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# ENVIRONMENTAL ENGEL CURVES

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**ABSTRACT**

Environmental Engel curves (EECs) plot the relationship between households' incomes and the pollution embodied in the goods and services they consume. They provide a basis for estimating the degree to which observed environmental improvements, which come in part from changing consumption patterns, can be attributed to income growth. We calculate a set of annual EECs for the United States from 1984 to 2002, revealing three clear results. First, EECs are upward sloping: richer households are indirectly responsible for more pollution. Second, EECs are convex, with income elasticities of less than one. Third, EECs have been shifting down over time: at every level of income households are responsible for decreasing amounts of pollution. We show that even without changes to production techniques, the pollution necessary to produce the goods and services American households consume would have declined 5 to 8 percent, despite a 13 percent increase in real household incomes. Most of this improvement is attributable to households consuming a less pollution-intensive mix of goods, driven about equally by two factors: household income growth represented by movement along convex EECs; and economy-wide changes represented by downward shifts in EECs.

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## Introduction

This paper presents the first estimates of household-level environmental Engel curves (EECs), which show the relationship between households' incomes and the amount of pollution embodied in the goods and services those households consume. Traditional Engel curves plot relationships between income and consumption of particular goods or services. They are named for Ernst Engel, a German economist writing in the mid-1800s who studied the degree to which household food expenditures increase with income. Engel curves have since been applied to many different categories of consumption and form the basis for "equivalence scales" that are used to determine eligibility for means-tested entitlements, such as food stamps and Medicaid.

Environmental Engel curves describe how households' pollution changes with income. This calculation is less straightforward than it is for traditional Engel curves, because households generate pollution not only directly as a consequence of their activities such as driving cars, but also indirectly as a consequence of consuming products whose production generates pollution, such as manufacturing the rubber and steel used to make those cars and refining the gasoline used to fuel them. We focus on this larger and less studied component, the indirect pollution generated to produce the goods and services households consume.

Why is this important? Over the past 30 years, total pollution emitted by U.S. producers has declined considerably, even though the real value of U.S. production has increased.[1] Some of this improvement has come from employing cleaner production technologies in cars and factories, but much of it comes as a result of consuming a cleaner mix of goods—more computers and services and less steel and cement. A key question is whether this cleaner consumption has been a consequence of economy-wide trends, such as regulation-induced increases in the prices of polluting goods, or an underlying and possibly coincidental preference by richer households for cleaner goods.

Some analysts have pointed to the improvements in the United States and other developed countries as evidence that richer countries automatically pollute less, implying that economic growth alone will improve the environment.[2] But rich countries might have less

[1] From 1980 to 2012, emissions of carbon monoxide and sulfur dioxide declined by roughly 80 percent, ground-level ozone by 25 percent, and nitrogen dioxide by 60 percent, even though real GDP and real personal consumption expenditures more than doubled (U.S. Environmental Protection Agency, 2014; FRED, 2014a and 2014b).
[2] For example, John Tierney wrote in the *New York Times* in 2009 that "the richer everyone gets, the greener the planet will be in the long run" ("Use Energy, Get Rich and Save the Planet," April 20). And Bruce Bartlett wrote in

pollution because they enact strict environmental regulations—or because they outsource polluting industries to poor countries.

To consider these possibilities systematically, economists have parsed the relationship between economic growth and pollution into three components: scale, technique, and composition (Grossman and Krueger, 1993; Copeland and Taylor, 2005). The scale component merely describes a proportional increase in economic activity—if the economy doubled in size, the scale effect would double pollution. The technique component describes changes to the pollution intensity of any particular activity. Refining a barrel of petroleum creates less pollution today than 30 years ago because refineries have more abatement equipment. And the composition component describes changes to the mix of activities that compose the economy.

We focus on this third component. The composition effect could arise for two reasons: changes in the mix of goods produced or consumed. U.S. households could consume the same mix of goods and services over time, but an increasing share of the pollution-intensive ones could be imported rather than produced domestically. Or households could consume a less polluting mix. Since our interest is to separate the effects of regulation-induced price changes from coincidental preferences of richer households for cleaner goods, we study this second possibility, shifting household consumption. We ask how much of that shift is merely due to the fact that households today are on average richer than they were 30 years ago—a movement *along* an EEC—and how much is due to changes in the mix of goods consumed by all households, holding incomes constant—a *shift* in the EEC.

One approach to estimating these EECs would be to compare pollution, income, and consumption choices across countries at a point in time or across time within a country, similar to the way environmental Kuznets curves (EKSs) have been estimated.[3] But EKCs are simply conditional correlations, without meaningful interpretations other than that pollution does not necessarily increase with economic growth. EECs, on the other hand, are meant to be structural, representing income expansion paths holding individuals' preferences and all else equal. EECs based on comparisons across countries or over time would be difficult because prices and characteristics of available goods change. Richer countries might pass regulations making

the *Wall Street Journal* in 1994 that "existing environmental regulation, by reducing economic growth, may actually be reducing environmental quality" ("The High Cost of Turning Green," September 14).

[3] The EKC refers to the representation—typically as an inverted U shape—of the aggregate relationship between pollution and national income. See for example, Grossman and Krueger (1995) or Hilton and Levinson (1998).

pollution-intensive goods costlier or less desirable, causing households to consume proportionally less of them. That difference would not be interpretable as the slope of an Engel curve because it would not represent the change in consumption that results from a ceteris paribus change in income.

Instead, our approach compares pollution, income, and consumption across U.S. households and repeats the analysis separately each year from 1984 to 2002. Households within a given year each face the same relative prices, available products, and environmental regulations. In each year, we combine production-side pollution intensity data with detailed information on household consumption to calculate the total pollution created as a result of producing the goods and services that each household consumes. Plotting that indirect pollution against those households' incomes yields a set of annual EECs.

We find that EECs display three key characteristics. First, not surprisingly, EECs are upward sloping, reflecting that richer households are responsible for more overall pollution. Second, EECs are concave, indicating that although pollution increases with income, it does so at a decreasing rate. And third, EECs shift down over time, meaning that for any level of real household income, households in later periods consume a less polluting mix of goods. Between 1984 and 2002 real household incomes in the Consumer Expenditure Survey (CEX) grew by 13 percent, while the predicted pollution necessary to produce the goods those households consumed decreased by 5 to 8 percent.[4]

This reduction in pollution per dollar of expenditures at the household level must come from one of two phenomena: either richer households consume a less pollution-intensive mix of goods holding all else equal—a movement along a concave EEC—or households consumed fewer polluting goods in 2002 than did households with the same real incomes in 1984—a downward shift in the EECs. We show that the decline in pollution per dollar was about evenly split between these two effects.

## Data and Methods

Estimating EECs requires information on household income and the pollution attributable to each household's consumption. Since we are focusing on indirect pollution, we estimate the

[4] Gertler et al. (2013) show that demand for energy-using assets such as refrigerators increases less than proportionally with income in Mexico, which means that Engel curves for energy may be concave. But their data cannot reveal whether those curves shift up or down over time as the country develops.

amount of pollution that was created in order to produce the specific goods and services consumed by each individual household in our sample, using information from the Consumer Expenditure Survey (CEX) and the Trade and Environmental Assessment Model (TEAM).

The CEX is collected each quarter by the Census Bureau on behalf of the U.S. Bureau of Labor Statistics and provides detailed information on itemized household consumption expenditures. It contains a nationally representative sample of roughly 7,000 households selected on a rotating panel basis.[5] Households are tracked for five consecutive quarters, over which they provide information on a wide range of expenditures, income, and other demographics. Expenditure and income data in the CEX interviews are organized into approximately 700 separate universal classification codes (UCC) and capture around 80 to 95 percent of total household expenditures.[6]

Each round of CEX contains households from every stage of the five-quarter interview process. These data have been combined and extracted into a publicly available, user-friendly format by the National Bureau of Economic Research (NBER, 2000). These extracts consolidate records across interview rounds and provide a single record for each household showing annual expenditure values. In addition, the roughly 700 UCC codes are collapsed into 109 spending and income categories that remain consistent across all sample rounds. Of these expenditure categories, 47 correspond to various goods and services, while the remaining categories cover income, taxes and transfers, and measures of wealth. These consolidated data form the starting place for our investigation.

