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Growth Sustainability and the Quality Dimension of Consumption[*]

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Abstract

What factors shape the environmental sustainability of economic growth? This paper shows that the shift in advanced economies from *quantity to quality growth* (i.e., from producing more units of identical goods to producing more valuable varieties) is a potentially important mechanism favoring the decoupling of economic growth from resource use and environmental impacts. First, the paper introduces a parsimonious and tractable model that distinguishes the environmental impacts of quantity and quality growth and identifies the key parameter to be estimated empirically. Second, to estimate the quality elasticity of the environmental impacts, the paper uses the US automobile industry as an important and illustrative case. The environmental impact of quality growth is found to be significantly smaller than the impact of quantity growth. Accounting for the distinct impacts of quantity and quality growth would help improve sustainability projections and policies.

Keywords: sustainable development; decoupling; quality growth; environmental Kuznets curve.

JEL classification numbers: O44, Q56.

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1 Introduction

Over the 20th century, material use (biomass, fossil energy carriers, ores, and minerals) increased more than 8-fold, thus raising concerns on resource depletion and resulting in large amounts of waste and emissions (Behrens et al. 2007; Krausmann et al. 2009 and 2017; Fischer-Kowalski et al. 2011). As urged by United Nations Environment Program, decoupling economic activity from the consumption of natural resources and environmental impacts is fundamental to sustainable development and future human wellbeing (UNEP 2011). What are the key factors that affect the decoupling of economic growth from environmental impacts? Three of these key factors are well-know: technical progress improving resource efficiency, structural change shifting consumer expenditure shares from manufactures to services, and resource price and environmental regulation raising the impacts' private costs (Shapiro and Walker 2018, on the latter). This paper is a first effort to analyze an additional and potentially important factor that has been disregarded so far, the gradual within-product shift from *quantity* to *quality* growth in developed economies. Accounting for this additional mechanism will help in understanding the decoupling process, developing better projections on environmental impacts, and implementing more comprehensive policies.

Real GDP grows through the production of more goods (*quantity growth*) and more valuable varieties (*quality growth*; Bils and Klenow 2001). Increasing quality requires different inputs than increasing quantity. Quality is likely to be relatively intensive in knowledge and skilled labor and less intensive in natural resources. Given the technology, producing and consuming two units of a given product variety will require twice as many materials and generate twice as many residuals and pollutants as producing and consuming one unit. In contrast, producing and consuming one unit of a variety that, as a result of its higher quality, is twice as expensive as another variety, is unlikely to double the environmental impact of the lower-quality variety. However, both doubling the number of units being produced and doubling the value of a given number of units (as a result of quality upgrading in the latter case) generate an identical GDP contribution. Consequently, GDP growth along the quality dimension is likely to have a lower environmental impact than GDP growth along the quantity dimension. The claim by Ekins, Drummond, and Watson (2017) that "unlike physical growth, there is no theoretical limit to economic growth, because money per se has no physical dimension" becomes particularly clear when distinguishing quantity and quality growth: while quantity growth does have a physical dimension (with constant technology, material inputs grow linearly with output quantity), quality growth does not necessarily requires additional material inputs but better knowledge, design, and craftsmanship.

Is quality growth important as a share of GDP? Moulton and Moses (1997) estimate that

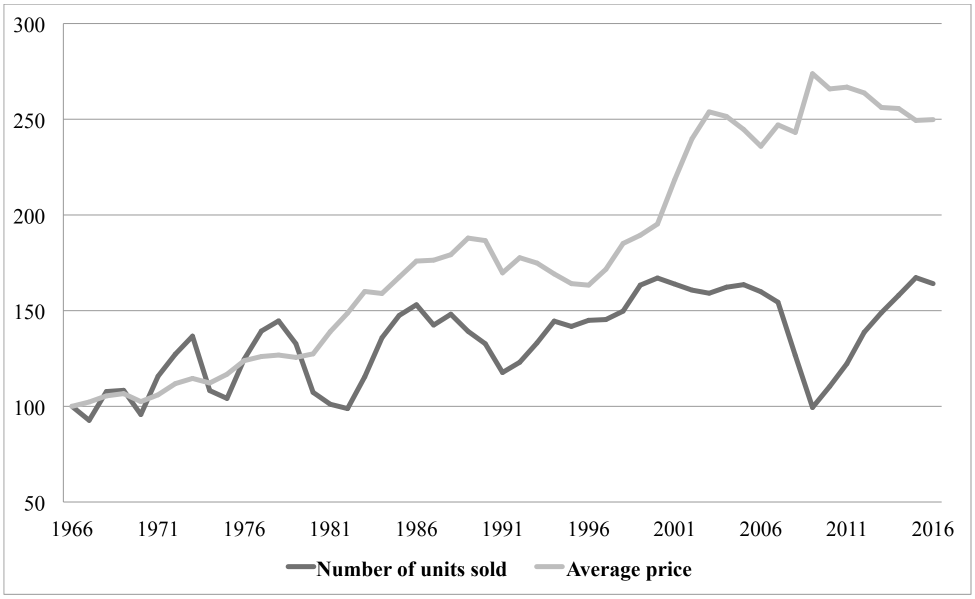

Figure 1: US motor vehicle sales (number of units) and average expenditure per unit at constant prices (1966 = 100).

the BLS methods probably allowed for as much as one percent average quality growth in the US GDP growth of 1995. Moreover, BLS methods are likely to significantly underestimate quality growth (Boskin Commission Report 1996, and Goshen et al. 2017), so that quality growth could account as much as half of per capita GDP growth in the US. The importance of quality growth relative to quantity growth can be illustrated with the automobile industry. Over the past 50 years, real personal consumption expenditures on new motor vehicles grew in the US at an average annual rate of 2.82%. Figure 1 shows the annual sales of cars in units and the average expenditure per car at constant prices between 1966 and 2016 (indexes 1966 = 100).[1] The average annual growth rate of sales in units was 0.99%, whereas the average annual growth rate of the average unit value was 1.83%. Thus, quality growth was almost double quantity growth. Bils and Klenow (2001) estimate that the annual average quality growth of 66 durable goods over the 1980-1996 period averaged 3.7 percent. Also, the international trade literature presents ample evidence of the positive relationship between consumption quality and income (e.g., Hallak 2006; Crino and Epifani 2012).

Different fields in economics provide different approaches to modeling production and growth along the quality dimension (e.g., Flam and Helpman 1987, Grossman and Helpman

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[1] The data on real personal consumption expenditures on new motor vehicles (quantity indexes) are from the Bureau of Economic Analysis and the data on motor vehicle unit retail sales (autos and light trucks) are from WardsAuto, which are available at http://wardsauto.com/data-center. The average price per vehicle is calculated by dividing the real personal consumption expenditure on new motor vehicles by their unit retail sales.

1991, Hallak 2006). However, none of the available models consider its particular environmental impact, as opposed to the impact of increasing output quantity, and the implications of the quantity-quality composition of output for growth sustainability. First, this paper introduces a parsimonious and tractable model that distinguishes the environmental impacts of quantity and quality growth. The model clarifies the basic conceptual issues and identifies the key parameter to be estimated empirically. Second, the paper uses the automobile industry in the US as an illustrative case to estimate the quality elasticity of the environmental impact. The automobile industry is an especially relevant case because cars constitute the single most important consumption good in developed economies[2] and because their manufacture, usage, and disposal consumes vast amounts of resources and discharges large quantities of residuals (Maclean and Lave 1998). For this industry, the analysis shows that the environmental impact of quality growth is significantly smaller than the impact of quantity growth. Assessing the overall quantitative implications of the shift from quantity to quality growth on the sustainability of economic growth will require ample empirical work across many industries and countries. Hopefully, the analysis here will help stimulate this line of research.

As measures of the environmental impact of automobiles, I use automobile weight, gas consumption, and CO2 emissions. Weight is the standard proxy for material use,[3] whereas gas consumption and CO2 emissions are indicators of energy consumption and pollution (here I consider only energy consumption and emissions linked to the use of automobiles but not to their production). I estimate automobile quality elasticities of these three environmental impacts using cross-sectional data and instrumental variables. Cross-sectional data allow for the estimation of quality elasticities keeping constant other determinants of the impacts that vary over time (such as technology, relative prices, and regulation), whereas the instrumental variables address potential endogeneity and reverse causality concerns.

