ENVIRONMENTAL ENGEL CURVES: INDIRECT EMISSIONS OF COMMON AIR POLLUTANTS

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Abstract—Environmental Engel curves (EECs) describe households' incomes and the pollution necessary to produce the goods and services they consume. We calculate 29 annual EECs from 1984 to 2012 for point-source air pollutants in the United States, revealing three clear results: EECs slope upward, have income elasticities less than 1, and shift down over time. Even without changes to production techniques, pollution would have declined despite growing incomes. This improvement can be attributed about equally to two trends: household income growth represented by movement along inelastic EECs and economy-wide changes represented by downward shifts in EECs over time.

I. Introduction

ENVIRONMENTAL Engel curves (EECs) show the relationship between households' incomes and the amount of pollution embodied in the goods and services they consume. Traditional Engel curves plot relationships between income and consumption of particular goods or services, holding prices constant. They are named for Ernst Engel, a nineteenth-century economist who studied the degree to which food expenditures increase with income. EECs are less straightforward than traditional Engel curves because households generate pollution both directly as a consequence of their activities, such as driving cars, and indirectly as a consequence of consuming products whose production generates pollution, such as manufacturing the 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 thirty years, total pollution emitted by U.S. producers has declined considerably, even though the real value of U.S. production has increased. Prior research has parsed this relationship between economic growth and pollution into three components: scale, technique, and composition (Copeland & Taylor, 2005). Scale describes a proportional increase in economic activity: if the economy doubles, the scale effect doubles pollution. Technique describes changes to the pollution intensity of particular activities, like refining petroleum or generating electricity. And composition describes changes to the mix of activities that make up the economy. In the United States, pollution due to the growing scale of production has been more than offset by some combination of technique and composition.

Recent research has shown that pollution reductions in the United States have resulted mostly from changes in technique. Estimates range from 35% to nearly 100%, depending on the pollutant and time period studied.[1] The remaining change in the composition of production has two sources: consumption and trade. The United States can shift to producing cleaner products by either consuming cleaner goods or, in theory, importing the relatively pollution-intensive goods and exporting the clean ones. But Brunel (2016) and Levinson (2009) both show that changing trade patterns have been small or even work in the opposite direction. The composition of U.S. imports has been shifting toward cleaner goods, not more polluting ones, and doing so even faster than the composition of domestic production. That means that the domestic consumption composition change toward cleaner goods—the focus of this paper—is larger than the domestic production composition change measured by all those prior papers.

We study that consumption composition shift directly, using data from the Consumer Expenditure Survey (CEX), industry-by-industry emissions factors for five major air pollutants from the EPA's National Emissions Inventory (NEI), and input-output tables from the Bureau of Economic Analysis. We use those data to estimate the air pollution required to produce each household's consumption, including all the necessary intermediate goods and services. And from that we calculate EECs separately for each of the five pollutants for every year from 1984 until 2012. With those EECs in hand, we then ask how much of the shift in U.S. consumption toward clean goods comes solely from the fact that the average household today is richer than the average household thirty 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.

Some observers have pointed to environmental improvements in the United States and other developed countries as evidence that income growth alone will reduce pollution. But rich countries might have less pollution because they enact strict environmental regulations. The EECs we estimate can help differentiate those sources of cleanup. Economy-wide trends, such as regulation-induced increases in the prices of polluting goods, will appear as downward shifts in EECs. By contrast, an underlying and possibly coincidental preference by richer households for cleaner

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[1] See Levinson (2009, 2015), Brunel (2016), and Shapiro and Walker (2015).

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goods will appear as movements along concave EECs. Only movements along EECs might be considered an automatic result of income growth, without policies or price changes.

A related idea involves so-called environmental Kuznets curves (EKCs), which refer to aggregate relationships between pollutants and national income. Hundreds of published empirical articles regress various measures of pollution on flexible functions of national or regional income.[2] Low-income and high-income regions typically exhibit the least pollution, and middle-income regions the most, resulting in an inverted-U shape or EKC. But EKCs are nothing more than conditional correlations, without meaningful interpretations other than that pollution does not necessarily increase with economic growth. As Grossman and Krueger (1995) stressed, "There is nothing at all inevitable about the relationships that have been observed in the past. These patterns reflected the technological, political, and economic conditions that existed at the time." Richer countries might have less pollution for any of several reasons. They might enact stricter regulations, use cleaner fuels,[3] have more service-based economies, import relatively more of the most pollution-intensive goods, or—relevant to this exercise—perhaps their citizens choose to consume a less pollution-intensive mix of goods. EKCs cannot tell us why middle-income countries have historically had more pollution than poorer or richer countries.