We pair the NBER CEX extracts with pollution intensity data from the TEAM, which provides the pollution intensity of production for various goods and services. The TEAM framework was originally developed for the U.S. Environmental Protection Agency to study the environmental consequences of U.S. trade policies, but the model can be used to assess any

[5] The CEX is organized based on consumer units, rather than households. A consumer unit is smaller than a household and consists of “(1) All members of a particular household who are related by blood, marriage, adoption, or other legal arrangements; (2) a person living alone or sharing a household with others or living as a roomer in a private home or lodging house or in permanent living quarters in a hotel or motel, but who is financially independent; or (3) two or more persons living together who use their incomes to make joint expenditure decisions” (U.S. Bureau of Labor Statistics, 2008). For convenience the U.S. Bureau of Labor Statistics occasionally treats the terms “households” and “consumer units” interchangeably, and we follow suit.

[6] The interview survey collects detailed data covering 60 to 70 percent of household expenditures, along with global estimates each period for food and related items that capture an additional 20 to 25 percent of expenditures. For detailed information on the CEX, UCC codes, and the structure of the survey, see U.S. Bureau of Labor Statistics (2008).

change in economic activity (Abt Associates Inc., 2009). TEAM has as its core a list of emissions intensities by six-digit North American Industry Classification System (NAICS) codes. For each of more than 1,000 industries, TEAM reports the amount of pollution emitted per dollar of industrial output.

The TEAM data indicate the pollution generated during the production process of each good directly, but we also want to consider pollution from production of the inputs to those goods. For example, if a household purchases a sofa, we would want to know not only the pollution emitted while manufacturing of the sofa itself but also the pollution from tanning the leather for its upholstery, milling the wood for its frame, and manufacturing the steel for its springs. Moreover, each of those inputs also required their own inputs, which also resulted in pollution. To fully capture the total pollution associated with each household's consumption, we want to include pollution from manufacturing the products consumed, inputs to those products, and inputs to those inputs ad infinitum up the supply chain.

Upstream pollution from the entire chain of inputs for each item can be estimated using a Leontief (1970) analysis based on the input-output (IO) tables published by the U.S. Bureau of Economic Analysis. These tables show the dollar amount of each input necessary to produce a dollar's worth of output for every other industry. Using the IO tables, we transform the TEAM emissions intensities into measures that include the pollution to manufacture each final product, all of its inputs, the inputs to those inputs, and so on.[7]

Using these total pollution intensity coefficients combined with the CEX, we estimate the total amount of pollution created in order to produce each of the goods consumed by every household in the survey. Adding up pollution for all items within a household gives the total amount of pollution attributable to the consumption of each household. As a last step, we exclude any households with incomplete or partial-year income reporting and drop the top and bottom 1 percent of households based on total expenditures to account for top-coding in the CEX survey. The final result is a sample of 57,704 households spread across 19 annual cross sections from 1984 to 2002, in which each household has an estimated total pollution associated with its

[7] See Leontief (1970) for the original, Levinson (2009) for a more recent application, or Miller and Blair (1985) for a textbook explanation.

expenditures.[8] We begin by focusing on particulate matter smaller than 10 microns (PM10) because of its significant public health consequences and importance to cost-benefit analyses, but we also show similar results for other major local air pollutants. Table 1 shows mean values for indirect pollution, income, and other variables for 1984 and 2002.

A few points are worth detailing here. First, because the CEX and TEAM use different industry definitions, we manually created a concordance to match consumption items in the CEX with the pollution intensity of industries in the TEAM. Since the TEAM coefficients (based on NAICS codes) have more categories than the CEX, most CEX codes were matched to several NAICS categories. We calculated the weighted average pollution intensity based on total output for each NAICS code.[9]

A second point involves our treatment of technology. One of the important changes explaining the decline in pollution in the United States has been technological change, or the technique effect.[10] But since here we are interested in the income-driven composition effect—the income–pollution relationship holding all else constant—one of the factors we hold constant is technology. We apply the same 1997 TEAM emissions intensities to all cross sections of consumption data, regardless of year, essentially calculating the predicted pollution generated to manufacture households' consumption choices, but holding constant the pollution intensity of that production at 1997 levels.

A third issue concerns international trade. One possible explanation for the decline in U.S. pollution could be imports.[11] If the United States imports more of the pollution-intensive goods its residents consume, domestic pollution could decline with no change in consumption. But once again, we want to hold changes in trade patterns constant. By using the U.S.-based 1997 TEAM coefficients for every year, we calculate the pollution that would have occurred each year if all goods had been manufactured domestically using 1997 technology.

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[8] We exclude CEX rounds prior to 1984 because this is the first year with integrated diary and interview data, and the first year with both urban and rural households included (See U.S. Bureau of Labor Statistics 2014). The year 2002 is the most recent CEX round with all four quarters available as NBER extracts.

[9] The NAICS was developed jointly by the United States, Mexico, and Canada to classify industries based on similarities in production processes. The UCCs used in the CEX categorize goods based on similarities in consumption patterns. A separate data appendix is available from the authors describing the matching between NAICS and CEX categories.

[10] See Levinson (2009) or Shapiro and Walker (2015).

[11] Brunel (2014) shows that this international trade component is small.

Although the mechanics involved with estimating indirectly generated household pollution has been complex, several aspect of EECs make their estimation simpler than traditional Engel curves. For one, estimates of traditional Engel curves must account for the obvious endogenity of income and consumption. Both income and consumption are at least partly choice variables, so it is not clear whether people choose the goods they consume based on their incomes or choose their incomes in order to purchase the goods they desire to consume. Estimating traditional Engel curves therefore involves tricky issues of identification (Blundel et al., 2007). But with EECs, we believe we are safe assuming people do not concern themselves with the pollution indirectly generated to produce the goods and services they desire when choosing how hard to work or what jobs to take. The pollution might affect their choice of goods if they are environmentally conscious but probably not their level of income. Income is thus arguably exogenous with respect to the pollution content of household consumption.

A second challenge to estimating traditional Engel curves is determining the appropriate degree of aggregation. Demand for narrow categories can vary widely across households and over time, making patterns difficult to discern. But broader categories may combine inferior and normal goods and mask the shapes of the underlying Engel curves. The Engel curve for beef may be ambiguously shaped if hamburger is a necessity and steak a luxury. When estimating EECs, however, the overall pollution created indirectly as a result of each household's consumption matters, not the specific consumption of individual goods or services.

One challenge that applies equally to ordinary and environmental Engel curves involves prices and quality. If richer households purchase more expensive, higher quality goods, they may spend more on those goods without consuming larger physical quantities or being responsible for more pollution. Because we estimate pollution by multiplying itemized expenditures by per-dollar pollution intensity coefficients, expensive items are assigned more pollution than inexpensive items. For example, if rich and poor households each purchase one bottle of wine, but the rich households' wine is pricier, our EECs will falsely attribute more pollution to the rich households even if both bottles were produced in the same manner. This results in a bias against finding that EECs are concave. Any concavity we find in those EECs and any share of the cleanup we attribute to that concavity can thus be interpreted as a conservative estimate.