Although there is an abundant empirical literature on the automobile market (e.g., Berry, Levinsohn, and Pakes 1995, for an influential work, and Greene et al. 2018, for a survey), this literature's goals and, consequently, its approach are substantially different from the ones here. The usual purpose of that literature is to estimate the effect of automobile characteristics (e.g. safety features, power, AC, size, electronic mechanisms) on automobile prices. In contrast, the purpose of the analysis here is to assess the extent to which the cars that have higher prices due to higher quality generate higher environmental impacts. Moreover, as the

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[2] According to BLS, vehicle purchases plus other vehicle expenses such as gas represented over 20% of the consumption expenditure in the US in 2015.

[3] According to Kuhndt and Bilitewski (2000), the weight of a generic US vehicle (weighing 1,438 kg) is distributed as follows: 67% is steel and iron, 8% is plastic, 2.8% is glass, 4.2% is rubber, 6% are fluids and lubricants, 8% is non-ferrous metal, and 4% is other materials.

purpose of the previous literature is to price car characteristics, it values them within a linear framework. In contrast, the relationship between car prices and environmental impacts is not necessarily linear and, in fact, when I explore potential non-linearities I find that the quality elasticity of the environmental impacts decreases with quality. This is important (and positive) for the future potential effect of quality growth on decoupling.

The empirical results confirm that quality is less intensive than quantity in resource use and other environmental impacts. These results are consistent with the empirical literature finding that material productivity (the inverse of material intensity) decreases at the early stages of development and increases in advanced economies (e.g., Behrens et al. 2007, Steinberger 2010 and 2013, Fischer-Kowalski et al. 2011, Krausmann et al. 2017).[4] As income grows in poor countries, households' consumption of the different goods often goes from nothing to positive amounts and, therefore, quantity growth takes the lion's share of economic growth in these countries. High population growth in poor societies also favors quantity growth that goes along with an increasing environmental impact. Then, at more advanced stages of economic development, the gradual shift from quantity to quality growth appears to favor the relative decoupling of GDP growth from environmental impacts and helps explain the *environmental Kuznets curve* (EKC) in terms of environmental impact intensities (i.e., in terms of the ratios of the impacts to GDP).[5]

The distinction between the quantity and quality dimensions of production and consumption is also relevant for policy. Although the relative importance of quality growth tends to increase at higher stages of development, this trend can be can be seriously slowed down by some distortionary phenomena. One of these phenomena is planned obsolescence, the design of lower-quality products that wear out prematurely to increase the quantity of sales (Bulow 1986, Guiltinan 2009). Similarly, the globalization of markets boosts the number of brands and models available to consumers, which reduces the per-product consumer information and increases the market share of short-lived low-quality products (Alcalá et al. 2014).

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[4] The specifics of the dynamics of material productivity depend on the indicators being utilized. The reason is that different indicators account differently for the offshoring of resource-intensive activities from developed to developing countries. For instance, *Domestic Material Consumption*, DMC, considers all the raw materials extracted from the domestic territory plus all physical imports minus all physical exports. Alternatively, *Material Footprint*, MF, also includes the upstream raw materials used in imported products (that are calculated using input-output analysis) and shows a smaller productivity increase in richer countries. In particular, Wiedmann et al. (2015) find an elasticity of material productivity with respect to per capita GDP of 0.85 when it is defined as GDP/DMC and of 0.4 when material productivity is defined as GDP/MF.

[5] The EKC suggests that the relationship between income and human environmental impacts has an inverted-U shape: the impacts increase with income until a certain level, after which they decrease. This hypothesis has a variety of versions depending on the particular impact being considered and on whether it is calculated in absolute or relative terms. See Dinda (2004) and Carson (2010) for surveys. These surveys emphasize the importance of identifying the factors explaining the EKC in order to design appropriate policies.

These phenomena call for policies aimed at improving consumers' information, reinforcing quality standards, and prolonging products' lifetime. These types of policies would help curb quantity growth and favor quality growth, and are being proposed and implemented in some countries of the EU (Maitre-Ekern and Dalhammar 2016, Montalvo et al. 2016).

The rest of the paper is organized as follows. Section 2 sets a quantity-quality model with two types of environmental impacts and identifies the key parameters to be assessed empirically, namely, the quality elasticities of the environmental impacts. Section 3 develops the empirical analysis and estimates those elasticities for the case of the US automobile industry. Section 4 summarizes and concludes.

2 Environmental impacts in a quantity-quality model

This section introduces a parsimonious and tractable model that distinguishes the environmental impacts of quantity and quality growth and identifies the key parameter that needs to be estimated empirically to assess the distinct environmental impact of these two components of economic growth. The model has two versions. The model set forth in the first subsection is the simplest possible one and the environmental impact there takes the form of an externality (e.g., CO2 emissions) that does not enter the firms' cost function. In the second subsection, the model is generalized in several directions and the environmental impact takes the form of a natural resource that is used as an input in the production of manufactures together with labor (hence, producers have to pay a price for using the resource). Besides distinguishing the environmental impacts of quantity and quality growth, this second model also accounts for the other factors highlighted by the literature as potential facilitators of the decoupling of economic growth from environmental impacts, namely, increasing technical efficiency, structural change, and the resources' relative market price (which encompasses the impact of environmental taxes and regulations).

2.1 Environmental externalities

Consider a simple economy with two sectors: *manufacturing*, which can be produced along a continuum of qualities $q \in (0, \infty)$ and have a negative environmental externality, and *services*, which have a single quality and no environmental impact. Quality q summarizes all the manufacturing product attributes that increase the consumers' willingness to pay for the product. The representative agent maximizes the utility function $u = u(x, q, s)$, where x and q are the number of units and the quality being consumed of the manufacturing product, s is the consumption of services, and $u(.)$ is a concave function that increases with x, q, and

s.

Denoting GDP (which is equal to consumption) by Y and assuming that all the individuals consume an identical quality, we have $Y = x \cdot p_x(q) + s \cdot p_s$, where $p_x(q)$ and p_s are the price of manufactures and services, respectively, with the price of the manufactures depending on their quality. Denoting the growth rate over time of a variable z by $g(z)$ (i.e., $g(z) \equiv \partial \ln(z)/\partial t$), and by m the share of manufacturing in GDP (i.e., $x \cdot p_x = m \cdot Y$), the growth rate of GDP is $g(Y) = m \cdot g(x) + m \cdot g(p_x(q)) + (1-m) \cdot g(s)$.[6] This expression for GDP growth can be broken down into a quantity component, which is equal to $m \cdot g(x) + (1-m) \cdot g(s)$, and a quality component, which is equal to $m \cdot g(p_x(q))$.

Goods are produced using labor. Specifically, the number of units of manufactures with quality q being produced is given by the following production function:

$$x = B \frac{L}{q^{\gamma_L}}, \gamma_L > 0, \tag{1}$$

where L is the labor input and $B > 0$ is a labor efficiency parameter. Because the parameter γ_L is positive, producing higher quality comes at the cost of producing fewer units for any given labor input. In turn, the environmental impact of producing and consuming these manufactures is:

$$I = \frac{x}{E_I} q^{\gamma_I}, \tag{2}$$

where $E_I > 0$ is an environmental efficiency parameter and γ_I is the elasticity of the impact with respect to quality. Thus, the environmental impact is linear in the quantity of the consumption of manufactures, whereas increasing their quality has an environmental impact that depends on γ_I.

Denote the wage per unit of labor by w. Using expression (1), assuming perfectly competitive markets, and taking the variety with quality equal to 1 as the *numeraire* (i.e., $p_x(1) = 1$), the price function $p_x(q)$ is given by the following expression:

$$p_x(q) = \frac{q^{\gamma_L}}{B} w = q^{\gamma_L},$$

where the second equality uses the fact that $p_x(1) = 1$ implies $w = B$. Using this price

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[6] This growth rate is calculated at constant prices, which means keeping constant p_s and the price function $p_x(q)$.

function to substitute in (2) yields the following expression:[7]

$$I = Y \cdot m \frac{p_x^{\eta_I - 1}}{E_I}, \tag{3}$$

where $\eta_I = \gamma_I / \gamma_L$. We refer to η_I as the quality elasticity of the environmental impact (using prices as an observable index of quality).[8] The *relative decoupling* of GDP growth from environmental impacts is defined as $g(Y) - g(I) > 0$ (whereas *absolute decoupling* requires $g(Y) > 0$ and $g(I) \leq 0$). Rearranging and writing equation (3) in terms of growth rates yields the following expression for the relative decoupling of GDP growth:

$$g(Y) - g(I) = -g(m) + g\left(E_I\right) + \left[1 - \eta_I\right] g(p_x). \tag{4}$$

Hence, the relative decoupling depends on the structural changes in the sectoral composition of demand (from resource intensive manufactures to other less resource-intensive sectors, as captured by a reduction in m), the progress in environmental efficiency E_I, and the importance of quality growth in the sectors with negative environmental impacts (as measured by the growth rate of their average unit value of output at constant prices $g(p_x)$). The literature has discussed the role played by the first two factors but has disregarded the third factor. If the quality elasticity of the environmental impact η_I satisfies $\eta_I < 1$, then increasing output along the quality dimension favors the relative decoupling of GDP growth.

