\log(\text{GDP}_t))$ denotes the kernel regression estimate of the conditional expectation of the log-transformed environmental indicator per capita given the log-transformed GDP per capita at time t. The variable $\log(\text{GDP}_t)$ is the logarithm of GDP per capita at the target time t, while $\log(\text{GDP}_s)$ is the logarithm of GDP per capita at each observed time point s, with $s = 1, \cdots, n$ indexing all n observations in the sample. The term $\log(\text{environmental indicator}_s)$ is the logarithm of the environmental indicator per capita observed at time s. The function $k(\cdot)$ is the kernel function, which in our implementation is Gaussian and assigns weights to observations depending on the distance between $\log(\text{GDP}_t)$ and $\log(\text{GDP}_s)$; closer observations receive higher weights. The parameter h is the bandwidth, which controls the degree of smoothing by determining the width of the neighbourhood around $\log(\text{GDP}_t)$ over which observations contribute to the estimate. Thus, the numerator is a weighted average of $\log(\text{environmental indicator}_s)$ across all time points s, while the denominator normalises the weights so that they sum to one for each evaluation point t.

The estimator provides a smooth, nonparametric estimate of the conditional mean:

$$m(logGDP_t) = \in \{\log environmentalindicator | logGDP_t\} \quad (6)$$

In this expression, $m(\log(\text{GDP}_t))$ denotes the conditional mean function: it gives the expected value of the log-transformed environmental indicator per capita when the log-transformed GDP per capita takes the value $\log(\text{GDP}_t)$. The symbol $\mathbb{E}[\cdot|\cdot]$ is the conditional expectation operator, so $\mathbb{E}[\log(\text{environmental indicator}_t) \mid \log(\text{GDP}_t)]$ represents the expected value of $\log(\text{environmental indicator}_t)$ given $\log(\text{GDP}_t)$. The variable $\log(\text{environmental indicator}_t)$ is the natural logarithm of the environmental pressure indicator per capita in year t, and $\log(\text{GDP}_t)$ is the natural logarithm of GDP per capita in year t. Thus, this equation formalises what the kernel regression estimator in Equation (5) aims to approximate in a smooth, non-parametric way.

Following Anonymous for peer review (2025), the primary goal of this analysis is to determine if the kernel regressions estimate fall within the confidence intervals of the second-degree polynomial regression model, which represents the Environmental Kuznets Curve hypothesis. Polynomial regression, particularly of the second degree, imposes a specific quadratic functional form on the data, which may not accurately reflect the true underlying relationship. This form can lead to several problems, such as overfitting or underfitting, depending on the nature of the data and the selected model. Kernel regression, on the other hand, does not assume any predefined functional form. By smoothing the data based on the observed values and the selected bandwidth, kernel regression can more accurately reflect the actual relationship between GDP per capita and Material Footprint per capita.

To achieve this, we tuned bandwidth selection and minimizes the Mean Squared Error (MSE) between the polynomial regression fitted values and the kernel regression predictions, ensuring alignment with the polynomial model's fit.

$$h^* = arg_h min\left\{\frac{1}{n}\sum_{t=1}^{n}\left[\widehat{m}_h(logGDP_t) - \left(\alpha + \beta_1 logGDP_t + \beta_2(logGDP_t - \overline{logGDP})^2\right)\right]^2\right\} \quad (7)$$

In this expression, $\hat{h}$ denotes the selected bandwidth, defined as the value of h that minimises the criterion inside the braces; the operator $\arg\min_h\{\cdot\}$ means "the value of h that minimises" the objective function. The index t runs from 1 to n, where n is the total number of observations (years), and logGDP_t is the logarithm of GDP per capita in year t. The term $\widehat{m}_h(\text{logGDP}_t)$ is the kernel regression prediction of the log environmental indicator evaluated at logGDP_t when using bandwidth h. The expression $\alpha + \beta_1 \text{logGDP}_t + \beta_2(\text{logGDP}_t - \overline{\text{logGDP}})^2$ is the fitted value from the parametric quadratic model, where α is the intercept, β_1 is the linear coefficient on logGDP_t, β_2 is the coefficient on the centred squared term, and $\overline{\text{logGDP}}$ is the sample mean of logGDP. The squared difference inside the sum measures, for each observation t, how far the non-parametric kernel fit is from the quadratic polynomial fit, and the outer factor $1/n$ converts this into an average (the Mean Squared Error). By minimising this average squared distance over all candidate bandwidths h, we obtain a bandwidth $\hat{h}$ that aligns the kernel regression as closely as possible with the parametric quadratic model.

As a robustness test, we will also use the Bayesian Information Criterion (BIC) to select the bandwidth.

By comparing the kernel regression estimates to the confidence bands of the polynomial regression, we can better test the validity of the Environmental Kuznets Curve hypothesis. If the kernel regression estimates, which provide a more flexible and potentially more accurate representation of the data, lie within the confidence bands of the polynomial regression, it would provide stronger evidence in support of the EKC hypothesis. This approach leverages the strengths of both methods: the interpretability of polynomial regression and the flexibility of kernel regression.

Beyond the kernel estimator, we also employ a neural-network (MLP) smoother as a flexible, model-free benchmark for the income–environment relationship. The network takes log GDP per capita as its single input and produces a smooth fitted curve for log resource use; inputs and targets are standardized for estimation and mapped back to the original scale for reporting. Training minimizes mean-squared error with weight decay and early stopping, which together regularize the fit and play a role analogous to bandwidth control, preventing over-wiggling while retaining gentle nonlinearities. After fitting two flexible curves—a kernel smoother tuned to the quadratic reference and a standardized MLP with regularization—we locate the turning point as the interior peak and then evaluate only the post-peak shoulder. Robustness is judged on three simple ideas: first, the slope on the right must be negative once we account for uncertainty using a one-sided, simultaneous derivative band built from a residual bootstrap; second, there must be enough data on that right side, checked by requiring observations to be spread across equal-width bins; third, the decline must be sustained, meaning the curve falls a meaningful amount below its post-peak maximum and stays there for a sufficiently long stretch or ends the sample below that level. "Meaningful" is defined relative to a robust noise scale (the median absolute deviation), so that results are comparable and not driven by outliers. Exact settings—band construction, binning, gap size, and the kernel/MLP specifications—are detailed in the S9.

In our analysis, we employed second-degree polynomial regression, kernel regression and Neural Network methods. First, we examined the trajectories of 105 countries over the period 1970–2022 to assess how many have successfully decoupled GDP growth from their Material Footprint. Second, we conducted second-degree polynomial panel regressions across 105 countries to provide a broader perspective on global green growth trajectories. Next, we have also performed second-degree polynomial regression and kernel regression on a year-by-year basis across the panel data. This approach provided a comprehensive view of how the relationship between GDP per capita and Material Footprint per capita evolves over time. Finally, we focused on the United Kingdom—frequently cited as a green growth model and for which Material Footprint data has been reconstructed dating back to 1875—to compare the Environmental Kuznets Curve (EKC) across different time periods. This targeted approach allowed for a detailed examination of the UK's economic and environmental evolution within the EKC framework.