**Nonparametric Estimates of Environmental Engel Curves**

No theory dictates the form of the income-pollution relationship, so we begin by examining the shape and structure of the EECs with as few restrictions as possible.[12] We first separate households in the 1984 cross section of the CEX into 50 groups based on income, where each group represents 2 percent of the overall 1984 income distribution. Then we calculate the average level of pollution associated with households' consumption within each group. Plotting these 50 points with income on the horizontal axis and pollution on the vertical axis yields a non-parametric EEC for 1984. This EEC for PM10 is shown as the top line in Figure 1. Average pollution is calculated using 1997 TEAM coefficients, so this EEC represents the pollution associated with household consumption in 1984 if all goods and services were produced in the United States using 1997 production technology. A household in the 25th income bin ($32,128 to $33,999, measured in 1997 dollars) would have been indirectly responsible for an average of 147 tons of PM10.

To observe how the EEC relationship may be evolving over time, Figure 1 also depicts a second EEC estimated using the 2002 CEX paired with the 1997 TEAM coefficients. In order to keep the two curves directly comparable, we use the same income bin cutoff values in the 2002 EEC as are used in the 1984 EEC.[13] Households with income in 2002 between $32,128 and $33,999 would have been indirectly responsible for 132 tons of PM10 on average, 15 fewer tons than households earning the same income in 1984.

Three phenomena are apparent from the set of EECs shown in Figure 1. First, richer households are responsible for more overall pollution. This is not surprising since richer households spend more on consumption and are therefore expected to have more pollution created as a result of producing the goods and services they consume.

Second, EECs are concave, meaning that richer households consume less pollution-intensive mixes of goods and services, even if they are responsible for more overall pollution.[14]

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[12] Common approaches others have taken range from simply plotting the data to nonparametric kernel estimation (Lewbel, 1991; Hausman, et al. 1995).

[13] In this case, each point of the 2002 EEC does not represent an equal number of households. Income growth between 1984 and 2002 led to a rightward shift of the income distribution, but since income bin cutoff values are determined based on the 1984 income distribution, relatively fewer households fall in low bins and relatively more households fall in higher bins.

[14] Under standard Engel curve definitions, goods whose consumption increases with income are considered "normal," and among normal goods, those whose consumption increases less than one-for-one are considered "necessities." Pollution, according to these EECs, is a necessity.

Although much of the concavity appears at the top of the income distribution, rich households account for more spending. As a result, concavity has large effects on overall pollution, as we show later. And in fact, the EECs' concavity in Figure 1 may be understated if richer households consume more expensive versions of the same goods.

Third, the set of EECs in Figure 1 suggest that EECs are shifting down over time. The shape and concavity are generally consistent in both years, but households represented by the 2002 EEC are responsible for less pollution than their 1984 counterparts with similar real incomes. These EECs suggest that households with similar real incomes adjusted the composition of their consumption toward a less pollution-intensive mix of goods and services over time. This downward shift is not due to improvements in technology or abatement because we have fixed the pollution intensity of production using the 1997 TEAM coefficients for both years. Instead, the shift over time observed in Figure 1 reflects a change in consumption due to some combination of changing prices, regulations, or social norms.

One possible concern about the EECs in Figure 1 involves the progressivity of the U.S. tax system. Because the EECs are based on total household income reported to the CEX and higher income households pay a higher share of their income in taxes, the EECs in Figure 1 may have exaggerated concavity. Richer households might appear to be responsible for less pollution per dollar of income simply because they pay a higher fraction of their incomes in taxes. To account for this, we repeat the analysis using after-tax income on the horizontal axis in Figure 2a. The concavity and downward shift of the EECs appear similar.

A similar concern involves savings rates. The EECs in Figure 1 may appear concave because richer households save a higher fraction of their incomes. To account for that concern we repeat the analysis with total consumption expenditure on the horizontal axis in Figure 2b. Again the concavity and downward shift remain apparent, if less pronounced.

One drawback of the otherwise flexible approach to estimating EECs depicted in Figures 1 and 2 is that they do not account for additional factors that may affect household consumption. Households appear to have consumed a less pollution-intensive mix of goods and services in 2002 than in 1984, but an alternative explanation for the downward shift in the EECs may be that average household sizes decreased. Or perhaps the changes were due to migration patterns as the U.S. population shifted toward regions with different climates and transportation infrastructures. Table 1 shows the change in average indirect pollution and income for U.S. households between

1984 and 2002, along with changes in demographic variables. Over this period, the average indirect PM10 emissions decreased 6 percent (from 155 tons to 146 tons), while average real income increased 13 percent (from \$40,970 to \$46,370). At the same time, the average household became older, smaller, better educated, more urban, and more likely to live in the South and West. To account for these changes, we turn to a parametric estimate of the EECs.

**Parametric Estimates of Environmental Engel Curves**

To account for household characteristics aside from income that affect the quantity and mix of goods and services consumed, we estimate a series of linear regressions with household pollution on the left-hand side and income, income squared, and other covariates on the right-hand side:

$$\mathrm{P}_{it} = \alpha_t Y_{it} + \beta_t Y_{it}^2 + X_{it}\delta_t + \varepsilon_{it} \tag{1}$$

where $\mathrm{P}_{it}$ and $Y_{it}$ are pollution and income associated with individual households in the CEX, and $X_{it}$ is a vector of other covariates. The coefficients are indexed by *t* because we run separate regressions for each year to obtain a set of annual coefficients. Column (1) of Table 2 shows a version of that regression for PM10 pollution with only the income quadratic, excluding all the other household characteristics, using the 1984 cross section of the CEX. Coefficients on both income terms are significantly different from zero (19.0 and −0.39) and corroborate the increasing and concave EECs depicted in Figure 1.

The second column of Table 2 adds additional control variables for age, household size, marital status, indicators for race and education of the household head, and regional indicators. Nearly all covariates are statistically significantly correlated with total PM10. Overall the results suggest that larger families, older households with more education, and non-Black households in the East were indirectly responsible for more pollution. All these differences stem from underlying differences in consumption. More educated households spend more on food, airfare, and clothing. Households in the East spent more on food, natural gas, and electricity.

Including these additional household characteristics also has a substantial effect on the shape of the EEC. The income coefficients both decrease (to 10.28 for income and -0.13 for income squared). But the estimated EEC is still upward sloping and concave (although the squared income term is only statistically significant at the 10 percent level).[15]

To compare the EECs across time, columns (3) and (4) of Table 2 repeat the regression from column (2) using the 1993 and 2002 cross sections of the NBER CEX extracts (the middle and last years of available extracts). The coefficients on income and income squared in 2002 relative to 1984 suggest an EEC that is lower and less concave in recent years. Column (5) of Table 2 shows the difference between coefficients in 1984 and 2002 (from columns (2) and (4)) and indicates whether there is a statistically significant difference. Older high school graduates were responsible for proportionally less pollution in 2002 than in 1984, whereas western and rural households were responsible for more.

Figure 3 plots the predicted relationship between income and PM10 pollution based on the EECs estimated in columns (2) and (4) of Table 2. Each line is drawn by fixing the other covariates aside from income at their average values for their respective years. So the EECs in Figure 3 plot income expansion paths holding other observable household characteristics constant. These parametrically estimated EECs mirror those without controlling for the other household characteristics: they are upward-sloping, concave, and shift down over time.

The same patterns observed for PM10 are also apparent in EECs based on other common air pollutants. Volatile organic compounds (VOCs), nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$), and carbon monoxide (CO) all exhibit similar income expansion paths to that of PM10. Table 3 shows coefficient estimates for parametric EECs for these other air pollutants using the 1984 cross section of the CEX. We calculate total emissions due to household consumption using the same technique as in Table 2 and utilize the same set of demographic control variables. In all cases, the coefficient on income is positively and statistically significant. For all pollutants except CO, the effect of income squared is negative and statistically significant. Further, the sign and significance of other covariates is consistent with the PM10 EEC across different pollutant types. The hallmark attributes of the individual PM10 EECs—upward sloping, concave, and shifting down over time—are also exhibited by other common air pollutants.[16]

[15] To account for potential nonlinear EECs beyond a quadratic form, we also ran regressions including higher-order polynomial terms (cubics and quartics). They captured much of the influence of the income variable, which was no longer individually significant, but the joint significance of income terms, fitted values, and goodness-of-fit remained essentially the same.