EECs, however, are structural, representing income expansion paths holding prices constant. In fact, use of EECs to divide households' consumption-related pollution changes into two parts yields two of the many possible explanations for the observed inverse-U-shaped EKC patterns of national pollution. Movements along EECs represent changes in preferences as incomes grow, holding prices, technologies, and regulations fixed. And shifts in EECs represent changes in all of those other national characteristics over time.

One conceivable approach to estimating EECs empirically would compare incomes and the pollution content of consumption across countries at a point in time or across time within a country, similar to the way EKCs have been estimated. But EECs based on comparisons across countries or over time would be difficult to interpret because prices and characteristics of available goods change. Richer countries might pass regulations causing households to consume proportionally fewer pollution-intensive goods. That difference would not be interpretable as the slope of an Engel curve because it would not represent the change in consumption 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 2012. Households in any year all face the same prices, available products, and regulations.[4] For every year, we combine detailed information on household consumption with production-side pollution intensities to calculate the air pollution created as a result of producing each household's consumption. Plotting that indirect pollution against those households' incomes yields a set of annual EECs.

We construct these EECs separately for indirect emissions from each of five major air pollutants: particulates smaller than 10 microns (PM10), volatile organic compounds (VOCs), nitrogen oxides (NOx), sulfur dioxide (SO_2), and carbon monoxide (CO). We estimate separate EECs because each is measured in different units and has different environmental consequences. We could imagine other analyses using other data sets that might estimate EECs for other indirect pollutants or the direct pollution from consumption, such as burning gasoline in car engines. In this paper, we develop the proof of concept by estimating EECs using these five most commonly studied air pollutants for which the data are most complete.

We also estimate two versions of each EEC: one based solely on income and one that controls for household characteristics correlated with income, such as education and age. As the "Engel Curve" entry in *The New Palgrave Dictionary of Economics* notes, "Engel curves may also depend on demographic variables and other consumer characteristics" (Lewbel, 2009). We show that adding those common demographic variables has little effect on the conclusions about the shapes of EECs or how they have changed over time.

Ours is not the first paper to combine household-level consumption data with pollution data to generate pollution by income. Metcalf (1999) combines the 1994 CEX with pollution data from twelve industries to study the incidence of a proposed pollution tax. Hassett, Mathur, and Metcalf (2009) combine CEX data from 1987, 1997, and 2003 with pollution data across fifty industries to show that a carbon tax would be increasingly regressive, presumably because EECs are becoming increasingly convex, though they never use that language. And Grainger and Kolstad (2010) and Burtraw, Sweeney, and Walls (2009) use the CEX to show that a carbon tax would be regressive if not offset by lump-sum transfers or reductions in other regressive taxes.

Several papers have studied the relationship between household income and pollution in countries other than the United States. Gertler et al. (2016) examine energy use among poor households in Mexico that receive large, randomly timed cash transfers. The randomization addresses

[2] For examples, see Harbaugh, Levinson, and Wilson (2002) and Millimet, List, and Stengos (2003).

[3] A separate literature on "energy ladders" studies whether richer households choose cleaner cooking fuels (Hanna & Oliva, 2015). But indoor pollution from cooking does not represent an obvious market failure, or externality. Households face the full trade-off between expensive fuel and worse indoor air quality. We examine whether richer households in the United States choose a mix of goods whose upstream production generates less pollution.

[4] Prices and regulations do vary across the United States, but we can control for that empirically. In some of the parametric analyses that follow, we include geography fixed effects, comparing indirect pollution from households with different incomes in the same Census region or state.

concerns about the endogeneity of income and energy use. They find evidence of credit constraints, leading to an S-shaped path of adoption for energy-using appliances, like refrigerators, and nonlinear Engel curves. Allan, Kerr, and Campbell (2015) use New Zealand household expenditure data from 2006 and 2012 to show that the income elasticity of indirect greenhouse gases is less than 1 and that the EEC shifted down marginally during those six years.