2.1. Data collection

This study employs the Material Footprint as a key indicator. This captures the total amount of raw materials—specifically biomass, fossil fuels, metal ores, and non-metallic minerals—allocated globally to meet the final demand of an economy. It accounts for the comprehensive resource input required for products consumed within a country, including indirect inputs like the energy, materials, and resources necessary to produce imported goods. By assessing the Material Footprint on a per capita basis, we gain insight into the real burden of consumption on global resources, offering a more accurate portrayal of a nation's resource use.

While the methodology demands extensive processing and relies on detailed input–output tables—which may compromise data quality—(Lutter et al., 2016) the Material Footprint remains the preferred indicator precisely because it provides a comprehensive measure of total resource consumption.

This indicator is derived from the UNEP IRP Global Material Flows Database (Schandl et al 2024)., with data spanning from 1970 to 2024, offering a comprehensive overview of material usage over time. This measurement, divided by population, illustrates the per capita material demand and its implications for global resources.

To correlate material consumption with economic activity, we utilized GDP data in constant 2015 US dollars, sourced from the World Bank, providing a stable basis for comparison over time. Initially, we aimed to analyse GDP in terms of purchasing power parity (PPP) to better account for the relative costs of living and inflation rates across countries. However, PPP-adjusted GDP data were only available from 1990 onwards, limiting our ability to conduct a full historical analysis using this metric. Despite this constraint, the chosen indicators—Material Footprint from the UNEP IRP Global Material Flows Database and constant GDP from the World Bank—allow for a robust examination of the relationship between economic growth and material consumption.

We benchmark countries' Material Footprint against prospective limits but do not treat any single value as a definitive boundary. Aggregate, expert-based mass caps—such as the widely cited 50 Gt yr^{-1} proposal (Dittrich et al., 2012; Bringezu, 2015); recent reviews judge such proposals immature and heterogeneous (Dudka, Hauschild, & Owsianiak, 2025). Following this guidance, we use limits as scenarios rather than normative boundaries and report results across absolute caps of 25/50/100 Gt yr^{-1} and per-capita corridors. The per-capita diagnostics include published corridors—notably the IRP SDG think piece (2014) proposing 6–8 t/capita by 2050 and Bringezu (2015)'s material footprint 3–6 t/cap corridor. We also note related estimates in the literature, e.g., Lettenmeier et al. (2014)'s ∼ 8 t/cap target at the household level and Vélez-Henao & Pauliuk (2023)'s ∼ 6 t/cap·yr requirement for Decent Living Standards (with a 3–14 t/cap·yr range). Accordingly, we treat 6.3 t/cap only as an assumed threshold used for readability within these published ranges, not as a commonly agreed value. For each scenario, we compute a safe-space share (Material Footprint ÷ cap). We use these scenario-based diagnostics to assess the robustness of our findings to alternative, plausible limits on materials use.

2.2. Historical reconstruction of the Material Footprint and GDP for the UK (1875–2024)

To reconstruct the UK's Material Footprint per capita from 1875 to 2024, we transformed historical Domestic Material Consumption data from Streeck et al. (2020)) into Material Footprint estimates aligned with Eurostat's Raw Material Equivalent approach. Our reconstruction employs a regression model that integrates standardized historical data on the goods trade deficit, household consumption, gross fixed capital formation, and the service sector's share of GDP—all sourced from the Bank of England's millennium dataset—to capture accurately the material implications of trade, consumption, investment, and structural economic shifts. Comparing our reconstructed Material Footprint series (1875–2016) against available actual MF data (1970–2016), we find a strong alignment (adjusted R2 = 0.9) and confirm cointegration of the variables, indicating a stable long-term relationship. Detailed methodology, equations, robustness tests, diagnostic statistics predicted Material Footprint data are provided in the supplementary materials S1 and S2 and Supplementary Data.

For the historical Environmental Kuznets Curve analysis of the UK, we used GDP per capita data from multiple sources. The primary dataset comes from The Maddison Project (Bolt et al., 2018) (1875–2018, in constant 2011 US), supplemented with World Bank data (2018–2022, in 2015 US) and extended to 2024 using IMF projections for real GDP growth. The complete methodology for data collection is detailed in Supplementary Material S1.

3. Results

In this section, we first analyse data from 105 countries between 1970 and 2023, aiming to identify where economic expansion appears to diverge from material consumption. Next, we employ panel regressions to compare the United Kingdom's contemporary trajectory with global patterns and assess its position relative to sustainability-limit scenarios. Finally, we reconstruct the UK's Material Footprint data back to 1875 to evaluate the Environmental Kuznets Curve in a long-term historical context.

3.1. Evidence for decoupling

Analysing an expanded dataset on Material Footprints across 105 countries, we have identified compelling evidence of decoupling between Material Footprint and GDP in 25 countries. This subset exhibits a distinctive turning point, where beyond a specific income threshold, continued GDP growth no longer corresponds with proportional increases in Material Footprint. Our statistical analysis reveals significant decoupling patterns that contrast with previous findings by Wiedmann et al. (2015), whose 1990–2010 dataset indicated Material Footprints consistently rising alongside GDP across most high-income countries. By employing second-order polynomial regressions, we demonstrate that these economies, spanning various income levels, diverge meaningfully from the general trend. All countries exhibit a negative and significant quadratic coefficient (β_2), with the United Kingdom demonstrating particularly strong evidence and a peak income value well within the observed range (further supported by regression results and cointegration tests detailed in S3). Johansen cointegration tests further validate these findings, with the UK's trace statistic (32.82) exceeding the 10% critical value threshold (32.06), suggesting the presence of stable long-run equilibrium relationships. Non-parametric kernel regressions generally fall within the robust confidence intervals derived from our polynomial fits, further substantiating the decoupling pattern.

To test robustness beyond the quadratic screen, we re-estimated each series with two flexible smoothers—a Nadaraya–Watson kernel (bandwidth chosen by minimum distance to the quadratic fit) and a standardized MLP with weight decay and early stopping—and applied a right-dominant diagnostic on the post-peak shoulder combining a one-sided simultaneous derivative test, coverage, and persistence relative to a median-based noise yardstick. Among the 25 screened series, concordant acceptance under both smoothers is observed for Bahrain, Benin, Cuba, Malta, Papua New Guinea, Portugal, South Africa, and the United Kingdom. Kernel-only acceptance occurs for Austria, Germany, Japan, Spain, and Zambia, whereas neural-network-only acceptance is found in Burkina Faso and Haiti. The remaining series—Belgium, Belize, Burundi, Cameroon, Ghana, Liberia, Niger, Peru, Somalia, and Uruguay—do not pass once derivative uncertainty, coverage, and persistence are enforced.

Across the 25 cases, patterns differ. In European economies such as the United Kingdom, Germany, Belgium, Austria, and Spain, post-2008 declines in material footprint track the financial and housing downturn, rather than technology-led dematerialization (Belda & Requena-i-Mora, 2025 and Schaffartzik and Duro, 2025). In commodity-dependent exporters such as Zambia, Cameroon, and Papua New Guinea, national income can rise on external price upswings while material footprint falls if domestic absorption of material-intensive goods and construction remains subdued and spending tilts toward services. In constrained or externally restricted settings such as Somalia and Cuba, economic output can expand through services, remittances, or tourism while fuel and import constraints curb material-intensive consumption; in Cuba, the material footprint is largely biomass, and long-standing agroecological and urban farming systems provide a constructive pathway to sustain lower material intensity. These mechanisms are heterogeneous, and a full causal decomposition exceeds this study's scope; our focus is to assess whether observed decoupling is sufficient relative to sustainability thresholds—that is, decoupling within limits.