[16] Engel curves drawn for VOC, $NO_x$, $SO_2$, and CO closely resemble those drawn for PM10 in Figure 3 and are available from the authors.

**An Application: Decomposing the Composition Effects**

Movements along and shifts in the EECs affect the level of pollution embodied in the goods and services consumed by households, but there is an important distinction between the two effects. Movements along the EEC depend on underlying preferences of richer households relative to poorer households. The environmental consequences of movement along the EEC are independent of any particular policy intervention. In this sense, movements along the EEC may be predictive of future levels of pollution under status quo environmental regulations if household incomes increase but nothing else changes.

In contrast, shifts in the EEC are the direct result of evolving aggregate preferences or environmental policies that change the relative supply and demand for pollution-intensive goods. There is no reason to expect the environmental benefits of downward shifting EECs to continue without the accompanying change in preferences or tightening of environmental policy.

Comparing annual sets of EECs allows us to decompose changes in this indirect household pollution into a component due to income growth (a movement along the EEC) and a component due to aggregate conditions (a shift in the EEC). For example, we could use the 1984 EEC to assign a hypothetical level of total PM10 to each household in 2002. This would tell us how much pollution to expect if the EEC was fixed based on 1984 conditions, but households move along the EEC as their incomes change. The difference between this hypothetical level of PM10 and the actual emissions (after holding production technology constant) is due to shifts in the EEC between 1984 and 2002.

The Oaxaca-Blinder decomposition provides a formal way of separating these components.[17] Define the average level of pollution in a given year based on the regressions from Table 2:

$$\overline{\mathrm{P}}_t = \alpha_t \bar{Y}_t + \beta_t \overline{Y_t^2} + \bar{X}_t \delta_t \tag{2}$$

where $\overline{\mathrm{P}}_t$ is average indirect pollution, $\overline{Y_t}$ and $\overline{Y_t^2}$ are average income and income squared, and $\bar{X}_t$ is the average of other included covariates. The error term disappears because the average error in ordinary least squares (OLS) is zero by construction.

[17] Oaxaca (1973) and Blinder (1973). For additional discussion of decomposition techniques, see also Fortin, Lemiuex, and Firpo (2010).

Then based on equation (2), the change in average pollution between 1984 and 2002 can be written as:

$$\begin{aligned}\overline{\mathrm{P}}_{02} - \overline{\mathrm{P}}_{84} = {} & \alpha_{02}\bar{Y}_{02} + \beta_{02}\overline{Y_{02}^{2}} + \bar{X}_{02}\delta_{02} \\ & -\alpha_{84}\bar{Y}_{84} - \beta_{84}\overline{Y_{84}^{2}} - \bar{X}_{84}\delta_{84}\end{aligned} \tag{3}$$

By adding and subtracting $\alpha_{84}\bar{Y}_{2002} + \beta_{84}\overline{Y^2}_{2002} + \bar{X}_{2002}\delta_{84}$ and grouping terms, we have:

$$\begin{aligned}\overline{\mathrm{P}}_{02} - \overline{\mathrm{P}}_{84} = {} & \alpha_{84}\,(\bar{Y}_{02} - \bar{Y}_{84}) + \beta_{84}\left(\overline{Y_{02}^{2}} - \overline{Y_{84}^{2}}\right) \\ & +(\alpha_{02} - \alpha_{84})\bar{Y}_{02} + (\beta_{02} - \beta_{84})\overline{Y_{02}^{2}} \\ & +\bar{X}_{02}(\delta_{02} - \delta_{84}) + (\bar{X}_{02} - \bar{X}_{84})\delta_{84}\end{aligned} \tag{4}$$

The first two terms in equation (4) capture the effect of changing income on total pollution, holding constant the 1984 OLS coefficients. This is equivalent to a movement along the 1984 EEC. The second two terms capture the effect of different OLS coefficients on income and income squared in 2002 relative to 1984. This is equivalent to a shift (or change in shape) of the EEC. Finally, the last two terms account for changes in all other covariates, including demographics, migration, and household size, and their changing coefficients.

Table 4 presents the results of this decomposition. Consider column (1), for PM10. Each row is calculated by multiplying the change in average values of the variable (column (3) of Table 1) by the 1984 OLS coefficients (column (2) of Table 2) and represents the change in pollution predicted by the change in that particular variable. At the bottom of Table 4 we have grouped these effects into those due to income, or movement along the EEC, and those due to other covariates. The level of total particulates (PM10) embodied in the average household's consumption decreased 9.5 tons between 1984 and 2002 (from Table 1). Changes in average income and income squared led to a hypothetical increase of 4.16 tons (5.55 increase from income and 1.39 decrease from income squared). At the same time, changing demographics offset this increase by 2.71 tons. The remaining difference, 10.93 tons, is attributable to shifts in the EEC.

Columns (2) through (5) of Table 4 present similar analyses for VOC, $NO_x$, $SO_2$, and CO. The scale effects and offsetting compositional shifts due to changes in average income resulted in modest increases in emissions (3.63 tons, 3.95 tons, 0.91 tons, and 14.84 tons, respectively). Unlike the case of PM10, these increases were not substantially offset by the effects of demographic changes. But like PM10, the remaining portions of the total changes for each pollutant in Table 4 were large, ranging from 2.18 tons for $SO_2$ to 36.88 tons for CO.

The increases in emissions due to changes in household income, such as the 4.16 ton increase in PM10, can be further decomposed into separate household-level scale and composition components. Along a given EEC, richer households consume more goods and services overall, but they also consume a less pollution-intensive mix relative to poorer households. The balance of these two effects depends on the shape of the EEC. To the extent that EECs are more concave, the compositional component is stronger and households with higher income are responsible for less than proportionally more pollution. On the other hand, two perfectly straight EECs would indicate a pure scale effect, with pollution growing at the same rate as income.

Table 5 summarizes these calculations, decomposing changes in pollution derived from household consumption into those due to the scale of income growth, the composition of consumption, movements along the EEC, shifts in the EEC, and other demographic changes. Column (1) repeats the predicted change in household pollution, holding technology fixed, from Table 1. All five pollutants decline due to changes in household demographics and the scale and composition of household consumption. The second column describes the household-level scale effect. Between 1984 and 2002 average household income increased 13 percent. With no compositional shift in consumption, we would expect emissions of each pollutant in Table 5 to also increase by 13 percent. In the case of PM10, we would see an increase of 20.4 tons. The difference between columns (1) and (2)—29.9 tons of PM10—represents the reduction in pollution collectively explained by movement along the 1984 EEC, changes in household demographics, or shifts in the EECs over time.

The difference between the 20.4 ton increase in PM10 and our movement-related estimate of 4.16 from Table 4 represents the mitigating effect of compositional shifts along the 1984 EEC. In this case, compositional changes in consumption along the EEC offset 16.3 tons of PM10 from the scale effect, reported in column (4) of Table 5. In total, the sum of the compositional offsets (-16.3 from movement along the EEC and -10.9 tons from shifts in the EEC) together with the effects of demographics (-2.71 tons) counteract the scale effect (20.4 increase) to equal the overall predicted change of -9.5 tons.

A key conclusion from Table 5 is that movements along the EECs and shifts in the EECs are about equally responsible for reductions in household pollution. This can be seen by comparing columns (4) and (8), which set aside the demographic changes in column (6) and the technique changes that are held constant throughout. Column (4) contains the pollution reduction due to movements along the concave EEC, and column (8) contains the pollution reductions due to shifts in the EEC between 1984 and 2002. They are of approximately equal magnitude. Columns (5) and (9) of Table 5 express these two effects—movements and shifts—as percentages of the overall pollution decline to be explained in column (3). We find that movements along EECs explain 46 to 54 percent of the overall compositional effect and shifts in the EECs explain 37 to 56 percent. But the fundamental point is similar across pollutants. Changes in the goods and services households consumed between 1984 and 2002 were responsible for large declines in the pollution those households were indirectly responsible for. And those changes are about evenly split between those due to growing household incomes along concave EECs and those due to downward shifts of the EECs over time.