No research to date has involved the detailed, year-by-year approach we take. None have the same level of disaggregation as our 850 income and consumption categories and 1,000 six-digit North American Industrial Classification System (NAICS) industries. And none maps the results into annual EECs or uses those EECs to decompose changes in U.S. pollution over the past three decades.

We find that EECs display three key characteristics. First, not surprisingly, EECs are upward sloping, meaning that richer households are responsible for more overall pollution. Second, EECs have income elasticities of less than 1, indicating that although pollution increases with income, it does so at a rate of less than one-for-one. And third, EECs shift down and become more concave over time, meaning that for any level of real household income, households in more recent years consume a less polluting mix of goods, and pollution increases with income at a decreasing rate. Between 1984 and 2012, real after-tax household incomes in the CEX grew by 19%, while the various pollutants necessary to produce the goods those households consumed grew at most by 1% and declined by as much as 19%.

This reduction in pollution per dollar of expenditures must come from two phenomena: either richer households consume a less pollution-intensive mix of goods, holding all else equal—a movement along an inelastic EEC—or households consumed fewer polluting goods in 2012 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.

II. Data and Methods

All of the data and sources are described in detail in the online appendix. The CEX is collected each quarter by the Census Bureau and provides detailed information on itemized household consumption expenditures. We exclude households with expenditures on nursing homes (0.5% of the sample), students, the top and bottom 1% of households based on after-tax income, and any households with incomplete income data. This trimming of the data reduces the sample size from 236,605 to 95,512. To address possible bias that might arise, we reweight the sample based on age groups and homeownership status. Consumption and income data in the CEX are categorized by approximately 850 separate universal classification codes (UCC) that capture around 80% to 95% of total household expenditures.

To calculate the pollution emitted by producing the goods and services associated with those expenditures, we pair the CEX with emissions intensities calculated from the NEI. The NEI contains detailed estimates of air pollution emissions in the United States organized by facilities and classified by NAICS industry. We calculate the per dollar emissions intensity of each industry by aggregating industry-level emissions in the 2002 NEI and dividing by the total sales from the 2002 economic and agricultural censuses.[5] Since nonpoint sources of air emissions are not assigned to specific industries in the NEI, our emissions intensities include only pollution associated with specific facilities.

The NEI reports the pollution generated producing each final product, but we also want to consider pollution from producing the inputs to those final products, the inputs to those inputs, and so on up the supply chain. All of this upstream pollution can be estimated using the input-output (IO) tables published by the U.S. Bureau of Economic Analysis, which show the dollar amount of each industry necessary to produce a dollar's worth of output for every other industry. Using the IO tables and a Leontief (1970) analysis, we transform the NEI emissions intensities into total emissions coefficients that include the pollution to manufacture each final product and all its inputs. (See the online appendix for details.)

We combine these total pollution intensity coefficients with itemized expenditures in the CEX to estimate the total amount of pollution created to produce each of the categories of goods and services consumed by every surveyed household. Adding up pollution across all categories, we obtain the total pollution attributable to each household. The final result is a sample of households spread across 29 years of data from, in which each household has an estimated total pollution associated with its expenditures. Table 1 shows the average per household values for this indirect pollution, income, and other household characteristics for 1984 and 2012, the first and last years of our series.

A few points are worth detailing here. First, because the CEX and NEI use different industry definitions, we created a concordance to match consumption items in the CEX with industries in the NEI. Since the NAICS has more industry codes than the CEX has consumption codes, most CEX codes were matched to several NAICS categories. We calculated the weighted average pollution intensity based on total sales for each NAICS code.

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. But here we are interested in the income–pollution relationship holding all else constant, including technology. Thus, we apply the same 2002 NEI-based emissions intensities to all years of consumption data,

[5] We use 2002 as that was the last year the NEI and the Census of Manufactures coincided.