3.2. The context of decoupling I: Sustainability-limit scenarios

While our analysis identifies the United Kingdom as exemplifying Material Footprint decoupling from GDP this achievement must be contextualized within broader sustainability thresholds. Despite its recent downward trend, the UK's Material Footprint remains substantially above the sustainability-limit scenarios thresholds (Fig. 3), indicating that achieving a statistical turning point does not yet equate to ecological sustainability. The other high-income cases shown in red—Austria, Belgium, Germany, and Spain—also lie above these corridors (see also Fig. S8), indicating that a statistical turning point does not yet amount to ecological sufficiency, not even when the sustainability-limit scenario is set at 100Gt. Low-income cases such as Somalia and Papua New Guinea (see also S8) operate within or below these corridors and have reduced MF while GDP rose—evidence of absolute decoupling within corridor limits. Cuba is a middle case: MF rises to about 12 t/cap (ln≈2.5) and then declines back toward/below the corridor range as GDP per capita approaches 8–9 k USD (ln≈9), illustrating a more complete EKC trajectory within sustainability limit scenarios when corridors are set at 100Gt or 50Gt per year.

Conversely, the trajectories of countries like Bangladesh or Burundi are not near the Environmental Kuznets Curve's turning point, suggesting that their economic growth still has increasing resource uses. However, their current position below the sustainability-limit scenarios line offers an opportunity to steer towards a development path that avoids the overshoot demonstrated by the UK, when the sustainability limit scenario is set at 50Gt or 100Gt.

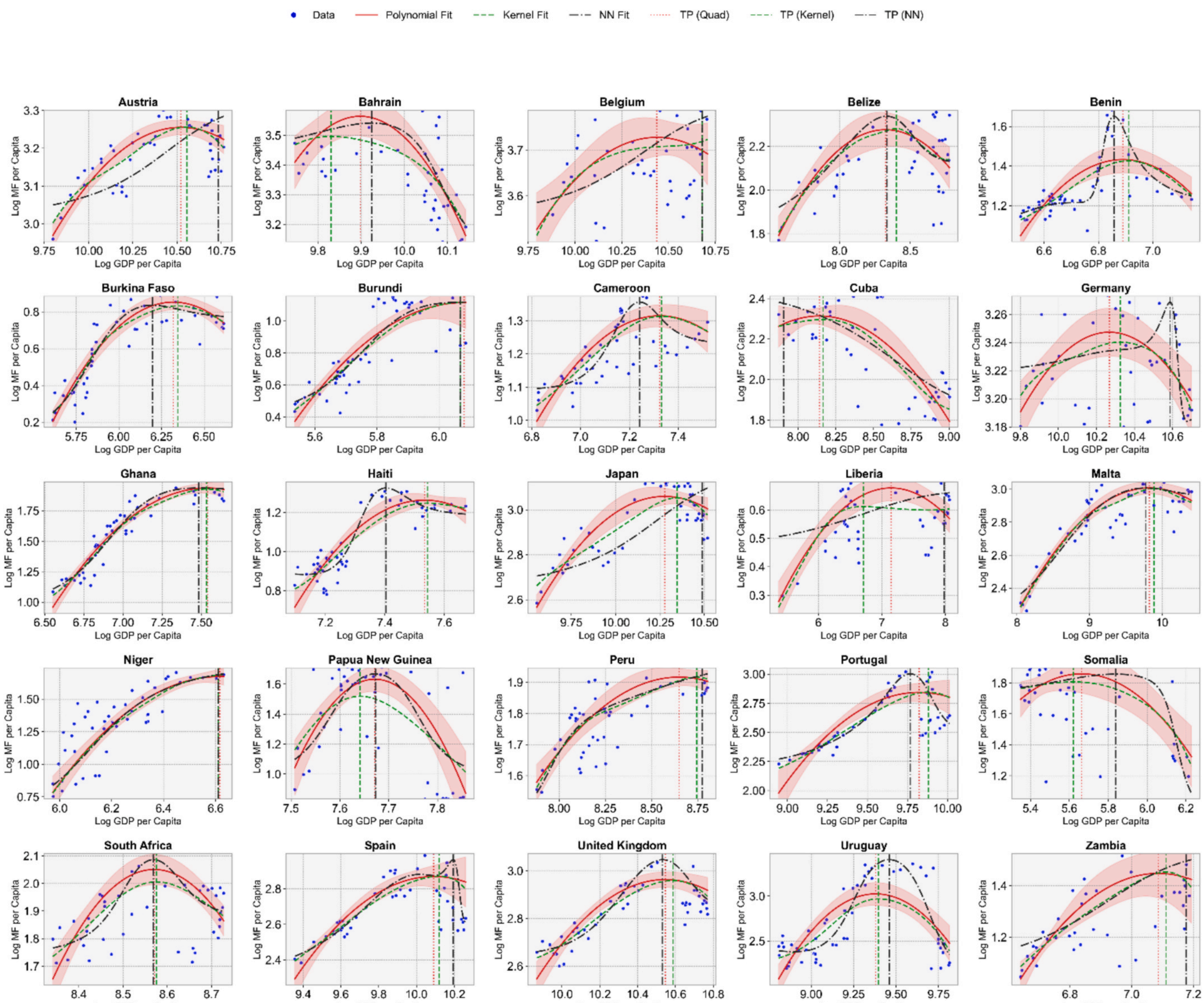

Fig. 2. Environmental Kuznets Curves for Material Footprint in 25 selected countries showing evidence of decoupling (1970–2022). Each panel displays the relationship between log GDP per capita (x-axis, constant USD) and log Material Footprint per capita (y-axis, tonnes per capita) for individual countries. Blue dots represent annual observations. Three estimation methods are shown: solid red line (second-degree polynomial fit), short-dashed line (Nadaraya-Watson kernel regression), and dash-dot line (neural network with weight decay). Vertical lines indicate estimated turning points where Material Footprint peaks: TP (Quad) for polynomial fit (solid vertical line), TP (Kernel) for kernel regression (dashed vertical line), and TP (NN) for neural network (dash-dot vertical line). Pink shaded areas represent confidence intervals for polynomial fits using HAC (Heteroscedasticity and Autocorrelation Consistent) robust standard errors with maximum 5 lags. Countries are selected from a 105-country sample based on significant negative quadratic coefficients (β_2) and peak income values within the observed range. Data . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: the World Bank and UNEP IRP Global Material Flows Database

3.3. The context of decoupling II: Collective international experience

When data from all available countries are considered, the Environmental Kuznets Curve apparent in some individual countries cannot be seen. Fig. 4 shows 105 countries from 1970 to 2023, plotting the logarithm of GDP per capita against the logarithm of Material Footprint per capita. The grey points represent the collective data from all countries, while the data for the UK is highlighted in red and Bangladesh in black. There is no clear inverted U-shape pattern. Instead, the trend for the collective data shows that on a global scale, economic growth is still coupled with increased Material Footprint.