Figure 4 depicts the relative magnitude of these effects for PM10 over time by applying the same decomposition to all interim years between 1984 and 2002. The top line depicts the level of pollution that would occur if the proportions of goods and services households consumed remained constant as household incomes grew. That is the scale effect at the household level.[18] The second line captures the hypothetical effect of movements along the 1984 EEC. The vertical difference between these two lines (16.3 tons in 2002) is the offsetting compositional effect reflected in the concavity of EECs. The third line shows the contribution of changing demographics in addition to changing income and falls below the second line because the balance of other factors, such as household size, education, and geography, led to a net decrease in the pollution intensity of consumption.

The fourth line of Figure 4 shows the predicted level of pollution in each year calculated by pairing the 1997 TEAM pollution coefficients with each round of the NBER CEX extracts. This is the level of pollution that would occur if technology were fixed based on 1997 pollution intensities, but where we account for the true mix of goods and services consumed by households

[18] A curious feature of our CEX data is that real household incomes did not grow between 1984 and 1985. Hence all of the changes we describe in Table 5 stem from income growth in later years. But the predicted changes in household-level pollution coming from movements along the Engel curves are derived from comparisons across households with different incomes in 1984.

in each period. The vertical distance between the third and fourth lines (10.9 tons in 2002) is due to downward shifts in the EEC over time.

Similar figures drawn for the other four pollutants in Table 5 all make the same point. Shifts in the mix of goods and services consumed by the average household have more than offset any pollution increase due to growth in the scale of household income growth. About half of those composition changes come solely from the fact that richer households consume a less pollution-intensive mix of goods, and the other half comes from the fact that households at every income level consume a less pollution-intensive mix in 2002 than they did in 1984.

**Conclusion**

Over the past 30 years, overall pollution in the United States has declined despite increases in total production. Some of this improvement has come from employing cleaner production technologies in cars and factories, but much of it comes as a result of consuming a cleaner mix of goods and services. Has this cleaner consumption been a consequence of economy-wide trends, such as regulation-induced price changes, or an underlying and possibly coincidental preference by richer households for cleaner goods? Environmental Engel curves describing the relationship between income and the pollution-intensity of household consumption provide a means for disentangling these two effects.

Whether estimated parametrically or non-parametrically, EECs display three key characteristics: they are increasing, concave, and shifting down over time. These characteristics allow us to decompose changes in the pollution associated with household consumption into movements along the EEC and shifts in the EEC. Between 1984 and 2002 we find that compositional changes in consumption due to movements along EECs and downward shifts of EECs more than offset the 13 percent increase in household incomes. For five common air pollutants, about half the overall offsetting compositional effect was due to movements along EECs and the other half to shifts in the EECs.

This distinction between movements along the EECs and shifts in the EECs is critical. An important reason pollution in the United States has not increased one-for-one with income growth is that households have moved away from pollution-intensive goods and services. Our analysis shows that this change is not entirely automatic. Rich households in any given year do consume a mix of goods proportionally less pollution-intensive than lower-income households.

Given higher incomes and no other changes, 1984 households would have consumed a cleaner mix of goods, and that accounts for about half of the overall household shift. But households with the same real incomes consumed a cleaner mix of goods in 2002 than they did in 1984, an improvement that accounts for an approximately equal shift and must come from changes to aggregate conditions, such as prices, social norms, or environmental policies.

In the end, decomposing income growth into movements along and shifts in the EECs represents just one aspect of the environmental consequences of economic growth. A large portion of the cleanup in the United States comes from changes in technology, the composition of production, and the pollution intensity of U.S. imports and exports. Nevertheless, isolating the consumption-related compositional changes in pollution suggests that household-level composition changes have more than offset the increased pollution from growing household incomes.

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## Table 1. Average Values for Selected Variables 1984 and 2002

| Variable | Cross section 1984 | Cross section 2002 | Difference |
|---|---|---|---|
| | (1) | (2) | (3) |
| Pollutant (tons, 1997 technology) | | | |
| Particulate matter less than 10 microns (PM10) | 155.1 | 145.6 | -9.48* |
| | (1.7) | (1.2) | (2.14) |
| Volatile organic compounds (VOCs) | 97.63 | 90.24 | -7.39* |
| | (1.19) | (0.88) | (1.48) |
| Nitrogen oxides ($NO_x$) | 108.10 | 103.0 | -5.12* |
| | (1.30) | (0.97) | (1.62) |
| Sulfur dioxide ($SO_2$) | 22.43 | 21.21 | -1.22* |
| | (0.30) | (0.23) | (0.38) |
| Carbon monoxide (CO) | 444.3 | 421.2 | -23.19* |
| | (4.9) | (3.6) | (6.04) |
| Income ($10,000, 1997 dollars) | 4.1 | 4.6 | 0.54* |
| | (0.1) | (0.1) | (0.10) |
| Household size | 2.7 | 2.6 | -0.17* |
| | (0.03) | (0.02) | (0.04) |
| Age of household head | 46.7 | 48.4 | 1.68* |
| | (0.4) | (0.3) | (0.50) |
| Head is married (share of pop.) | 0.6 | 0.5 | -0.08* |
| Race of head is Black (share of pop.) | 0.10 | 0.11 | 0.01 |
| Education of head (share of population) | | | |
| Elementary only | 0.27 | 0.16 | -0.11* |
| High school | 0.32 | 0.27 | -0.04* |
| Some college | 0.19 | 0.30 | 0.11* |
| College | 0.12 | 0.17 | 0.05* |
| More than college | 0.11 | 0.10 | -0.01 |
| Region (share of population) | | | |
| Northeast | 0.18 | 0.19 | 0.01 |
| Midwest | 0.22 | 0.23 | 0.01 |
| South | 0.27 | 0.36 | 0.09* |
| West | 0.17 | 0.21 | 0.04* |
| Rural | 0.16 | 0.13 | -0.04* |
| Observations | 3,187 | 4,363 | |

Notes: Values calculated using sample weights. Standard errors are shown in parentheses. Differences may not match exactly due to rounding.
*Differences statistically significant at the 5 percent level.

## Table 2. Parametric Environmental Engel Curves for PM10
## 1984, 1993, and 2002

| **Dependent variable:** | **1984** | | **1993** | **2002** | **Coefficient change between 1984 and 2002** |
|---|---|---|---|---|---|
| **Total PM10 per household** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** |
| Income ($10,000, 1997 dollars) | 19.04* | 10.28* | 9.46* | 8.28* | -2.00 |
| | (1.31) | (1.21) | (1.97) | (0.55) | (1.33) |
| Income squared | -0.39* | -0.13 | -0.128 | -0.089* | 0.037 |
| | (0.08) | (0.07) | (0.12) | (0.025) | (0.07) |
| Household size | | 39.10* | 37.37* | 38.71* | -0.40 |
| | | (2.94) | (4.66) | (2.65) | (3.95) |
| Household size squared | | -1.93* | -2.01* | -2.36* | -0.43 |
| | | (0.38) | (0.70) | (0.35) | (0.51) |
| Age | | 3.43* | 2.57* | 1.91* | -1.53* |
| | | (0.40) | (0.47) | (0.32) | (0.51) |
| Age squared | | -0.03* | -0.021* | -0.02* | 0.01* |
| | | (0.004) | (0.004) | (0.003) | (0.005) |
| Married | | 8.59* | 7.93* | 6.08* | -2.51 |
| | | (2.94) | (3.56) | (2.55) | (3.90) |
| Race (White omitted) | | | | | |
| Black | | -26.88* | -17.76* | -20.89* | 5.99 |
| | | (3.68) | (3.74) | (2.42) | (4.40) |
| Asian | | 6.46 | -6.90 | -10.43 | -16.89 |
| | | (17.95) | (10.97) | (5.55) | (18.78) |
| Other | | 2.18 | -6.22 | -7.64 | -9.82 |
| | | (11.13) | (15.58) | (6.39) | (12.83) |