Table 1.—Average Values for Selected Variables

	Cross Section		
	1984	2012	Difference
Variable	(1)	(2)	(3)
Pollutant (pounds, 2002 technology)			
PM10	11.69	11.27	−0.42
	(0.15)	(0.11)	(0.19)
VOCs	19.62	15.82	−3.80
	(0.30)	(0.21)	(0.36)
NO_x	72.27	69.56	−2.72
	(0.89)	(0.64)	(1.09)
SO_2	117.00	118.20	1.17
	(1.51)	(1.10)	(1.86)
CO	44.65	37.88	−6.78
	(0.68)	(0.52)	(0.86)
After-tax income	3.78	4.51	0.73
($10,000 in 2002 dollars)	(0.06)	(0.07)	(0.09)
Household size	2.71	2.50	−0.22
	(0.03)	(0.03)	(0.04)
Age of household head	47.03	50.00	2.98
	(0.38)	(0.32)	(0.50)
Head is married (share of population)	0.604	0.506	−0.098
Race of head is black	0.107	0.115	0.008
Education of head (share of population)			
Elementary only	0.293	0.130	−0.162
High school	0.299	0.244	−0.055
Some college	0.201	0.296	0.095
College	0.106	0.209	0.103
More than college	0.102	0.121	0.019
Region (share of population)			
Northeast	0.183	0.179	−0.004
Midwest	0.219	0.212	−0.008
South	0.261	0.374	0.113
West	0.169	0.225	0.056
Rural	0.167	0.082	−0.085
Observations	3,184	3,538	

Values calculated using sample weights. Standard errors in parentheses. Nominal incomes adjusted using the CPI for all items; nominal expenditures adjusted using the corresponding price series for food and beverages, gasoline, electricity, fuel oil, and core expenditure.

essentially calculating the predicted amount of pollution that would be necessary to produce each household's consumption each year if all industries used their 2002 technologies and associated emissions intensities.[6]

As an illustration, note that in table 1, the SO_2 embodied in the typical household's consumption rose slightly between 1984 and 2012, from 117.0 to 118.2 pounds. But the national average ambient sulfur pollution fell during that same period by 73%.[7] The increase observed in table 1 is based only on changes in the quantity and composition of household consumption, setting aside changes in the technology used to produce those goods and services.

A third issue concerns international trade. We use U.S.-based emissions intensities for each industry. Readers can think of that as an assumption that all goods are manufactured in the United States, including intermediate inputs, or as an assumption that all production everywhere uses U.S. technology with U.S. emissions intensities, but where we account for pollution no matter where in the world it is emitted.

If we were interested in accounting for actual worldwide emissions, these EECs would have measurement error affecting the results in a number of ways. If over time, Americans have been importing more from countries with higher pollution intensities, actual EECs have been shifting down less quickly than we have estimated, or might even be shifting up. That point is refuted by Levinson (2009, 2015) and Brunel (2016), who show that shifting U.S. imports have not accounted for a significant change in U.S. pollution.

Another way imports might affect our estimated EECs would be if high-income households typically consume more imported goods and other countries use more pollution-intensive processes. In that case, rich households would be responsible for more worldwide pollution than we have estimated and actual EECs in any year would be steeper or less concave. Alternatively, if low-income households consume more imports and other countries pollute more, then actual EECs in any year would be less steep.

To be clear, we do not know the pollution intensities of foreign producers, so we cannot account for overseas pollution. By concentrating on U.S. consumers and U.S. emissions intensities, we focus on two simpler and as yet unstudied questions: How much has U.S. consumption shifted toward cleaner goods, as defined by U.S. emissions intensities, and how has that shift been divided between movements along and shifts in the EECs?

Although assembling the data to estimate 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. People might choose their incomes in order to purchase the goods they desire to consume. Estimating traditional Engel curves therefore involves tricky issues of identification (Blundel, Chen, and Kristensen 2007). But for EECs, we believe we can safely assume 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. 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 underlying relationships. The Engel curve for beef may be ambiguously shaped if hamburger is a necessity and steak a luxury. When estimating EECs, however, what matters is the overall pollution created indirectly as a result of each household's total consumption, 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

[6] Others have studied how regulations drive technological change—for example, Popp (2002), Aghion et al. (2016), and Brunel (2017). Our focus is on consumption, so any regulation-caused change in pollution that we predict comes from changes to goods' prices or availability.