The panel results confirm significant and meaningful relationships between income and environmental degradation. The Hausman test indicates that a fixed-effects specification is preferred over random effects. This means that fixed effects control for unobserved, country-specific factors that are constant over time—such as geographical characteristics, cultural attitudes, or institutional settings—which could otherwise bias the estimates if not accounted for. Additionally, a Wald test of the time dummy variables yields a p-value of 0.0, providing strong evidence that time effects are statistically significant. Including these time fixed effects explicitly captures global factors, such as economic crises, technological advancements, or international policy shifts, which simultaneously impact all countries. This combined specification thus mitigates potential biases arising from omitted country-specific and global variables (see results in S4).

Specifically, the positive and statistically significant coefficient for GDP ($\beta_1 = 0.51$, $p < 0.05$) indicates that resource use increases with rising income. Additionally, the quadratic term for GDP ($\beta_2 = 0.01$, p =

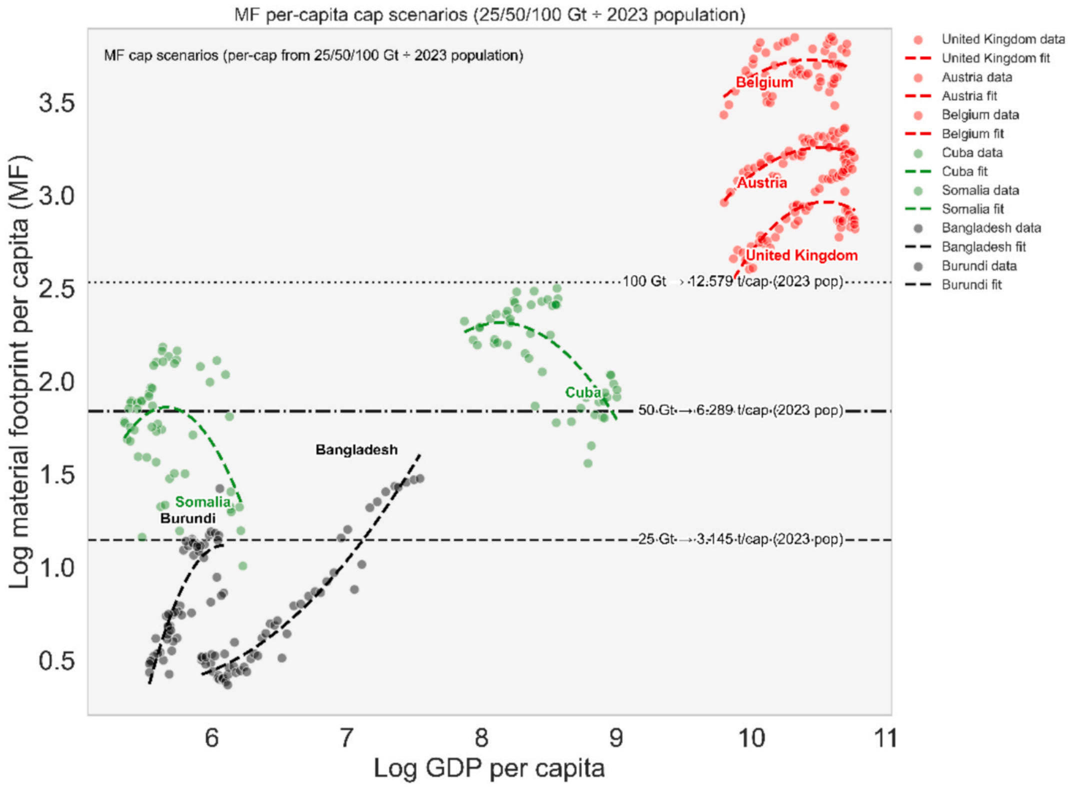

Fig. 3. Environmental Kuznets Curve trajectories for selected countries compared against sustainability-limit scenarios (1970–2022). Log Material Footprint per capita (y-axis, tonnes per capita) versus log GDP per capita (x-axis, constant USD) for countries representing different decoupling outcomes. Colored dots represent annual observations with fitted trend lines (dashed): red colors indicate countries achieving decoupling but operating above sustainability-limit scenarios (United Kingdom, Austria, Belgium); green colors show countries achieving decoupling within sustainability-limit scenarios (Cuba, Somalia); black/gray colors represent countries with no evidence of decoupling (Bangladesh, Burundi). Horizontal dashed lines indicate global Material Footprint sustainability-limit scenarios based on 2023 population: 25 Gt global budget → 3.145 tonnes per capita; 50 Gt global budget → 6.289 tonnes per capita; 100 Gt global budget → 12.579 tonnes per capita. Countries above these thresholds exceed sustainable resource consumption levels despite any decoupling achieved. Data . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: the World Bank and UNEP IRP Global Material Flows Database

0.01) is also positive and significant. Contrary to the typical inverted U-shape hypothesized by the Environmental Kuznets Curve, the positive quadratic term in this dataset indicates that such a downturn is not observed. Instead, material resource use accelerates at higher income levels within the observed data range.

Examining the year-specific coefficients reveals an evolving dynamic in the relationship between GDP and environmental degradation over time (see S4). Notably, the intercept has steadily risen from 1.92 in 1970 to 2.23 in 2023, suggesting that the baseline level of environmental degradation, independent of income, has increased. The GDP coefficient remains positive and relatively stable—ranging from 0.51 to about 0.57—indicating that economic growth consistently contributes to greater environmental pressure. However, the positive quadratic term for GDP shows a declining trend, dropping from around 0.06 in earlier years to approximately 0.02–0.03 in later periods, which implies that while environmental degradation continues to escalate with higher income levels, the acceleration of this effect has moderated over time.

Fig. 5 and 6 illustrate the persistent relationship between GDP per capita and Material Footprint per capita from 1970 to 2023. Fig. 5 reveals an important evolution in the relationship between economic growth and resource use. For 1970, the polynomial fit shows a negative linear term (β_1 = -0.42) combined with a positive and statistically significant quadratic coefficient ($\beta_2 = 0.06$, $p < 0.01$). This pattern indicates a U-shaped curve, where material resource use initially decreases with early economic growth but then begins to accelerate upward after reaching a minimum point. By 2023, while the linear term becomes positive ($\beta_1 = 0.12$) though not statistically significant, the quadratic term remains positive and significant ($\beta_2 = 0.03$, $p < 0.1$). This suggests that the relationship has evolved toward an increasingly upward-bending curve over time.

These findings contradict the environmental Kuznets curve's inverted U-hypothesis. Instead, they suggest a more complex pattern where any initial reduction in resource use is eventually reversed, with resource use accelerating at higher income levels—providing evidence for what might be termed a “relinking” phenomenon rather than sustained delinking. This trend is further supported by the kernel regression fits, which show similar patterns across the two years, reinforcing the conclusion that economic growth continues to drive resource use.