2.2 Natural resources as an input

Consider now an economy in which the production of manufactures requires a natural resource in addition to labor and producers have to pay a price for this resource. As before, there are two sectors (manufacturing and services) whose output value adds up to the econ-

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[7] Note that this substitution is equivalent to relabeling qualities using prices as a new quality index. Quality is only a preference order over the different varieties of a given product and, thus, has no natural units of measurement. The quality index q is only a numerical representation of that preference order. Moreover, any strictly increasing transformation of q, such as the price function, represents the same preference order. Using the relative prices of the different product varieties as the new quality index has two advantages: they are observable and they directly relate to the contribution of quality growth to GDP growth.

[8] Expression (3) can be connected to the $IPAT$ identity, which is a simple framework that has been used to analyze the environmental impact of human activity (Chertow 2001, York et al. 2003; see also Ehrlich and Holdren 1972, and Commoner 1972, for an initial conceptual debate). The $IPAT$ identity presents the environmental impacts I as the product of three driving forces, namely, population (P), affluence (A), and technology (T). It can be set as follows: $I = P \cdot A \cdot T = P \cdot y \cdot (I/Y)$. Thus, affluence is captured by per capita GDP, $y = Y/P$, and the influence of technology is measured by the environmental impact per unit of GDP, I/Y. Hence, according to expression (3) we have $I/Y = m \cdot p_x^{\eta_I - 1}/E_I$. Thus, the I/Y factor of the $IPAT$ identity depends on the weight of the activities that are detrimental to the environment and on the quantity/quality composition of output.

omy's GDP. Manufactures are now produced according to the following CES production function:

$$x = \left[\left(\frac{B \cdot L}{q^{\gamma_L} h^{\delta_L}}\right)^{\theta} + \left(\frac{E_M \cdot M}{q^{\gamma_M} h^{\delta_M}}\right)^{\theta}\right]^{1/\theta}, \tag{5}$$

where M is the input of the resource and the technological parameters satisfy $B > 0$, $E_M > 0$, $\gamma_L > 0$, $\gamma_M > 0$, and $\theta < 0$. This latter assumption implies that labor and the natural resource are gross complements. In turn, q and h are bundles of *quality* and *non-quality* characteristics, respectively, that the manufacturing good can feature in different amounts. The difference between these two bundles is that the characteristics in the quality bundle q are desirable in general to all the consumers (and, thus, the demand for these characteristics increases as income rises), whereas the characteristics in the h bundle serve specific needs (and thus, their demand only increases if those specific needs become more frequent). According to expression (5), increasing any of these two bundles of characteristics may raise the labor and resources needed to produce a given number of units of the manufacturing good (and thus, may simultaneously affect a car's price and environmental impact).

Denote by r the resource's market price, which could include environmental or other taxes. Cost minimization implies the following first order condition:

$$\frac{L}{M} = \left(q^{\gamma_L - \gamma_M} h^{\delta_L - \delta_M} \frac{E_M}{B}\right)^{\theta/(\theta-1)} \left(\frac{r}{w}\right)^{1/(1-\theta)}.$$

Note that quality is relatively less intensive in the resource if and only if $\gamma_L > \gamma_M$. Using this expression to substitute in (5) yields an expression for material consumption as a function of technological parameters, inputs prices, and consumption quantity and quality.

$$M = x \cdot \frac{q^{\gamma_M} h^{\delta_M}}{E_M} \left[1 + \left(q^{\gamma_L - \gamma_M} h^{\delta_L - \delta_M} \frac{E_M}{B} \frac{w}{r}\right)^{\theta/(\theta-1)}\right]^{-1/\theta}. \tag{6}$$

Assuming perfectly competitive markets, manufacturing prices are given by the following expression:

$$\begin{aligned} p_x &= \frac{q^{\gamma_M} h^{\delta_M}}{E_M} r \left[1 + \left(q^{\gamma_L - \gamma_M} h^{\delta_L - \delta_M} \frac{E_M}{B} \frac{w}{r}\right)^{\theta/(\theta-1)}\right]^{(\theta-1)/\theta}. \\ &= \left[\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}\right]^{(\theta-1)/\theta} \end{aligned} \tag{7}$$

Note, that this is a differentiable function such that for any strictly positive vector $(q, h, r, E_M, w/B)$, we have $dp/dq > 0$. Hence, by the Implicit Function Theorem, we can define a mapping $q = \phi\left(p_x, E_M, h, r, w/B\right)$, $\phi : \mathbb{R}^5_{++} \rightarrow (0, \infty)$, such that for any $(p_x, E_M, h, r, w/B) >> 0$, the vector $\left(E_M, h, r, w/B, \phi\left(p_x, E_M, h, r, w/B\right)\right) \in \mathbb{R}^6_{++}$ satisfies (7). Using (7) and $\phi\left(.\right)$ to substitute in (6), yields:

$$M = x\cdot \left(\frac{\phi\left(.\right)^{\gamma_M} h^{\delta_M}}{E_M}\right)^{\theta/(\theta-1)} \left(\frac{r}{p_x}\right)^{1/(\theta-1)}. \tag{8}$$

For $a = h, E, r, w/B$, denote by $\epsilon_{q,a}$ the elasticity of q with respect to a calculated on $\phi\left(.\right)$ (i.e., $\epsilon_{q,a} \equiv \frac{\partial \phi}{\partial a}/\frac{a}{q}$). From equation (8), we find the following expression for resource consumption growth:

$$g(M) \quad = \quad g(x) \ + \ \eta_M g(p_x) \ + \ \mu_h g(h) \ + \ \mu_{E_M} g(E_M) \ + \ \mu_r g(r) \ + \ \mu_{w/B} g(w/B), \tag{9}$$

where

$$\eta_M = \frac{\theta}{\theta-1}\left(\epsilon_{q,p}\gamma_M - 1/\theta\right) = \frac{1}{1-\theta}\left[1 - \theta\frac{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}}{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \frac{\gamma_L}{\gamma_M}\left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}}\right] > 0, \tag{10}$$

and $\mu_h = \frac{\theta}{\theta-1}\left(\epsilon_{q,h}\gamma_M + \delta_M\right)$, $\mu_r = \frac{\epsilon_{q,r}\gamma_M\theta+1}{\theta-1} < 0$, $\mu_{E_M} = \frac{\theta}{\theta-1}\left(\epsilon_{q,E_M}\gamma_M - 1\right) < 0$, and $\mu_{w/B} = \frac{\theta}{\theta-1}\gamma_M\epsilon_{q,w/B} < 0$ (see the Appendix A for details). Inspection of the expression for η_M shows that $\eta_M < 1$ if and only if $\gamma_L > \gamma_M$. Therefore, quality growth has a smaller impact on resource use than quantity growth if and only if quality is relatively less intensive in natural resources than in the other inputs.

Taking into account that $g\left(x\right) = g\left(m\right) \cdot g\left(Y\right) - g\left(p_x\right)$, equation (9) can be reorganized to yield an expression for the growth of material productivity and the relative decoupling of GDP growth from the environmental impact:

$$\begin{aligned} g(Y/M) &= g(Y) - g(M) \\ &= -g(m) + \left(1 - \eta_M\right) g(p_x) - \eta_h g(h) - \eta_{E_M} g(E_M) - \eta_r g(r) - \eta_{w/B} g(w/B). \end{aligned} \tag{11}$$

Hence, if $\eta_M < 1$ (i.e., if the production of quality is relatively less intensive in the natural resource), then quality growth increases material productivity (Y/M) and helps GDP growth to relatively decouple from the environmental impact. Besides, decoupling is also favored by structural change reducing the share of manufacturing in GDP and by increases in the market price of the resource and technological efficiency.