(Continued on next page)

## Table 2 (continued)

| | 1984 | | 1993 | 2002 | Change between 1984 and 2002 |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| Education (< high school omitted) | | | | | |
| High school | | 9.42* | 6.57* | -0.13 | -9.55* |
| | | (3.28) | (3.22) | (2.51) | (4.13) |
| Some college | | 9.67* | 15.96* | 3.63 | -6.05 |
| | | (3.86) | (4.13) | (2.64) | (4.68) |
| College | | 18.10* | 16.50* | 9.92* | -8.18 |
| | | (4.92) | (4.72) | (3.32) | (5.93) |
| Graduate | | 24.47* | 19.93* | 15.71* | -8.76 |
| | | (5.29) | (4.91) | (3.98) | (6.62) |
| Region (Northeast omitted) | | | | | |
| Midwest | | -15.44* | -26.13* | -8.78* | 6.66 |
| | | (3.53) | (3.65) | (2.87) | (4.55) |
| South | | -11.62* | -17.72* | -6.60* | 5.03 |
| | | (3.44) | (3.62) | (2.74) | (4.40) |
| West | | -8.05* | -7.73 | 4.00 | 12.05* |
| | | (3.88) | (4.10) | (3.07) | (4.94) |
| Rural | | -28.56* | -26.76* | -9.92* | 18.63* |
| | | (3.84) | (4.05) | (2.44) | (4.55) |
| Constant | 87.9* | -58.59* | -27.18* | -18.40* | 40.19* |
| | (3.69) | (10.82) | (12.61) | (9.12) | (14.14) |
| Observations | 3,185 | 3,185 | 3,203 | 4,363 | |
| R-squared | 0.317 | 0.581 | 0.502 | 0.513 | |

Notes: Total household pollution is calculated by multiplying itemized household consumption with the pollution intensity of production for each type of good and summing for each household. All figures are calculated using 1997 production technology to estimate pollution.
*Figures are statistically significant at the 5 percent level.

## Table 3. Parametric EECs for Other Air Pollutants Based on 1984 Consumer Expenditure

| Dependent variable: | VOC | $NO_x$ | $SO_2$ | CO |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Income ($10,000, 1997 dollars) | 9.17* | 10.01* | 2.33* | 33.36* |
| | (1.02) | (1.07) | (0.27) | (4.00) |
| Income squared | -0.12* | -0.13* | -0.03* | -0.27 |
| | (0.06) | (0.06) | (0.02) | (0.24) |
| Household size | 19.18* | 21.82* | 4.38* | 100.5* |
| | (2.16) | (2.16) | (0.56) | (8.05) |
| Household size squared | -1.26* | -1.33* | -0.30* | -5.89* |
| | (0.25) | (0.25) | (0.06) | (0.97) |
| Age | 1.66* | 2.03* | 0.36* | 6.38* |
| | (0.30) | (0.31) | (0.08) | (1.14) |
| Age squared | -0.02* | -0.02* | -0.003* | -0.05* |
| | (0.003) | (0.003) | (0.001) | (0.01) |
| Married | 5.56* | 5.36* | 1.25* | 17.62* |
| | (2.37) | (2.37) | (0.61) | (8.58) |
| Race = Black | -18.37* | -19.82* | -4.64* | -82.93* |
| | (2.503) | (2.67) | (0.65) | (9.72) |
| Race = Asian | -5.636 | -5.67 | -2.15 | -12.79 |
| | (10.73) | (11.59) | (2.62) | (40.13) |
| Race = Other | -13.03* | -9.98 | -3.00* | -18.13 |
| | (5.286) | (6.43) | (1.41) | (28.77) |
| High school | 7.273* | 8.11* | 1.68* | 36.09* |
| | (2.334) | (2.43) | (0.67) | (8.79) |
| Some college | 13.21* | 14.16* | 3.06* | 56.12* |
| | (2.87) | (2.97) | (0.75) | (10.83) |
| College | 18.94* | 20.82* | 4.23* | 82.92* |
| | (3.90) | (3.99) | (0.97) | (14.37) |
| Graduate | 21.63* | 27.70* | 5.65* | 107.9* |
| | (3.96) | (4.48) | (1.07) | (16.18) |
| Midwest | -3.06 | -7.20* | -1.13* | -32.56* |
| | (2.49) | (2.59) | (0.62) | (9.69) |
| South | 0.37 | -3.22 | 0.08 | -18.69* |
| | (2.48) | (2.61) | (0.65) | (9.44) |
| West | 1.15 | -0.28 | 0.23 | -0.56 |
| | (2.66) | (2.98) | (0.71) | (10.90) |
| Rural | -7.05* | -13.52* | -1.72* | -62.54* |
| | (2.64) | (2.85) | (0.71) | (10.29) |
| Observations | 3,185 | 3,185 | 3,185 | 3,185 |
| R-squared | 0.514 | 0.539 | 0.468 | 0.572 |

See notes for Table 2.

## Table 4. Movement along Parametric EECs for Air Pollutants 1984–2002

| Dependent Variable: | Increase in Pollution due to movement along an EEC (tons) | | | | |
|---|---|---|---|---|---|
| | PM10 | VOC | $NO_x$ | $SO_2$ | CO |
| | (1) | (2) | (3) | (4) | (5) |
| Income ($10,000, 1997 dollars) | 5.55* | 4.95* | 5.40* | 1.26* | 18.01* |
| | (1.20) | (1.05) | (1.13) | (0.27) | (3.90) |
| Income squared | -1.39 | -1.32 | -1.45* | -0.35 | -3.17 |
| | (0.82) | (0.69) | (0.73) | (0.18) | (2.68) |
| Household size | -6.61* | -3.24* | -3.69* | -0.74* | -16.98* |
| | (1.70) | (0.87) | (0.98) | (0.20) | (4.37) |
| Household size squared | 2.20* | 1.44* | 1.52* | 0.34* | 6.72* |
| | (0.71) | (0.47) | (0.49) | (0.11) | (2.05) |
| Age | 5.74* | 2.79* | 3.39* | 0.60* | 10.68* |
| | (1.85) | (0.97) | (1.14) | (0.22) | (3.72) |
| Age squared | -4.16* | -2.17* | -2.54* | -0.47* | -7.33* |
| | (1.52) | (0.84) | (0.97) | (0.19) | (2.97) |
| Married | -0.65* | -0.42* | -0.40* | -0.09 | -1.32 |
| | (0.25) | (0.19) | (0.19) | (0.05) | (0.69) |
| Race dummies | 0.03 | -0.22 | -0.25 | -0.08 | -0.82 |
| Education dummies | 1.37* | 1.91* | 2.02* | 0.43* | 7.88* |
| Regional dummies | 0.64 | 0.30 | 0.08 | 0.07 | 0.03 |
| **Total change due to income (movement along EEC)** | 4.16 | 3.63 | 3.95 | 0.91 | 14.84 |
| **Total change due to other demographics** | -2.71 | 0.38 | 0.14 | 0.05 | -1.15 |
| **Unexplained difference (shift in EEC)** | -10.93 | -11.41 | -9.20 | -2.18 | -36.88 |

Notes: Estimates are based on Oaxaca-Blinder decompositions. Movement along each EEC can be calculated by multiplying the coefficients in Tables 2 and 3 by the corresponding changes in Table 1. Pollution is estimated based on 1997 production technology for all years. Values for race, education, and regional indicators are the combined effect for each category.
*Figures are statistically significant at the 5 percent level.