Fig. 6, with its density contours and fit lines, confirms this observation. depicting kernel regression fits for the entire period from 1970 to 2023, further solidifies this observation. The density contours and the fit lines for 1970 and 2023 reveal a persistent coupling of GDP per capita and Material Footprint per capita. The density points in the graph represent areas where the data points are more concentrated, with darker regions indicating higher concentrations of data points. This density representation helps to visualize the distribution of data and highlights regions where there is a stronger relationship between GDP per capita and Material Footprint per capita. The density contours, combined with the fit lines, show that despite the passage of over five decades, there is no significant change in the relationship, suggesting that higher economic growth consistently leads to increased resource use). Furthermore, second polynomial regressions confirm this result and show positive square coefficients throughout the period (see S5), indicating increasing Material Footprints with GDP growth.

Fig. 4. Global Material Footprint versus GDP relationship across all 105 countries (1970–2023) showing absence of Environmental Kuznets Curve pattern. Log Material Footprint per capita (y-axis, tonnes per capita) versus log GDP per capita (x-axis, constant USD). Gray dots represent annual observations from all 105 countries in the dataset, demonstrating the collective global experience. Highlighted countries show specific trajectories: red (United Kingdom), green (Cuba, Somalia), and black (Bangladesh, Burundi) with fitted trend lines (dashed). Horizontal dashed lines indicate global Material Footprint sustainability-limit scenarios based on 2023 population: 25 Gt global budget → 3.145 tonnes per capita; 50 Gt global budget → 6.289 tonnes per capita; 100 Gt global budget → 12.579 tonnes per capita. Panel regression results show positive GDP coefficient ($\beta_1 = 0.51$, $p < 0.05$) and positive quadratic term ($\beta_2 = 0.01$, $p = 0.01$), indicating continued coupling between economic growth and material use acceleration at higher income levels, contrary to Environmental Kuznets Curve hypothesis. Data . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: GLORIA Multi-Regional Input-Output database. Data source: the World Bank and UNEP IRP Global Material Flows Database

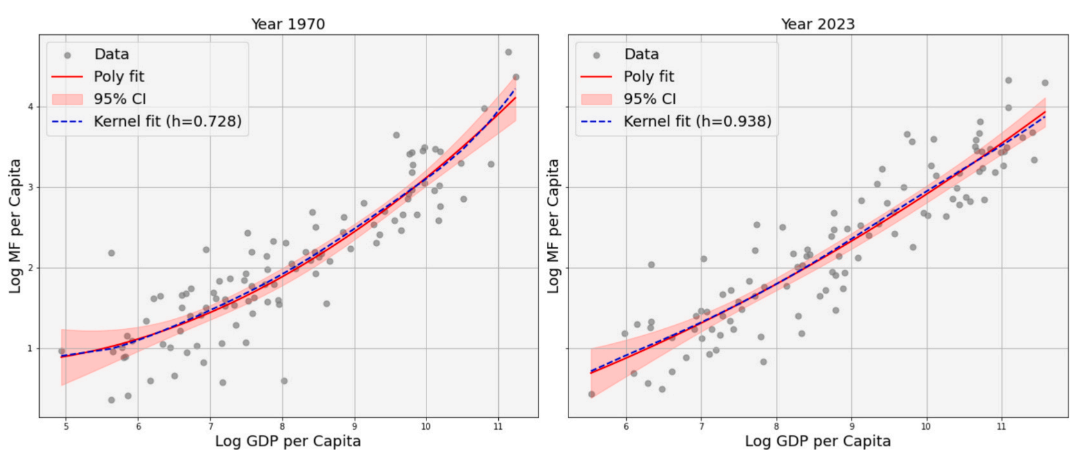

Fig. 5. Material Footprint-GDP relationship evolution from 1970 to 2023 showing persistent positive coupling. Log Material Footprint per capita (y-axis, tonnes) vs log GDP per capita (x-axis, constant USD) for (a) 1970 and (b) 2023. Gray dots: country observations. Red lines: polynomial fits with 95% confidence intervals (pink shading, HAC robust standard errors). Blue dashed lines: kernel fits (h = 0.728 in 1970, h = 0.938 in 2023). 1970: U-shaped pattern ($\beta_1 = -0.42$, $\beta_2 = 0.06$, $p < 0.01$). 2023: upward-bending ($\beta_1 = 0.12$n.s., $\beta_2 = 0.03$, $p < 0.1$). Positive quadratic coefficients in both periods contradict Environmental Kuznets Curve, indicating accelerating resource use with higher incomes across five decades. Source: the World Bank and UNEP IRP Global Material Flows Database. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

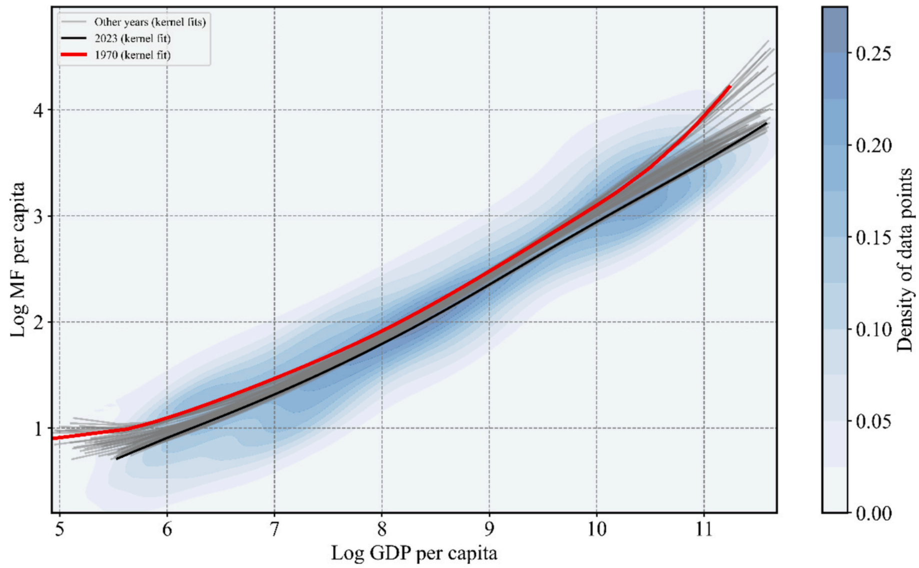

Fig. 6. Year-by-year kernel regression evolution showing persistent Material Footprint-GDP coupling across five decades (1970–2023). Log Material Footprint per capita (y-axis, tonnes per capita) versus log GDP per capita (x-axis, constant USD) with density contours representing data point concentrations across 105 countries per year. Blue shaded areas indicate density of observations with darker regions showing higher data point concentrations (scale: 0.00–0.25 density of data points). Kernel regression fits are shown for all years: red line (1970), black line (2023), and gray lines (all intermediate years 1971–2022). Despite five decades of global development, all trend lines demonstrate consistent upward-sloping patterns with no evidence of Environmental Kuznets Curve turning points. The persistence of positive relationships across all years, supported by density concentrations, indicates that higher economic growth consistently leads to increased resource use throughout the entire period, contradicting decoupling hypotheses and demonstrating stable long-run coupling between GDP per capita and Material Footprint per capita. Data source: UNEP IRP Global Material Flows Database and The World Bank. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Cointegration analysis supports these findings (see S5). Johansen tests reveal significant cointegration between GDP per capita and Material Footprint across all years (trace statistics consistently exceeding critical values, indicating a stable long-run relationship between economic growth and resource use).