3 Quality elasticities of impacts: the auto industry

3.1 Empirical strategy and data

In the following, I estimate the quality elasticities of material use and environmental impacts η_M and η_I for the automobile industry in the US. In principle, the equation to estimate would be a log-linearized version of expressions (3) and (8), which would have the same coefficients as equation (9) or (11). However, using cross-section data warrants omitting from the equation the determinants of the environmental impacts that only change over time, i.e., technological efficiency, the GDP share of the activities that have a negative environmental impact (e.g., manufacturing), and the relative price of resources and other inputs (as well as other determinants that are not explicit in these expressions, such as environmental taxes and regulation). Thus, the equation to be estimated is:

$$\log(I_i) = \alpha + \eta \log(p_i) + \mu_h h_i + u_i, \tag{12}$$

where I_i is an indicator of the environmental impact of car model i, p_i is the model's price, h_i is a vector of possible model characteristics that are unrelated to quality but can have an environmental impact and also affect the car price, and u_i is the error term. Because the quality elasticities of the environmental impacts might not be constant but change along prices, I also estimate the following quadratic version:

$$\log(I_i) = \alpha + \beta_1 \log(p_i) + \beta_2 (\log(p_i))^2 + \mu h_i + u_i. \tag{13}$$

In this case, the quality elasticity is different for each price and is given by $\eta(p) = \beta_1 + 2\beta_2 \log(p)$.

I estimate these two equations using cross-sectional data on new cars sold in the US in 2015. As indicators of the cars' environmental impact, I consider car weights (the standard proxy for material use), gas consumption, and CO2 emissions. The data on prices and weights are the manufacturer's suggested retail prices (MSRP), and the curb weights are from http://usnews.rankingsandreviews.com/cars-trucks/browse/, which lead to matched price and weight data for $1,565$ models and sub-models.[9] The same website is also the source for gas consumption and other characteristics such as being an SUV or a 4WD. There is consistent information on sales by model but not on sales by sub-model, which were col-

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[9] As an example of makes, models, and sub-models, Ford was selling 15 models in the US in 2015 (C-Max, Fiesta, Focus, Fusion, Mustang, etc.) with an average of more than five sub-models for each model, e.g., the Focus sub-models offered different combinations of sedans and hatchbacks with two different engines and some other alternative features.

lected from http://www.goodcarbadcar.net/p/downloads.html, whose original sources are automakers and ANDC (Automotive News Data Center). Matching these data on sales with those on prices and weights leads to a dataset with 242 car models (more precisely, there is information on 235 models and a few sub-models adding up to 242 observations). The price and weight considered for each of these 242 models is the simple mean of the highest and lowest price and weight across all the model's sub-models. Similarly, gas consumption is the arithmetic mean of consumption in the city and highway.[10] Finally, the data on CO2 emissions are from VCA, available at http://www.dft.gov.uk/vca/fcb/new-car-fuel-consump.asp .[11] VCA provides details on the exhaust pollution levels of most new cars on sale in the UK. The results of the CO2 emissions are reported in grams per kilometer. For this last analysis, the number of models in the analysis of emissions drops to 112.

To deal with the car non-quality characteristics that can have an environmental impact and affect car prices (which are denoted by h), there are two potential strategies. One strategy is to try to control for them in the regressions, whereas the second strategy is to instrument prices with a general predictor of the quality characteristics that is uncorrelated to h. With respect to the first strategy, it is not easy to identify car characteristics that increase a car's price but are unrelated to quality (i.e., that do not affect the general consumer willingness to pay for the car) and affect its environmental impacts. SUV and four-wheel drive features could be that type of characteristic as long as they do not affect the general consumer's willingness to pay for the car (which could happen if these characteristics are perceived as providing higher comfort and safety) but serve specific needs to particular consumers such as those living or working in rural areas or having to drive on dirt roads. Thus, in the estimations I check whether controlling for the SUV and four-wheel drive characteristics affects the results. With respect to the second strategy, I will estimate equations (12) and (13) by 2SLS using car makes as instruments for prices. Car models and sub-models are grouped into 32 makes or brands (Acura, Audi, BMW, Buick, Cadillac, etc.). The make is a key quality signal that conveys a reputation (and, thus, information) to the consumer on not-easily observable factors such as car reliability, safety, or after-sales service. In fact, car companies tend to have several makes to compete in different quality segments. These quality reputations translate into differences in price.

The identifying assumption using makes as an instrument in our estimations is that their different environmental impacts operate through their link to quality (e.g., the more reputed

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[10] I use only gasoline models as they represent the bulk of sales in the US and their data do not involve the suspicion of errors and misreporting involved in the data on gas-oil cars' emissions.

[11] VCA is an Executive Agency of the United Kingdom Department for Transport and the United Kingdom's national approval authority for new road vehicles and other vehicles. VCA provides expert international test and certification services for vehicles.

makes produce larger and more solid cars with more powerful engines and a wider series of mechanisms and accessories in order to produce cars of higher quality, all of which results in a higher consumption of materials, fuel, and greater emissions per car). SUVs and 4WDs are again possible exceptions to this assumption because there may be some makes that specialize in these types of cars. However, this exception is only relevant if the purchase of SUVs and 4WDs does not respond to seeking to increase the quality of the consumption experience (e.g., because they are perceived to be safer and more comfortable) but to specific needs and purposes (e.g., having to drive on dirty roads). At any rate, I will account for the possibility that the cited identifying assumption does not hold by controlling for SUVs and 4WDs in some estimations.

The standard errors are clustered by models in the regressions using OLS as errors are likely to be correlated within models across sub-models. In the regressions instrumenting prices with car makes, the standard errors are clustered by make.

3.2 Results

3.2.1 Quality and material use

Table 1 reports the results of estimating equations (12) and (13) using the data on prices and weights for all the 1,565 models and sub-models. The estimation method is OLS in columns 1 to 3. The standard errors are clustered by car model and are shown in parenthesis. Column 1 reports the estimates of equation (12), which results in a coefficient for log(*price*) of 0.23. Thus, a 1% increase in the car's price leads to an increase in material inputs of 0.23%.

Table 1: Car price and material use (weight) using data on $1,565$ models and sub-models

	Dependent variable is log *car weight*						
	OLS	OLS	OLS	2SLS	2SLS	2SLS	2SLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log *price*	0.23***	0.39***	3.98***	0.19***	0.28***	0.26***	5.15***
	(0.03)	(0.02)	(0.51)	(0.04)	(0.04)	(0.03)	(0.65)
(log *price*)^2			-0.18***				-0.23***
			(0.02)				(0.03)
SUV dummy						0.12***	
						(0.02)	
4WD dummy						0.05***	
						(0.01)	
Constant	5.80***	4.17***	-14.21***	6.20***	5.25***	5.41***	-20.46***
	(0.31)	(0.25)	(2.69)	(0.39)	(0.43)	(0.34)	(3.42)
Excl. if *price* > $55,000		Yes			Yes	Yes	
Observations	1,565	1,308	1,565	1,565	1,308	1,308	1,565
R-squared	0.42	0.54	0.55	0.40	0.50	0.62	0.57

Note: This table presents the results of estimating equations (12) and (13) using OLS in columns 1-3 and 2SLS in columns 4-7. In the 2SLS regressions, car log *price* is instrumented using car make and (log *price*)^2 is instrumented using the square of the predicted value of log *price* using car makes. The standard errors are clustered by car models in the OLS regressions and by car make in the 2SLS regressions. *** p-value < 0.01, ** p-value < 0.05, * p-value < 0.1.

The quality elasticity of material use need not be constant along prices. In fact, the scatter plot in Figure 2 suggests a non-linear relationship between prices and weights: the positive relationship appears to vanish for high-end cars. I follow two strategies with respect to this non-linearity. First, I repeat the previous estimations with a subsample that excludes the high-end models. Second, I estimate the specification in equation (13), which includes a quadratic term. Column (2) reports the result of excluding from the sample the cars with a price above $55000. The excluded cars represent 5% of sales in the US in 2015 (see Figure 3, which shows the cumulative distribution of sales with respect to prices). The estimated elasticity is now significantly larger, 0.39. Thus, not accounting for the non-linearity at the top of car price distribution leads to an underestimation of the quality elasticity of material use along the bulk of car models. Alternatively, to address the non-linearity of the relationship, I estimate the quadratic equation (13). The results are reported in column 3. Both the level and the quadratic terms on log(*price*) are very significant and imply a decreasing quality elasticity.