## Table 5. Pollution Offset Due to Compositional Changes in Household Consumption
## Summary of Other Local Air Pollutants

| | Total change (tons) | Scale increase (tons) | Total spread (2) – (1) | Offset by movement along EEC: Tons | Offset by movement along EEC: Share of spread | Offset by demographic changes: Tons | Offset by demographic changes: Share of spread | Offset by shifts in EEC (residual): Tons | Offset by shifts in EEC (residual): Share of spread |
|---|---|---|---|---|---|---|---|---|---|
| Pollutant | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| PM10 | -9.48 | 20.44 | 29.92 | 16.27 | 0.54 | 2.71 | 0.091 | 10.93 | 0.37 |
| VOC | -7.39 | 12.86 | 20.25 | 9.23 | 0.46 | -0.39 | -0.019 | 11.41 | 0.56 |
| $NO_x$ | -5.12 | 14.25 | 19.36 | 10.29 | 0.53 | -0.14 | -0.007 | 9.20 | 0.48 |
| $SO_2$ | -1.22 | 2.95 | 4.14 | 2.05 | 0.49 | -0.05 | -0.013 | 2.18 | 0.52 |
| CO | -23.19 | 58.55 | 81.74 | 43.71 | 0.53 | 1.16 | 0.014 | 36.87 | 0.45 |

Notes: The total change in pollution is predicted using CEX and TEAM data, based on 1997 production technology. The scale increase in pollution is calculated by multiplying pollution levels in 1984 by the proportional increase in income between 1984 and 2002. The total spread is calculated as the difference between the predicted change from the TEAM and the predicted increase due to the scale effect. Offsets in column (4) are calculated by subtracting the predicted level of pollution, including scale effects and movements along the EEC, from the scale effect alone (in column (2)). Offsets due to demographic changes are calculated in an analogous manner. Offsets due to shifts in the EEC are calculated as the residual, and the offsets in columns (4), (6), and (8) sum to column (3) by construction. Figures in columns (4) through (9) are based on EECs estimated in Tables 2 and 3.