[7] www.epa.gov/air-trends/sulfur-dioxide-trends.

households purchase higher-quality goods that are more expensive, they may spend more on those goods without consuming larger physical quantities or being responsible for more pollution. We estimate pollution using per dollar pollution intensity coefficients, so expensive items are assigned more pollution than inexpensive items. This results in an overestimate of the income elasticity of EECs. Any pollution reduction we attribute to movements along EECs can thus be interpreted as conservative.

III. Nonparametric Estimates of Environmental Engel Curves

No theory dictates the form of the income-pollution relationship, so a natural first step is to examine the shape and structure of the EECs with as few restrictions as possible.[8] We start by simply plotting pollution embodied in consumption at different income levels, without controlling for other household characteristics. In the next section, we estimate quadratic versions that account for household demographics and regional variations, including prices, but the results there do not differ notably from these initial nonparametric versions.

We first separate households in the 1984 cross section of the CEX into fifty groups based on after-tax income, where each group represents 2% of the overall 1984 income distribution. We use after-tax income because otherwise, changes in the shape of the Engel curve between 1984 and 2012 might be affected by changes in the progressivity of income tax policy. During that period, the top marginal federal income tax rate fell from 50% to 35%. If we ignore that decline in progressivity, along with the pollution emitted producing government goods and services, it would exaggerate the concavity of the EECs found in later years.

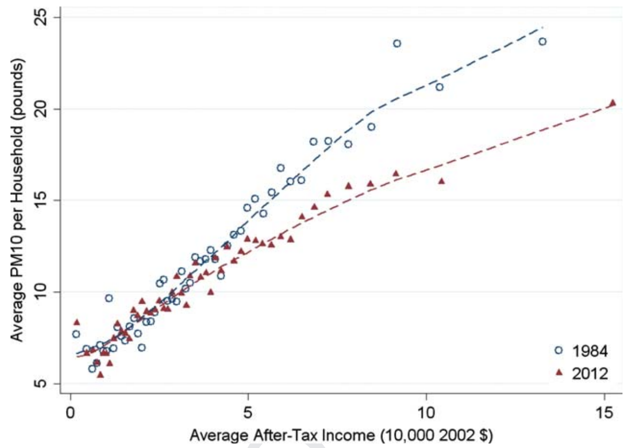
Next we calculate the average pollution associated with consumption for each of the fifty income groups. We start with PM10 because of its significant public health consequences and importance to cost-benefit analyses, but we also show similar results for other major local air pollutants. Plotting these fifty points with income on the horizontal axis and pollution on the vertical axis yields a nonparametric EEC for 1984, shown as the top line in figure 1. A household in the median income bin ($30,636 to $31,828 after taxes, in 2002 dollars) would have been indirectly responsible for an average of 11.14 pounds of PM10.

To show how the EEC evolves over time, figure 1 also depicts a second EEC estimated using the 2012 CEX. To keep the two curves directly comparable, we use the same income bin cutoff values in the 2012 EEC as are used in the 1984 EEC.[9] Households with 2012 after-tax income in the 1984 median bin ($30,636–$31,828) would have been indirectly responsible for 9.91 pounds of PM10 on average, 11% less than households with the same income in 1984.

[8] Common approaches others have taken range from simply plotting the data to nonparametric kernel estimation (Lewbel, 1991; Hausman, Newey, & Powell, 1995).

[9] Figure A.12 in the appendix compares the shares of households in each bin for 1984 and 2012.

FIGURE 1.—POLLUTION EMBODIED IN HOUSEHOLD CONSUMPTION: PM10



Income is adjusted for inflation using the all-items CPI. Consumption expenditure is adjusted using the core CPI with food, fuel, gasoline, and electricity adjusted separately using the corresponding CPI. Each pair of dots represents an income level corresponding to 2% of the 1984 CEX sample, with the highest and lowest 1% of households trimmed based on after-tax income. The top income bin includes all remaining households with real annual after-tax income higher than $110,529.

Three phenomena are apparent from the EECs in figure 1. First, EECs slope up. Richer households are responsible for more overall pollution. This is not surprising since richer households buy more goods and services.

Second, EECs have income elasticities less than 1. Pollution, according to these EECs, is a necessity.[10] Although much of the concavity appears at the top of the income distribution, rich households account for more spending. As a result, the slope and concavity depicted in figure 1 have large effects on overall pollution, as we show later. And the concavity in figure 1 may be understated if richer households consume more expensive versions of the same goods.