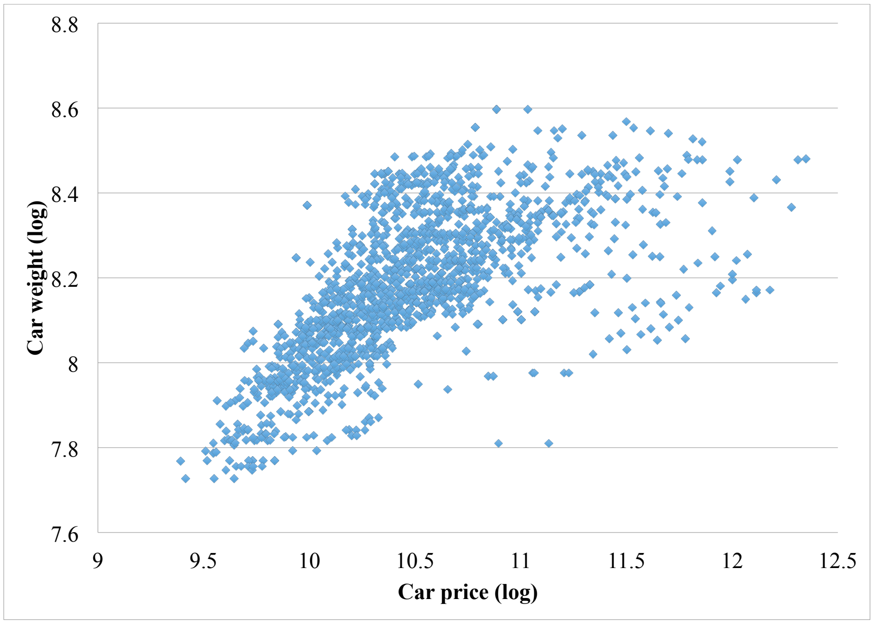

Figure 2: Car price and material use (as measured by car weight); $1,565$ car models and sub-models.

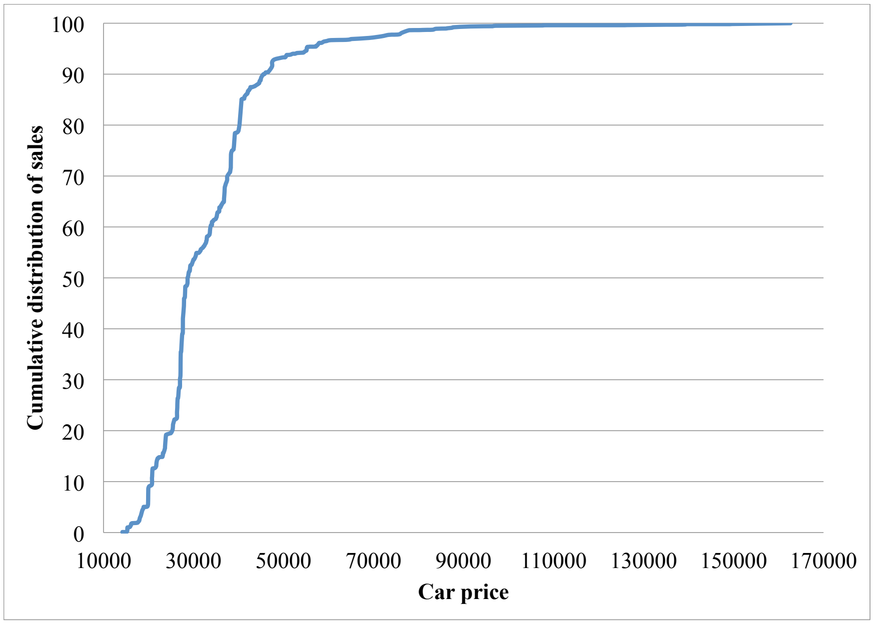

Figure 3: Cumulative distribution of car sales with respect to prices.

As already noted, a potential concern about the use of OLS to estimate equations (12) and (13) is that prices are endogenous and could be affected by non-quality car characteristics that are also responsible for some environmental impacts. If this is the case, OLS leads to biased estimates of the quality elasticity. As already indicated, I use car makes as instruments for car prices to re-estimate these equations. Car makes appear to be a good predictor of car prices. Specifically, the F-statistics of the first-stage regressions are always much above the standard benchmark of 10 (see Table 5 in Appendix B). Using data on all the models and sub-models, the F-statistic ranges between 66.7 and 40.1, depending on whether I consider the whole sample, exclude the high-end segment, or include the SUVs and 4WDs dummies.

Columns 4 to 7 in Table 1 report the results using car makes as instruments for car prices and 2SLS. Standard errors are then clustered by car make. Overall, the instrumental variable estimations lead to lower elasticities than OLS, 0.19 when considering the whole sample and 0.28 when considering only cars with a price below $\$55,000$. These lower estimated elasticities are consistent with a potential two-way positive causality between price and weight, which would introduce an upward bias in the OLS estimation. SUVs and 4WDs significantly increase the use of material inputs by 12% and 5%, respectively (column 6). However, controlling for the SUV and 4WD characteristics barely changes the estimated elasticity. Therefore, we can be confident that the overall results are not affected by whether the demand for SUVs and 4WDs is related to specific purposes or the demand for quality. In turn, column 7 shows the results of estimating the quadratic model using 2SLS. Again, both the level and the quadratic terms on $\log(price)$ are very significant, which implies a decreasing quality elasticity of material use.

Car sales in the US are not uniformly distributed across models but skewed towards the less expensive ones and, possibly, towards models with particular characteristics that could be related to their environmental impact (e.g., relatively low gas consumption). Hence, it is convenient to estimate equations (12) and (13) weighting car models by their sales, thereby adjusting the sample used in the estimation to the actual consumption of cars in the US. As noted in the data section, using the information on sales comes at the cost of reducing the dataset from the $1,565$ models and sub-models to 242 models. Missing data on sub-models could lead to an overestimation of the elasticity as the estimation ignores that consumers can upgrade car quality by moving within models along sub-models, which has little or no impact on material use. To check how important this overestimation might be, I first estimate equation (12) with the reduced number of 242 models but without weighting the data by sales. The results are in column 1 of Table 2, which shows a point-estimate of the quality elasticity of 0.29, to be compared to the 0.23 estimate in column 1 of Table 1. This result suggests that estimations using information only on models tend to slightly overestimate the quality elasticity of material use. However, using this reduced dataset and weighting observations by sales appears to be more preferable than assuming that all the car models are equally relevant. All the remaining columns in Table 2 show estimations weighted by sales using OLS in column 2 and 2SLS in the other columns.

As before, I use car makes as instruments for car prices in the 2SLS estimations. In the first-stage regressions, using the smaller sample (Table 6 in Appendix B), many of the initial car make dummy variables were not significantly different. This finding called for grouping car makes into 7 groups according to their initial estimated coefficients and then re-running these first-stage regressions. The car makes included in each group are reported in the note for Table 6. The F-statistics corresponding to these estimations range between 22.25 and 11.8. Hence, car makes are a good instrument for car prices both for the large and small sample.

Table 2: Car price and material use; weighted estimates using sales by model.

	Dependent variable is log *car weight*						
	Unweighted	Weighted by sales					
	OLS	OLS	2SLS	2SLS	2SLS	2SLS	2SLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log *price*	0.29***	0.40***	0.29***	0.36***	0.34***	8.32***	8.62***
	(0.04)	(0.05)	(0.06)	(0.10)	(0.09)	(2.48)	(2.50)
(log *price*)^2						-0.38***	-0.39***
						(0.12)	(0.12)
SUV dummy					0.10***		0.16***
					(0.03)		(0.02)
Constant	5.21***	4.03***	5.18***	4.49***	4.70***	-37.41***	-38.87***
	(0.38)	(0.53)	(0.62)	(1.07)	(0.94)	(13.19)	(13.26)
Excl. if *price* > $55,000				Yes	Yes		
Observations	242	242	242	189	189	242	242
R-squared	0.38	0.52	0.48	0.51	0.56	0.13	0.30

Note: This table presents the results of estimating equations (12) and (13) using OLS in columns 1-2 and 2SLS in columns 3-7. See Table 1 for the instruments. The standard errors are clustered by car make. *** p-value < 0.01, ** p-value < 0.05, * p-value < 0.1.

As expected, using instrumental variables, weighting the observations, and dropping the higher-end cars from the sample increases the estimated elasticity, whereas controlling for SUVs reduces it (columns 3 to 5 of Table 2). However, the differences in the instrumental variable estimates are small and range between 0.29 and 0.36. The first of these two values is the preferred estimation as it uses the data of all the models weighted by their sales and can, thus, be considered the mean quality elasticity of material use given the distribution of sales.