3.4. The context of decoupling III: Longer time frames

What do these relationships look like in the long durée? Here we focus on the UK, in part as the exemplar of recent apparent progress and in part because good data are available for it. For 1990–2021, an inverted U-shaped relationship between GDP and Material Footprint per capita emerges (Fig. 7), confirmed by quadratic regression with significant coefficients for both the linear ($\beta_1 = 0.42$, $p < 0.05$) and quadratic terms ($\beta_2 = -0.37$, $p < 0.05$), with a peak at ~ 31,469 USD. Johansen tests reveal strong cointegration between these variables (trace statistic = 79.54), indicating a stable long-run relationship. Gregory-Hansen tests (minimum ADF = -4.81) further demonstrate this relationship persists even accounting for structural breaks, validating our Environmental Kuznets Curve specification. The nonparametric acceptance rules corroborate this pattern for both methods Neural Networks and kernel: right-side coverage is ample and spread (7 bins with 6 hits, ≥5 required), the post-peak slope is negative on the right (the 95% upper slope band grazes zero but the nonnegative-slope share is ≤ 0.05), and the decline is persistent below a MAD-scaled threshold and the right tail finishes low, so the EKC is accepted for 1990–2021.

The 1970–2024 analysis reveals more complexity while maintaining statistical support for Environmental Kuznets Curve with significant coefficients for both linear ($\beta_1 = 0.20$, $p < 0.05$) and quadratic terms ($\beta_2 = -1.08$, $p < 0.05$), with peak at ~ 31,818 USD. Cointegration remains robust for this period (Johansen trace statistic = 50.09, Gregory-Hansen minimum ADF = -5.11), confirming the validity of our regression results despite the extended timeframe. The nonparametric checks point the same way for both kernel and Neural Network: the post-turning-point region is well represented on the right (seven bins with six hits, and eight bins with six hits—both meeting their respective requirements), the curve tilts downward after the peak (the 95% upper slope band brushes zero but the fraction of non-negative slopes stays within the 0.05 tolerance), and the drop is durable relative to right-side variability and the terminal segment finishing low in the neural-network fit. Hence, the EKC is upheld for 1970–2023.

Our 1875–2024 analysis challenges the universality of Environmental Kuznets Curve, revealing a predominantly linear relationship ($\beta_1 = 0.74$, $p < 0.05$) despite a significant negative quadratic coefficient ($\beta_2 = -0.17$, $p < 0.05$). The calculated peak occurs at approximately 126,000,000 USD, far beyond observed income levels, effectively making the inverted-U shape unattainable within realistic economic parameters. Notably, cointegration is weaker over this long horizon (trace statistic = 32.93, minimum ADF = -3.60), consistent with the visual observation that the Environmental Kuznets Curve pattern deteriorates when viewed across the longest timescales. This also suggests that rather than an Environmental Kuznets Curve we observe cycles around a linear tendency. For 1875–2024, the acceptance rules are not met for either the kernel regression smoother or the neural network smoother. The right side is extremely short ($p_n \approx 0.053$; about eight annual observations), so coverage fails by design. The derivative criterion also fails –the 95% upper slope band is not everywhere negative, and the non-negative-slope share exceeds the 0.03 tolerance. Persistence does not pass either: despite a long run below the MAD-scaled threshold (run_have ≈ 27 ≥ run_need = 12), the series does not finish low.

Supplementary S6 provides detailed regression diagnostics for all three periods, including confidence intervals for turning points and alternative model specifications testing the robustness of our findings. Supplementary Section S9 provides both methodological details and results for the EKC acceptance rules.

These econometric results collectively highlight the importance of temporal scale in environmental-economic analysis and caution against extrapolating short-term patterns into long-term predictions about sustainability transitions.