**Figure 1. Pollution Embodied in Household Consumption and Total Household Income**

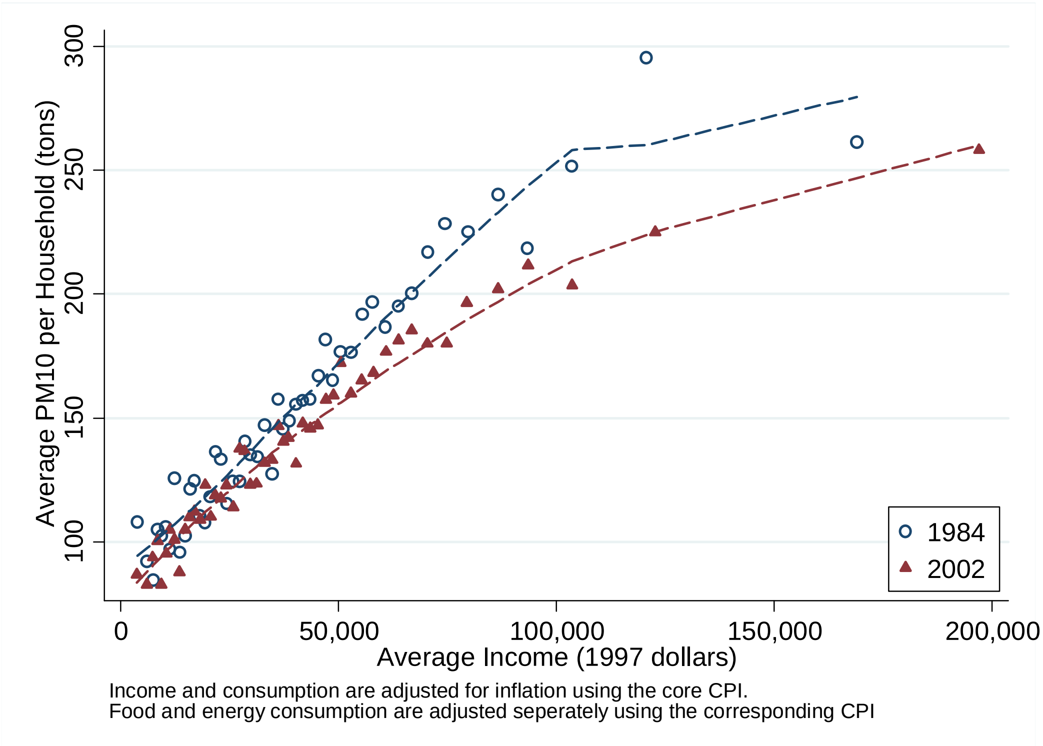



**Figure 2a. Pollution Embodied in Household Consumption and After-Tax Income**

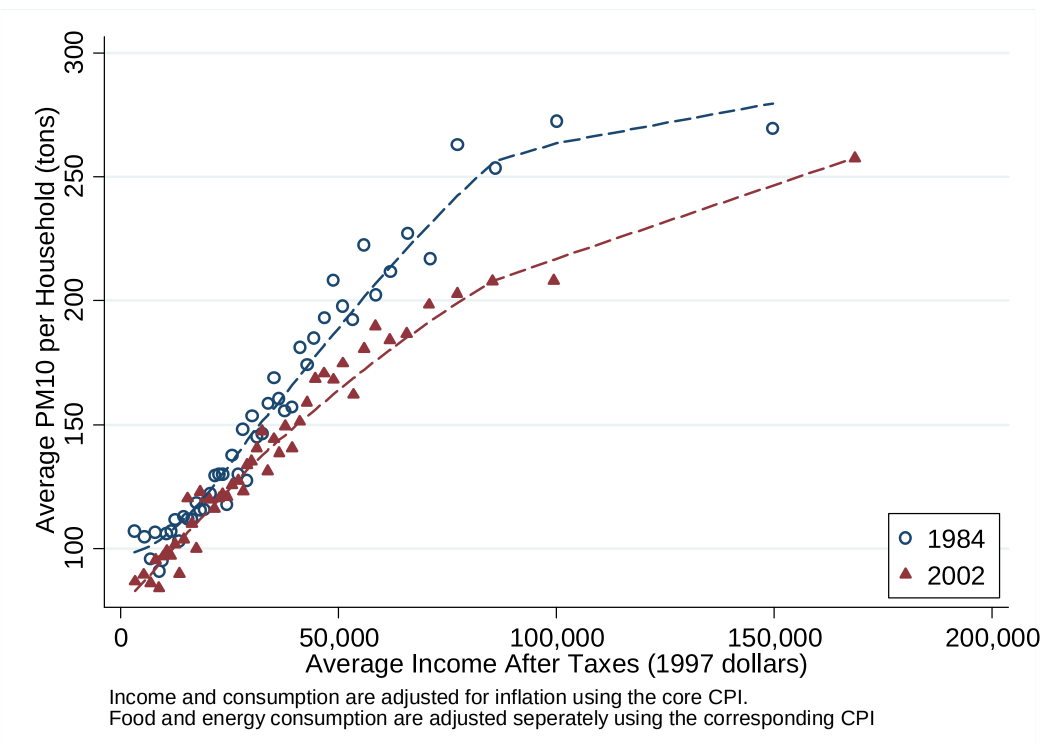
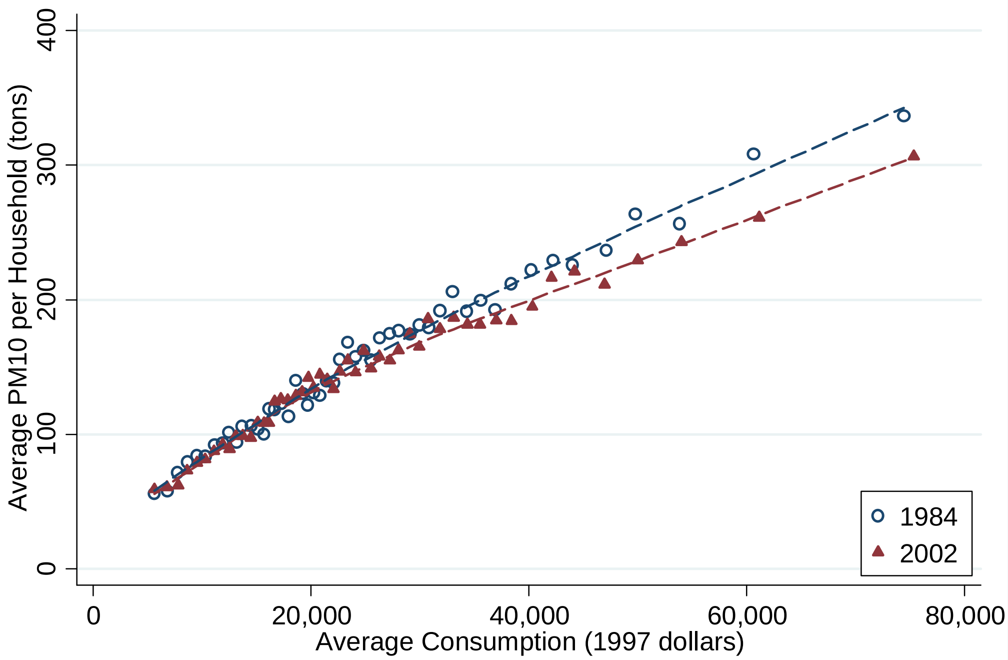
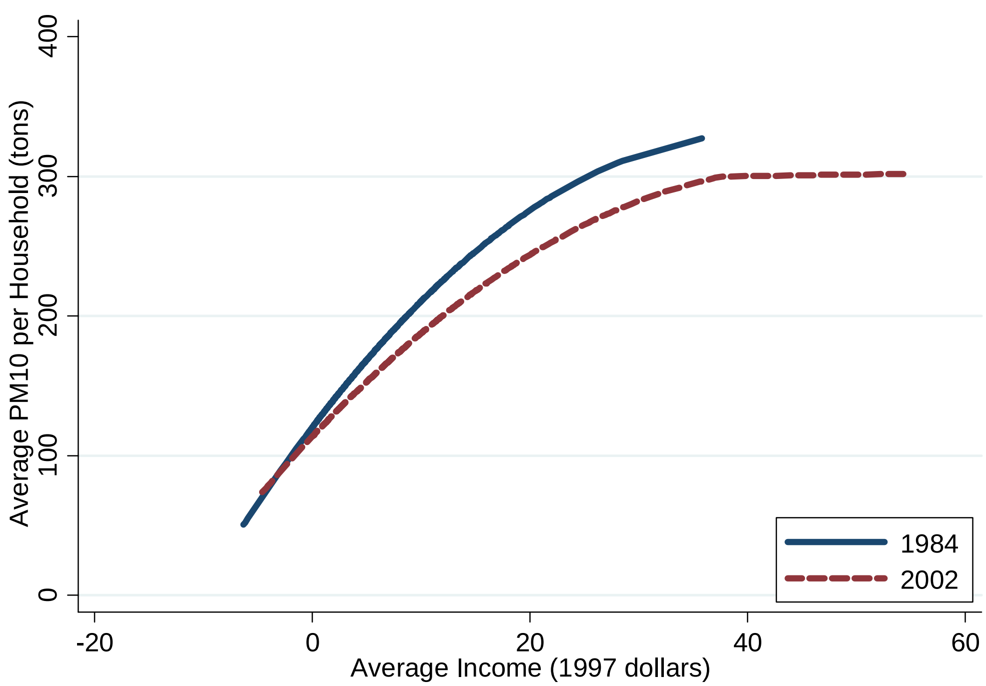


**Figure 2b. Pollution Embodied in Household Consumption and Total Consumption**



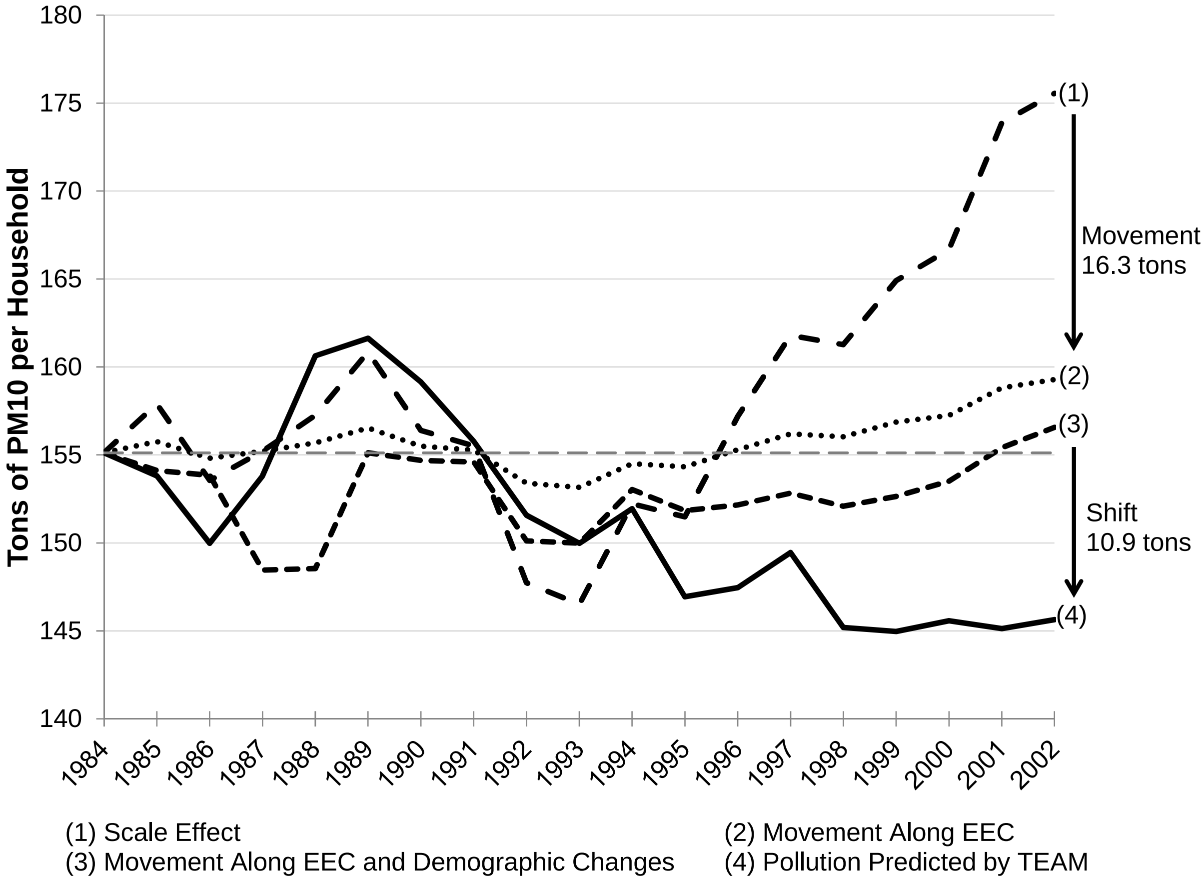

Income and consumption are adjusted for inflation using the core CPI.
Food and energy consumption are adjusted seperately using the corresponding CPI

**Figure 3. EECs Based on Parametric Estimates**




Note: All other covariates are fixed at their mean values.

**Figure 4. Decomposition of Predicted Pollution from Household Consumption**




Notes: The scale effect is calculated by increasing pollution in proportion to real income growth. Movements along and shifts in the EEC are calculated by estimating pollution in each year using the 1984 EEC coefficients. Pollution predicted by TEAM is estimated by matching itemized consumption expenditure in each year with 1997 TEAM pollution intensity data.