Columns 6 and 7 report the results of estimating the quadratic equation (13) with and without controlling for SUVs. The results are very similar in both cases. The pattern of this elasticity alongside prices can be calculated using the formula $\eta = \hat{\beta}_1 + 2\hat{\beta}_2 \log(p)$. Figure 4 depicts this pattern according to the specification without the SUV control for prices between \$20,000 and \$55,000, which represented 90% of sales. The quality elasticity of material use goes from approximately 0.8 for the cheapest cars to approximately zero for the highest-end cars.

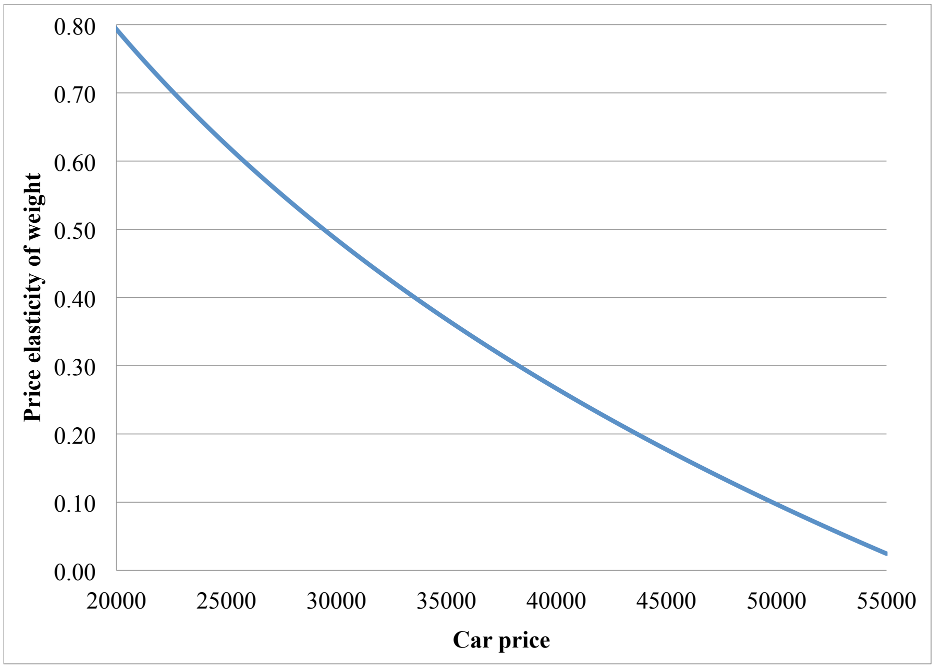

Figure 4: Car price elasticities of material use. The figure is based on the sales-weighted 2SLS estimates reported in column 6 of Table 2, using the formula $\eta = \hat{\beta}_1 + 2\hat{\beta}_2 \log(price)$.

To summarize, the estimated quality elasticity of material consumption using instrumental variables and accounting for the distribution of car sales is largely and robustly below 1 as its value ranges between .29 and .36. Hence, quality growth is substantially less intensive in resource use than quantity growth and, therefore, the shift from quantity to quality growth helps material productivity and growth sustainability .[12] Moreover, the elasticity decreases along prices, which suggests that the average elasticity (weighted by the distribution of sales) will tend to decrease as economies become richer.

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[12] The expression (11) for material productivity can be calibrated to illustrate how much quality growth might increase material productivity. For example, assuming a contribution of quality growth to GDP growth of 1% (which would be in line with the evidence for the US cited in the Introduction) and a quality elasticity of material consumption of 0.3, then the cited expression implies that quality growth annually raises material productivity by 0.7 percentage points (as opposed to the zero contribution of quantity growth).

3.2.2 Quality and gas consumption

Table 3 reports the results of estimating equations (12) and (13) using gas consumption (miles per gallon, MPG) as the environmental impact indicator. Columns 1 and 2 report the results corresponding to unweighted estimations using the dataset for all the models and sub-models (the information on gas consumption is missing for some sub-models, which reduces the sample from $1,565$ to $1,542$ observations). In turn, columns 3 to 7 report the results corresponding to sales-weighted estimations, which use the information on 213 models. Columns 1 and 3 report the results using OLS, whereas the remaining columns report 2SLS estimations using car makes as instruments for car prices. The estimated quality elasticities are always negative, indicating that higher-quality (more expensive) cars tend to travel fewer miles per gallon and, thus, consume more gas. The estimated absolute value of the elasticity ranges between 0.18 and 0.31. As before, using instrumental variables reduces the estimated elasticity (in absolute terms), whereas sales-weighted estimations and the exclusion of the high-end cars increase the elasticity. Controlling for SUVs barely changes the results. The preferred estimation of the mean quality elasticity of gas consumption is that in column 4 (reporting an elasticity of -0.21), which corresponds to the instrumental variable estimation weighting observations by the distribution of car sales.

Table 3: Car price and environmental impact as measured by gas consumption (MPG)

	Dependent variable is log *Miles Per Gallon*						
	Unweighted		Weighted by sales				
	OLS (1)	2SLS (2)	OLS (3)	2SLS (4)	2SLS (5)	2SLS (6)	2SLS (7)
log *price*	-0.26***	-0.18***	-0.31***	-0.21***	-0.28***	-0.27***	-7.78**
	(0.02)	(0.02)	(0.07)	(0.08)	(0.11)	(0.10)	(3.60)
(log *price*)^2							0.36**
							(0.17)
SUV dummy						-0.09***	
						(0.03)	
Constant	5.97***	5.17***	6.49***	5.44***	6.17***	6.12***	45.61**
	(0.17)	(0.25)	(0.67)	(0.82)	(1.12)	(1.06)	(19.18)
Excl. if *price* > $55,000					Yes	Yes	
Observations	1,542	1,542	213	213	161	161	213
R-squared	0.41	0.38	0.37	0.33	0.39	0.45	0.08

Note: This table presents the results of estimating equations (12) and (13) using OLS in columns 1 and 3 and 2SLS in columns 2 and 4-7. See Table 1 for the instruments. The standard errors are clustered by car model in column 1 and by car make in the remaining columns. *** p-value < 0.01, ** p-value < 0.05, * p-value < 0.1.

As with material use, the (absolute value of the) quality elasticity of gas consumption tends to decrease with quality. Figure 5 depicts this elasticity's profile along prices using the results from the quadratic specification reported in column 7 of Table 3, which includes a control for SUVs (the coefficients were not statistically significant when omitting this control). The elasticity goes from -0.65 to 0.10. Thus, as we move towards high-end cars, gas consumption does not increase but eventually stabilizes and can even decrease. Hence, as with material use, quality growth in the automobile industry has a substantially smaller environmental impact than quantity growth and will tend to decrease as societies become richer.

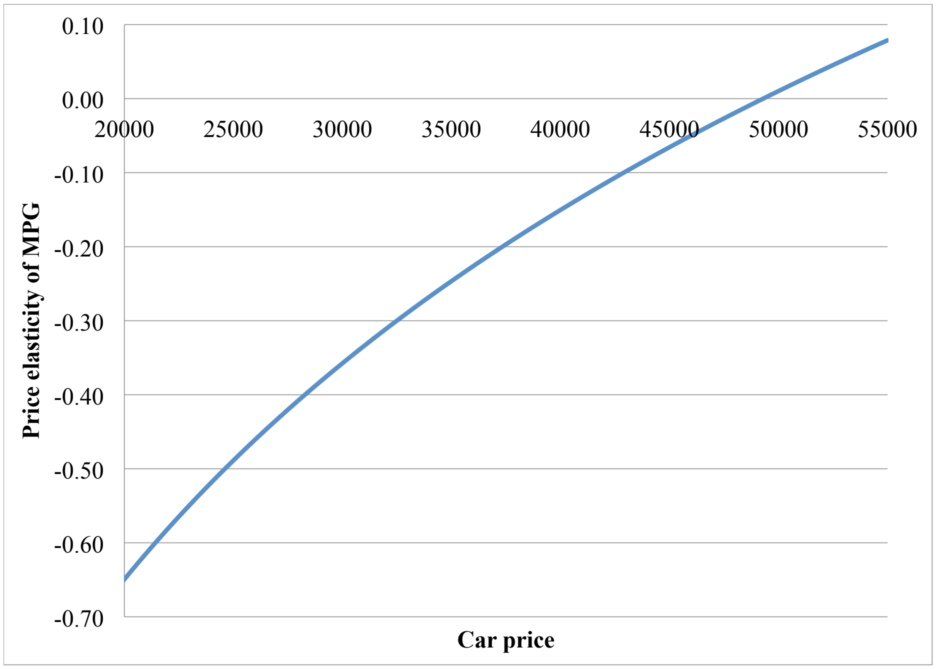

Figure 5: Car price elasticities of gas consumption (MPG). The figure is based on the 2SLS estimates reported in column 7 of Table 3 .