Non-parametric kernel regressions corroborate our polynomial

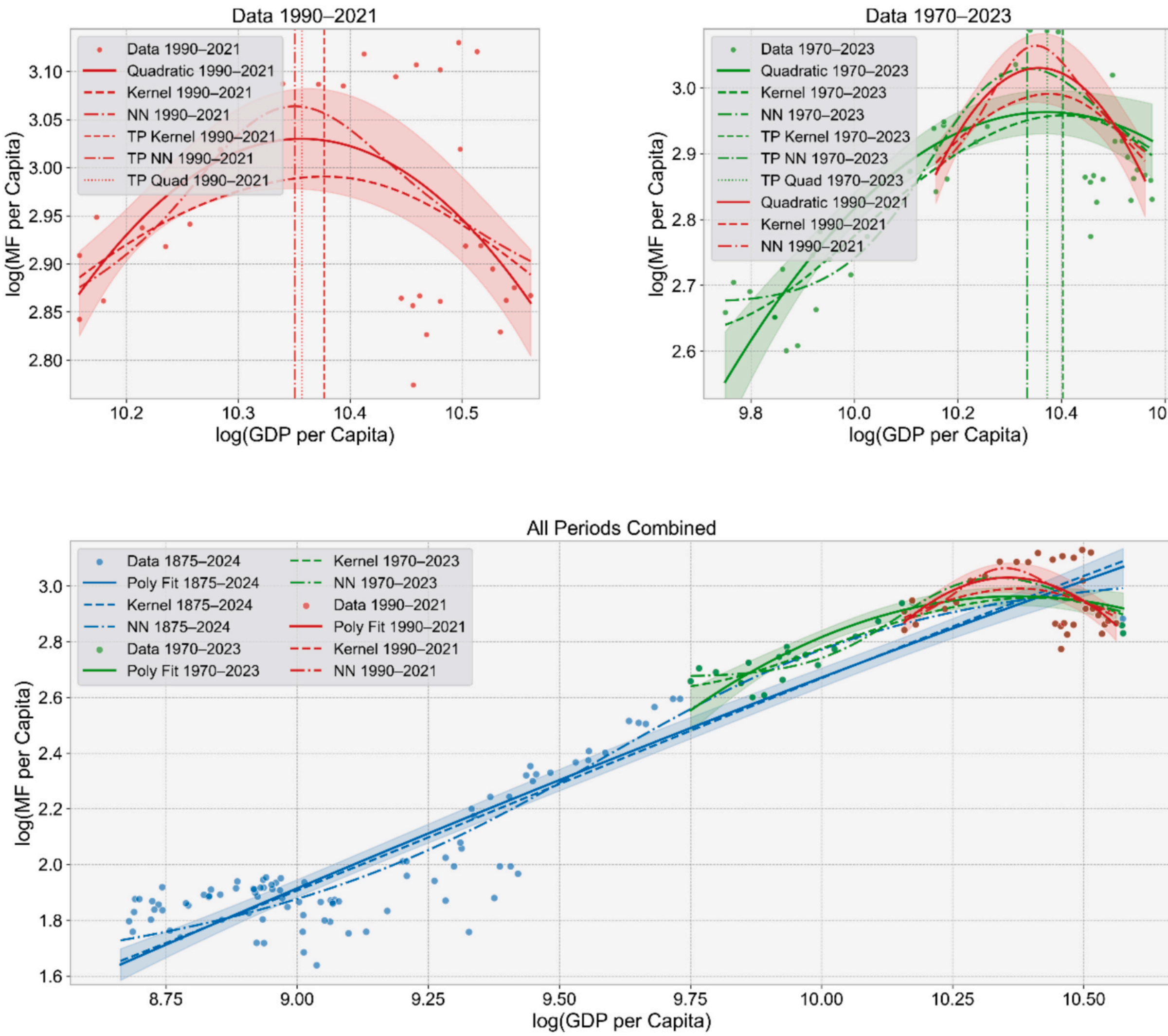

Fig. 7. UK Material Footprint versus GDP across multiple timeframes showing temporal dependence of Environmental Kuznets Curve evidence. Log Material Footprint per capita (y-axis, tonnes) vs log GDP per capita (x-axis, constant USD). Panel (a) 1990–2021: Inverted U-pattern (red dots, $\beta_1 = 0.42$, $\beta_2 = -0.37$, peak ~ 31,469 USD). Panel (b) 1970–2023: EKC confirmed (green dots, $\beta_1 = 0.20$, $\beta_2 = -1.08$, peak ~ 31,818 USD). Panel (c) 1875–2024: Linear relationship dominates (blue dots, $\beta_1 = 0.74$, unrealistic peak ~ 126 M USD). Multiple fits shown polynomial (solid), kernel (dashed), neural network (dash-dot), with turning points marked (TP). Shorter periods show decoupling patterns that disappear in long-term historical perspective, demonstrating temporal cherry-picking in sustainability assessments. Sources: Bank of England, UNEP IRP, Streeck et al. (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

findings across all three periods, with kernel fits falling within the confidence intervals of the polynomial specifications, further confirming the robustness of our conclusions regarding the time-dependent nature of the Environmental Kuznets Curve relationship (for Kernel using bandwidth selection BIC see S7).

4. Discussion

Our analysis challenges prevailing narratives about decoupling economic growth from material resource use by revealing how methodological choices—particularly in time frames and country selection—can predetermine findings about green growth. Our findings are informed by Material Footprint data from the UN Environment Programme's International Resource Panel Global Material Flows Database, which has undergone significant updates since earlier decoupling studies. Two key improvements to this database contribute to our results. First, the temporal coverage now extends to 2024, providing additional years of data that capture more recent material consumption trends not available to previous analyses. Second, and perhaps more importantly, the UN Resource Panel has revised its historical estimates for many countries, often showing lower material footprint values for earlier decades compared to previous database versions. For instance, the UK's revised estimates show material footprint per capita values that are 2.88 tonnes lower in 1970 and 1.80 tonnes lower in 1980 compared to earlier database versions, creating a steeper increase to current peak consumption levels. These official database revisions accentuate the Environmental Kuznets Curve pattern more than previous data versions, which partly explains why our analysis identifies apparent decoupling in 25 countries, more so than some earlier studies. The evidence of decoupling identified in a subset of 25 countries spanning various income levels initially appears to validate the Environmental Kuznets Curve hypothesis—that resource use eventually declines after economies reach a certain threshold of development. However, our analysis demonstrates that such conclusions are highly sensitive to temporal and spatial boundaries. Three critical insights emerge from our research:

First, some high-income countries exhibiting apparent decoupling remain substantially above sustainability-limit scenarios for material use. In particular, we show that the UK's Material Footprint, despite recent declines while increasing GDP, still exceeds the sustainable threshold of 6.3 tonnes per capita by a considerable margin. We also observed this pattern in Spain, Germany, Malta, Austria, Belgium, Japan, and Portugal (see S3 tables and S8 Figures).

Second, analysing all 105 countries collectively through panel regression, we find no global Environmental Kuznets Curve pattern. Our results instead reveal a persistent positive relationship between economic growth and material resource use, with the quadratic term remaining positive throughout 1970–2023. This indicates that observed decoupling in specific countries likely represents exceptional cases rather than a generalizable developmental pattern. Our results align with Fischer-Kowalski and Haberl (1997, 2015) and Bithas & Kalimeris (2018) comprehensive analyses of global trends demonstrating that economic growth has historically been tightly coupled with material use. They contend that even where national decoupling is observed—including on a consumption basis—it remains insufficient when benchmarked against global trajectories and sustainability thresholds. This perspective emphasizes that short-term evidence of decoupling frequently masks persistent growth in global resource extraction, reinforcing the view that genuine sustainability transitions must go beyond relative efficiency gains to include substantial reductions in absolute throughput. In addition, year-by-year regressions consistently support this positive relationship between material use and GDP, aligning with findings from Wiedmann et al. (2015, 2020), Haberl et al. (2020), and Krausmann et al. (2017), who emphasize the robustness of Material Footprint metrics in reflecting persistent environmental pressures linked to economic growth.

Third, extending the UK's Material Footprint analysis over 149 years (1875–2024) fundamentally alters interpretations of recent decoupling. The inverted U-shape visible in short timeframes (1990–2021) transforms into a predominantly linear relationship over the longer period, suggesting that recent trends represent temporary fluctuations rather than structural economic-environmental transformations. This finding aligns with recent work by Belda & Requena-i-Mora (2025), indicating cyclical rather than structural dematerialization.

Taken together we can view these methodological problems as a form of 'cherry-picking', that is a danger of choosing data that fit the argument. We theorize cherry-picking as a scope-selection problem: analysts choose where (countries), when (time windows), and which limits (ecological thresholds) to observe, thereby selecting particular outcomes and mistaking them for general patterns. For example a subset of 25 country EKCs (Fig. 2) presents a very different pattern from 105 countries. The bigger picture shows no inverted-U but a persistent positive (and sometimes accelerating) relationship between Material Footprint and income(Fig. 4–6). By scrutinising emblematic cases such as the UK we can test the robustness of these arguments. Our data shows that the UK overshoots plausible sustainability limits (Fig. 3). Extending data from the UK back to 1875 confirms how short term improvements vanish under longer horizons (Fig. 7).

By aligning long historical horizons, the complete international panel, and explicit sustainability-limits, we can more securely identify weak or temporary decoupling. This makes a stronger case for absolute throughput reductions rather than growth-led self-correction. This represents the study's primary contribution. By establishing a more reasonable empirical base it establishes the conditions in which optimism may be possible.

To propose clearer standardized measures for a decoupling typology that distinguishes relative, absolute, temporary and structural cases according to the time involved and limits recognised. We define structural decoupling as that which occurs within sustainability limits over the full continuous span since the onset of country industrialization (Table 1).

Table 1
Decoupling Typology.