Third, figure 1 suggests that EECs shift down over time. Households in the 2012 EEC are responsible for less pollution than their 1984 counterparts with similar incomes. This shift is not due to improvements in technology or abatement because both curves use the same 2002 emissions intensities. Instead, the downward shift in figure 1 reflects a change in consumption composition due to some combination of changing prices, regulations, or social norms.[11]

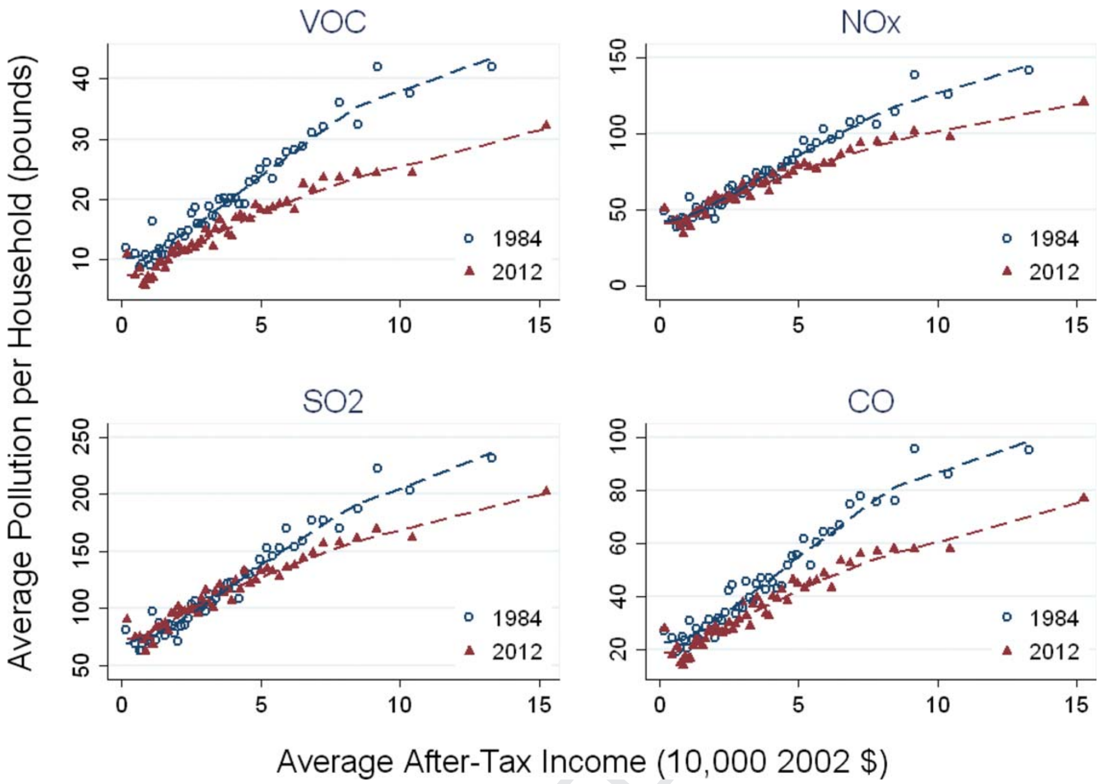
In figure 2 we plot these same nonparametric EECs for four other common air pollutants: VOCs, NO_x, SO_2, and CO. All are similarly increasing, concave, and shifting down over time.

One drawback of the otherwise flexible approach to estimating EECs depicted in figures 1 and 2 is that they do not

[10] Of course, households are not choosing pollution directly, so it may not be accurate to call pollution a "necessity." It might be more accurate, if awkward, to say that goods and services that generate relatively more pollution are, on average, necessities.

[11] Similar results obtain using pretax income or consumption on the horizontal axis rather than income. See online appendix figures A.8, A.9, and A.15.

FIGURE 2.—NONPARAMETRIC EECS FOR OTHER POLLUTANTS



See the notes to figure 1.

account for additional demographic factors related to household consumption. Standard Engel curves can vary with consumer characteristics (Lewbel, 2009). In our context, those other characteristics may account for both the shape of EECs and their changes over time. In any year, richer households consume a less pollution-intensive mix of goods and services, but they also have different household sizes, ages, and so on. And over time households appear to have consumed a less pollution-intensive mix of goods and services, but average household sizes, ages, and locations also changed.