3.2.3 Quality and CO2 emissions

CO2 emissions represent the third dimension of the environmental impact of cars I consider. Data limitations lead to a sample of matched emissions and price data with 112 car models. Table 4 reports the results of estimating equations (12) and (13) for carbon emissions. As in Table 3, Table 4 reports the results of estimating by OLS as well as by 2SLS (again, using car makes as instruments) and, alternatively, not weighting and weighting each model's observation by sales. Again, using instrumental variables reduces the estimated quality elasticity, whereas weighting by sales and excluding the high-end cars from the sample raises the elasticity. The point estimates of the mean quality elasticity of CO2 emissions range between 0.22 and 0.39, with 0.22 being the preferred estimation as this value corresponds to the results using instrumental variables and weighting by sales. As with the previous environmental impact measures, the quality elasticity of carbon emissions tends to decrease with prices. In fact, this elasticity even becomes negative at the high-end segment, see Figure 6. Lower gas consumption and carbon emissions are considered quality characteristics by an increasing portion of consumers, which is consistent with the pattern that was also found in (5). If this portion of consumers becomes the majority in the future, then the relationship between car quality and gas consumption and carbon emissions could turn negative.[13] In such a case, quality growth would not only lead to relative decoupling but to absolute decoupling. However, the current distribution of sales in the US is still far from approaching this outcome.

Table 4: Car price and CO2 emissions.

	Dependent variable is log *CO2 emissions*					
	Unweighted	Weighted by sales				
	OLS (1)	OLS (2)	2SLS (3)	2SLS (4)	2SLS (5)	2SLS (6)
log *price*	0.34***	0.39***	0.22***	0.26**	0.22*	11.68**
	(0.03)	(0.07)	(0.07)	(0.13)	(0.13)	(5.26)
(log *price*)^2						-0.54**
						(0.25)
SUV dummy					0.20	0.24**
					(0.12)	(0.10)
Constant	1.57***	1.15	2.85***	2.46*	2.85**	-57.94**
	(0.34)	(0.70)	(0.79)	(1.33)	(1.33)	(27.70)
Excl. if *price* > $55,000				Yes	Yes	
Observations	112	112	112	77	77	112
R-squared	0.51	0.38	0.31	0.27	0.38	0.34

Notes: This table shows the results of estimating equations (12) and (13) using OLS in columns 1-2 and 2SLS in columns 3-6. See Table 1 for the instruments. The standard errors are clustered by car make. *** p-value < 0.01, ** p-value < 0.05, * p-value < 0.1.

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[13] Hybrid and electrical cars are more efficient in terms of energy use and CO2 emissions and tend to be more expensive than non-hybrid cars with otherwise similar characteristics. However, hybrid and electrical cars represented less than 3% of car sales in the US in 2015. The expected increase in these cars' share in total sales in the future will likely reduce the quality elasticity of gas consumption and CO2 emissions and make possible of a negative quality elasticity of environmental impacts.

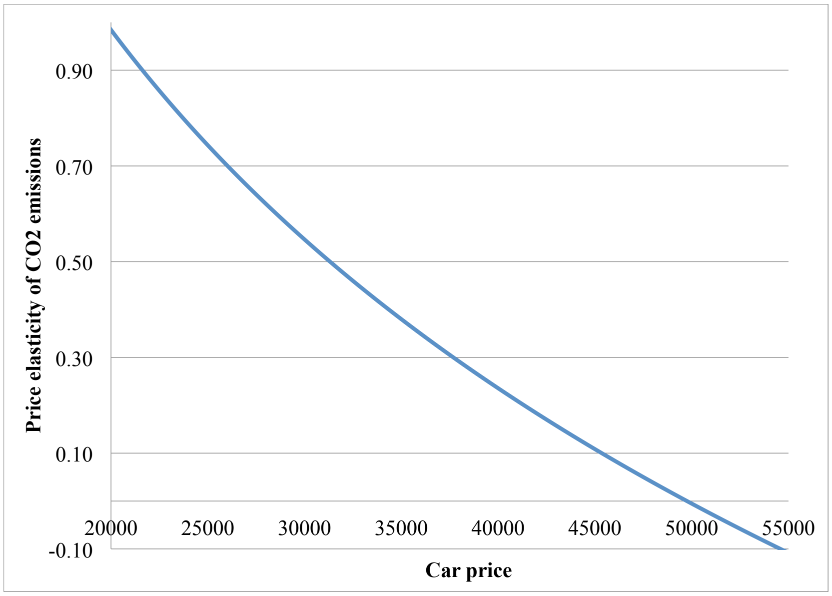

Figure 6: Car price elasticities of CO2 emissions. The figure is based on the 2SLS estimates reported in column 6 of Table 4.

4 Concluding remarks

The quantity-quality composition of GDP growth is an important factor determining material use and environmental impacts. While quantity growth has an almost unavoidable physical dimension that leads to resource depletion and environmental impacts, the key ingredients of quality growth are knowledge and skilled labor, which do not necessarily generate those impacts. This paper (i) introduced a parsimonious and tractable analytical framework that separates the environmental impacts of quantity and quality growth and identifies the key quality parameter to be estimated, and (ii) conducted an empirical assessment of this parameter for an illustrative and important case, namely, the automobile industry. According to the preferred estimations (using sales-weighted 2SLS), the mean quality elasticities of material use, gas consumption, and carbon emissions are 0.29, 0.21, and 0.22, respectively. Other estimates using different samples and estimation methods lead to similar results. Those elasticities are to be compared with the unitary elasticity of the environmental impacts with respect to quantity growth (for any given constant technology). Moreover, the quality elasticities tend to decrease with quality and, therefore, are likely to be further reduced as countries grow richer.

These results indicate that the gradual shift in developed economies from quantity to quality growth positively affects the long run sustainability of economic growth. At any rate, the ultimate goal of sustainability is the absolute decoupling of growth, whereas quality growth may only help relative decoupling. From this perspective, quality growth is not a panacea but only one of the factors that can contribute to reduce environmental impacts growth.

The arguments and findings in the paper are consistent with the evidence of an increasing material productivity in richer countries and can help explain the *EKC* linking resource use and environmental impacts intensities to income. These intensities rise when a growing number of households in developing economies start consuming an increasing number of manufactured goods and decline when households in developed economies start to become satiated in terms of quantities (per unit of time) and reorient their consumption expenditure towards quality upgrades. The fact that quality elasticities decrease with quality (as found for the automobile industry) implies that increasing economic wealth will tend to further reduce the environmental impact of quality growth in the future. However, this decreasing pattern also suggests that the mean quality elasticities are likely to be larger in economies that are poorer than the US.

A general assessment of the environmental implications of the gradual shift from quantity to quality growth in developed economies will require detailed empirical work on a wide range of products. The empirical analysis in this paper using the automobile case is meant only to provide an illustrative case of the distinct environmental impact of quality growth. Automobiles are a particularly important consumption good both in terms of share in consumers' expenditures and environmental impact. In the automobile industry, producing higher quality tends to imply larger and heavier cars and, therefore, a greater consumption of materials and energy as well as higher emissions. However, the additional inputs needed to produce higher quality in many other industries appear to be almost exclusively highly skilled labor (which is used to improve technology and design). Hence, it seems reasonable to conjecture that the quality elasticities found in this paper for the automobile industry are an upper bound for the average elasticity across all sectors and industries in developed economies.

In the paper, economic growth is identified with GDP growth. However, GDP is not a fully satisfactory measure of an economy's net output because it does not account for, among other things, environmental externalities or the depletion of free natural resources. In which direction would the conclusions of this paper change if we had a better measure of the economy's net output? A more accurate measure would likely lead to a lower measured output and growth. However, because quality is less intensive than quantity in environmental impacts, the costs and externalities that are being ignored are likely to be smaller whenever the quality dimension of output is more important. Therefore, the difference between GDP and the *true* net output (and their rates of growth) would likely be smaller the larger the quality component is. This circumstance would reinforce further the importance of favoring quality over quantity growth.