Label	Horizon	Flow-based test (operational)	Nonparametric EKC confirmation	Limits lens (sustainability)	When to use
No decoupling (coupling)	Any	GDP per capita growth > 0 and MF per capita growth ≥ 0; elasticity $\varepsilon = \Delta \ln MF / \Delta \ln GDP \geq 0$.	Not required.	Not applicable.	MF rises with GDP or does not fall—baseline case.
Relative decoupling	Any	MF grows slower than GDP (MF growth > 0 but < GDP growth). elasticity $\varepsilon = \Delta \ln MF / \Delta \ln GDP \in (0,1)$	Not required.	Not applicable.	Use when efficiency improves but MF still increases.
Absolute decoupling	Any (windowed)	Mean GDP growth > 0 and mean MF growth < 0 over a window Elasticity $\varepsilon = \Delta \ln MF / \Delta \ln GDP < 0$	Not required.	Not required.	Short statements about sign behavior in a given window or episode.
Temporary absolute decoupling	Short-run (SR): 15–20 years	Absolute decoupling in an SR window, but does not persist when analysing the long run	Required & joint: Right-shoulder decline accepted for both smoothers (Kernel & NN): one-sided derivative band mostly < 0 on the right, adequate right-side coverage, and a persistent/"finish-low" drop (MAD-scaled).	Still outside limits; no material overshoot reduction. Overshoot persists and shrinks too slowly. See for instance the UK Fig. 3	Label crisis/short dips where GDP grows but MF briefly falls. Multi-year improvements that aren't yet long-run transformations.
Temporary Absolute Decoupling within sustainability limits	Short run (SR): 15–20 years	Mean GDP growth > 0 and mean MF growth < 0 over a window Elasticity $\varepsilon = \Delta \ln MF / \Delta \ln GDP < 0$	Required & joint: Right-shoulder decline accepted for both smoothers (Kernel & NN): one-sided derivative band mostly < 0 on the right, adequate right-side coverage, and a persistent/"finish-low" drop (MAD-scaled).	Required: MF either enters/stays within a cap/corridor or MF overshoot shrinks materially See for instance Cuba Fig. 3	
Structural absolute decoupling within sustainability	Long-run (LR): full continuous span from industrial onset t_0 to latest year (use entire available era for the country; not a fixed minimum)	Over LR: (i) average GDP growth > 0; (ii) average MF growth < 0; (iii) at least 80% of years with GDP growth > 0 (avoid recession-driven artifacts).	Required & joint: Right-shoulder decline accepted for smoothers (kernel, Neural Networks, etc); one-sided derivative band mostly < 0 on the right, adequate right-side coverage, and a persistent/"finish-low" drop (MAD-scaled).	Required: MF either enters/stays within a cap/corridor or MF overshoot shrinks materially	Use only when the country's full industrial era shows a durable, shape-consistent, and sustainability-relevant fall in MF while GDP rises.

We propose Structural Decoupling within Limits as the indicator most useful for policies to aspire to. Decoupling counts only when (i) the decline is durable over the long run, (ii) material use is within (or credibly converging to) limit corridors, and (iii) consumption-based accounts rule out externalization. Framed this way, our contribution is practical: it turns a complex empirical pattern into a decision-making tool for climate and SDG tracking, while clarifying that short-window peaks, even when statistically robust, are not policy endpoints unless they pass Structural Decoupling within Limits.

Our findings carry implications for three interconnected debates in sustainability science. First, regarding rebound effects, our evidence of persistent coupling even in apparent success countries suggests that efficiency-driven dematerialization may be systematically undermined by scale and composition effects that current Environmental Kuznets Curve analyses fail to capture. The temporal instability we document—where apparent decoupling recedes over longer timeframes—aligns with Jevons' paradox and more recent rebound literature showing that efficiency gains are often offset by induced demand effects, behavioral responses, and economy-wide adjustments that manifest over extended periods (Sorrell, 2007; Wiedmann et al., 2020).

Second, our structural decoupling typology directly engages post-growth debates by demonstrating that green growth narratives rely on methodologically narrow evidence that weakens under critical scrutiny. Countries like Cuba and Somalia that achieve material footprint reductions within sustainability-limitss demonstrate that decoupling within ecological constraints is feasible, but this occurs at relatively modest consumption levels. In contrast, high-income nations that achieve statistical decoupling while remaining in severe ecological overshoot face fundamentally different challenges. This supports arguments by Jackson (2017) and Kallis (2017) that prosperity without growth may be both necessary and feasible, particularly as countries reach higher GDP and material footprint levels where green growth becomes increasingly difficult to achieve within sustainability-limit scenarios.

Third, our distinction between sustainability-limits and arbitrary thresholds contributes to ongoing debates about absolute biophysical limits versus context-dependent sustainability targets. While Rockström et al. (2009) and Steffen et al. (2015) emphasize fixed environmental boundaries, our analysis shows how different sustainability-limit scenario specifications (25/50/100 Gt scenarios) fundamentally alter decoupling assessments, suggesting that sustainability science must move beyond binary “success/failure” metrics toward nuanced evaluations of convergence trajectories within different sustainability-limit scenarios.

Ultimately, our findings challenge the techno-optimistic assumption underlying much green growth policy—that market mechanisms and technological innovation will spontaneously generate sufficient dematerialization—by showing that apparent progress often reflects methodological artifacts rather than genuine sustainability transitions. This aligns with Hickel and Kallis (2020) who systematically examine claims of green growth and find that evidence for absolute decoupling remains limited and insufficient to address climate targets within required timeframes. More critically, Vogel and Hickel (2023) demonstrate that even achieved decoupling in high-income countries falls dramatically short of Paris-compliant emission reduction rates, with countries requiring acceleration of decoupling rates by factors of ten or more to meet their fair-share carbon budgets, rendering green growth empirically out of reach. These findings demands policy frameworks that prioritize absolute throughput reduction within sustainability-limit scenarios rather than relying on growth-led efficiency improvements that our analysis suggests are insufficient for ecological sustainability.

Our methodological approach—integrating historical analysis, cross-country comparisons, and sustainability-limit scenarios assessments—offers a rigorous framework for evaluating sustainability transitions. Building upon Bertinelli and Strobl's (2005) and Luzzati et al. (2018) non-parametric Environmental Kuznets Curve analyses, our approach expands historical dimensions crucial for understanding long-term economic-environmental relationships. Future research should further investigate how middle and low-income countries decouple Material Footprint from GDP within sustainability-limit scenarios. Countries such as Cuba, Papua New Guinea, Somalia, Haiti, Cameroon, Liberia, or Zambia may provide valuable insights, as suggested by our preliminary analyses (Tables S3, Figs. S8). Extending historical Material Footprint analyses to additional countries would further test the robustness of Environmental Kuznets Curve hypotheses across diverse development pathways.

In conclusion, our three-stage analysis demonstrates how conventional interpretations of decoupling evidence, especially in high-income countries, often rely on limited temporal and spatial perspectives that can lead to misleading conclusions about green growth possibilities. Our findings support the original concerns of Grossman and Krueger (1991) and Kuznets (1955) that development relationships are complex and context-dependent, while demonstrating that the application of their curve to environmental indicators requires more rigorous methodological standards than typically applied. By integrating longer historical trajectories, broader geographical comparisons, and explicit sustainability thresholds we provide a more comprehensive framework for assessing whether economic growth can truly detach from environmental impact. The fundamental insight articulated by Georgescu-Roegen (1971)—that infinite economic growth is incompatible with a finite planet—remains central to sustainability discourse nearly five decades later.

CRediT authorship contribution statement

Marina Requena-i-Mora: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Brockington:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

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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characterise the Material Footprint–GDP relationship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103150.

Data availability

We will share our data in a public repositoryoy

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