Monitoring and accelerating the process of decoupling economic activity form material consumption and environmental impacts will require better projections and policies. The distinct impact of quantity and quality growth cannot be ignored in this respect. Moreover, the distinction between the quantity and quality dimensions of output can help set some specific problems and policies in a broader context. Phenomena such as planned obsolescence and the reduced consumer information per product caused by the current large global markets result in products with shorter lifespans, which reduce quality growth and increase environmental impacts. Policies improving consumer information and quality standards would help combat these phenomena by favoring quality over quantity growth and improve economic growth sustainability.

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Appendix A: The quality elasticities of the price function

Taking logarithms in expression (7) and fully differentiating yields:

$$\frac{dp_x}{p_x} = \epsilon_{p,q}\frac{dq}{q} + \epsilon_{p,h}\frac{dh}{h} + \epsilon_{p,r/E_M}\frac{d\left(r/E_M\right)}{r/E_M} + \epsilon_{p,w/B}\frac{d\left(w/B\right)}{w/B}.$$

where

$$\epsilon_{p,q} = \gamma_M \frac{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \frac{\gamma_L}{\gamma_M}\left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}}{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}},$$

$$\epsilon_{p,h} = \delta_M \frac{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \frac{\delta_L}{\delta_M}\left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}}{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}},$$

$$\epsilon_{p,r} = -\epsilon_{p,E_M} = \frac{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)}}{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}} < 1,$$

$$\epsilon_{p,w/B} = \frac{\left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}}{\left(q^{\gamma_M} h^{\delta_M} \frac{r}{E_M}\right)^{\theta/(\theta-1)} + \left(q^{\gamma_L} h^{\delta_L} \frac{w}{B}\right)^{\theta/(\theta-1)}} < 1.$$

Therefore, we have: $\epsilon_{qp} = 1/\epsilon_{pq} > 0$, $\epsilon_{qh} = -\epsilon_{ph}/\epsilon_{pq} < 0$, $\epsilon_{qr} = -\epsilon_{qE_M} = -\epsilon_{pr}/\epsilon_{pq} = \epsilon_{pE_M}/\epsilon_{pq} < 0$, and $\epsilon_{q,w/B} = -\epsilon_{p,w/B}/\epsilon_{pq} < 0$. Hence, $\mu_r = \frac{\epsilon_{q,r}\gamma_M\theta+1}{\theta-1} < 0$, $\mu_{E_M} = \frac{\theta}{\theta-1}\left(\epsilon_{q,E_M}\gamma_M - 1\right) < 0$, and $\mu_{w/B} = \frac{\theta}{\theta-1}\gamma_M\epsilon_{q,w/B} < 0$.

Appendix B: First-stage regressions

Table 5: Large sample (1,565 models and sub-models)

	Dependent variable is log *car price*		
	(1)	(2)	(3)
Make = 2	-0.80***	-0.45***	-0.44***
	(0.09)	(0.07)	(0.06)
Make = 3	-0.61***	-0.27***	-0.26***
	(0.08)	(0.06)	(0.06)
Make = 4	-0.65***	-0.41***	-0.39***
	(0.06)	(0.05)	(0.05)
Make = 5	-0.80***	-0.47***	-0.59***
	(0.06)	(0.05)	(0.05)
Make = 6	0.00	0.23	0.28
	(0.23)	(0.23)	(0.22)
Make = 7	-1.09***	-0.74***	-0.69***
	(0.09)	(0.07)	(0.07)
Make = 8	-0.41***	-0.06	-0.10
	(0.09)	(0.07)	(0.07)
Make = 9	-0.61***	-0.26***	-0.31***
	(0.07)	(0.05)	(0.05)
Make = 10	-0.20***	0.06	0.05
	(0.05)	(0.05)	(0.05)
Make = 11	-0.70***	-0.57***	-0.57***
	(0.05)	(0.04)	(0.04)
Make = 12	-0.55***	-0.20***	-0.32***
	(0.08)	(0.06)	(0.06)
Make = 13	-0.36***	-0.05	-0.09*
	(0.07)	(0.06)	(0.05)
Make = 14	-0.82***	-0.47***	-0.47***
	(0.05)	(0.04)	(0.04)
Make = 15	-0.87***	-0.56***	-0.58***
	(0.06)	(0.05)	(0.04)
Make = 16	-0.88***	-0.55***	-0.56***
	(0.05)	(0.05)	(0.04)
Make = 17	0.25***	0.16	0.20
	(0.08)	(0.23)	(0.22)
Make = 18	-0.04	-0.00	-0.07
	(0.09)	(0.11)	(0.10)
Make = 19	-0.89***	-0.54***	-0.54***
	(0.06)	(0.05)	(0.04)
Make = 20	0.10*	0.03	0.07
	(0.05)	(0.06)	(0.06)
Make = 21	-0.94***	-0.60***	-0.67***
	(0.08)	(0.06)	(0.06)
Make = 22	-0.30***	0.01	-0.03
	(0.06)	(0.05)	(0.05)
Make = 23	-0.70***	-0.42***	-0.43***
	(0.05)	(0.04)	(0.04)
Make = 24	-0.90***	-0.55***	-0.53***
	(0.06)	(0.05)	(0.05)
Make = 25	-0.18***	-0.03	-0.08
	(0.06)	(0.06)	(0.06)
Make = 26	-0.75***	-0.41***	-0.41***
	(0.05)	(0.04)	(0.04)
Make = 27	-0.78***	-0.43***	-0.43***
	(0.05)	(0.04)	(0.04)
Make = 28	-0.10**	-0.02	-0.05
	(0.05)	(0.04)	(0.04)
Make = 29	0.54***	0.18	0.15
	(0.06)	(0.14)	(0.13)
Make = 30	-0.78***	-0.43***	-0.40***
	(0.04)	(0.04)	(0.04)
Make = 31	-0.38***	-0.04	-0.09**
	(0.05)	(0.04)	(0.04)
Make = 32	0.33**		
	(0.16)		
SUV dummy			0.11***
			(0.02)
4WD dummy			0.11***
			(0.02)
Constant	11.01***	10.66***	10.62***
	(0.03)	(0.03)	(0.03)
Excl. if *price* > $55,000		Yes	Yes
Observations	1,565	1,308	1,308
R-squared	0.57	0.49	0.54
F-statistic	66.7	40.1	46.1

Table 6: Small sample (242 models)

	Dependent variable is log *car price*		
	(1)	(2)	(3)
Group B makes dummy	-0.72***		
	(0.18)		
Group C makes dummy	-1.18***	-0.45***	-0.42***
	(0.14)	(0.12)	(0.12)
Group D makes dummy	-1.00***	-0.33***	-0.32***
	(0.12)	(0.11)	(0.11)
Group E makes dummy	-1.10***	-0.44***	-0.44***
	(0.12)	(0.11)	(0.11)
Group F makes dummy	-0.51***	-0.05	-0.07
	(0.12)	(0.11)	(0.10)
Group G makes dummy	-1.39***	-0.67***	-0.63***
	(0.28)	(0.20)	(0.20)
Group H makes dummy	-1.28***	-0.56***	-0.57***
	(0.15)	(0.12)	(0.12)
Group I makes dummy	-1.02***	-0.35***	-0.35***
	(0.14)	(0.12)	(0.12)
Group J makes dummy	-0.98***	-0.31**	-0.28**
	(0.16)	(0.13)	(0.13)
SUV dummy			0.12***
			(0.04)
Constant	11.38***	10.66***	10.62***
	(0.11)	(0.10)	(0.10)
Excl. if *price* > $55,000		Yes	Yes
Observations	242	190	190
R-squared	0.46	0.34	0.38
F-statistic	22.25	11.8	12.02

Note: Makes included in each group. Group A (omitted dummy variable in column 1): Jaguar, Porsche, Tesla; group B (omitted dummy variable in columns 2 and 3 because there are no cars of group A below $55,000): Volvo; group C: Mini, Subaru; group D: Chrysler, Dodge, Ford, Buick, Chevrolet; group E: Honda, Hyundai, Kia, Nissan, Jeep; group F: BMW, Alfa Romeo, Lincoln, Cadillac, GMC, Acura, Land Rover, Mercedes-Benz, Infiniti, Lexus, Audi; group G: Fiat; group H: Mazda, Mitsubishi; group I: Toyota; group J: Volkswagen.

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