A related concern with the approach depicted in figures 1 and 2 is that the law of one price may not hold. If some regions of the country have higher household incomes and higher relative prices for goods that require more pollution to produce, then our curves conflate income elasticities and price differences. Or, if incomes and relative prices have changed over time at different rates in different regions, our division of the cleanup into movements along and shifts in Engel curves may be biased by price effects.

Table 1 reports some of these key household characteristics along with estimated indirect pollution. Between 1984 and 2012, the average indirect PM10 emissions decreased almost imperceptibly (from 11.69 pounds to 11.27 pounds), while average real after-tax income increased 19% (from $37,797 to $45,094). At the same time, the average household became older, smaller, better educated, more urban, less likely to be married, and more likely to live in the South and West. To assess whether these demographic changes account for the shape and movements in the EECs, we turn to parametric estimations.

IV. 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 begin by estimating a series of regressions with household pollution on the left-hand side and after-tax income, income squared, and other covariates on the right-hand side:

$$P_{it} = \alpha_t Y_{it} + \beta_t Y_{it}^2 + \boldsymbol{X_{it}\delta_t} + \varepsilon_{it}, \tag{1}$$

where P_{it} and Y_{it} are pollution and after-tax income and X_{it} is a vector of other covariates. The coefficients are indexed by t because we run separate regressions for each year.

Column 1 of table 2 shows a version of that regression for PM10 pollution with only the after-tax income quadratic, excluding all the other household characteristics, using the 1984 CEX. The estimated shape is concave, and the negative coefficient on income squared (–0.03) is statistically significant.

The second column of table 2 adds control variables for age, household size, marital status, indicators for race and

Table 2.—Parametric Environmental Engel Curves for PM10

Dependent variable: Pounds PM10 per Household	1984		1994	2005	2012	Coefficient change, 1984–2012
	(1)	(2)	(3)	(4)	(5)	(6)
After-tax income ($10,000 in 2002 dollars)	1.950	1.124	0.947	1.103	0.997	−0.127
	(0.132)	(0.154)	(0.145)	(0.110)	(0.087)	(0.177)
After-tax income squared	−0.0317	0.0045	0.0019	−0.0107	−0.0191	−0.0236
	(0.0119)	(0.0119)	(0.0131)	(0.0065)	(0.0053)	(0.013)
Household size		2.321	2.125	2.476	1.671	−0.65
		(0.232)	(0.250)	(0.249)	(0.210)	(0.313)
Household size squared		−0.158	−0.145	−0.202	−0.0786	0.0794
		(0.0255)	(0.0326)	(0.0289)	(0.0269)	(0.037)
Age		0.265	0.240	0.185	0.160	−0.105
		(0.0337)	(0.0333)	(0.0329)	(0.0314)	(0.046)
Age squared		−0.00238	−0.00206	−0.00135	−0.00111	0.00127
		(0.00032)	(0.00032)	(0.00030)	(0.00031)	(0.000)
Married		0.746	1.247	1.282	0.995	0.249
		(0.291)	(0.251)	(0.285)	(0.219)	(0.364)
Race: Black		−1.891	−0.942	(0.336)	−0.783	1.108
		(0.275)	(0.283)	−3.016	(0.272)	(0.387)
Race: Asian		−0.856	−1.902	(0.489)	−1.777	−0.921
		(0.950)	(0.677)	−0.362	(0.341)	(1.009)
Race: Other		−2.324	1.714	(0.634)	−0.182	2.142
		(0.718)	(1.151)	1.189	(0.623)	(0.951)
Education: High school		1.147	0.861	(0.270)	1.178	0.031
		(0.303)	(0.260)	1.103	(0.246)	(0.390)
Education: Some college		1.487	1.431	1.583	1.430	−0.057
		(0.305)	(0.306)	(0.297)	(0.241)	(0.389)
Education: College		1.821	1.657	2.058	1.677	−0.144
		(0.455)	(0.366)	(0.390)	(0.314)	(0.553)
Education: Graduate		1.978	1.907	1.495	2.411	0.433
		(0.456)	(0.435)	(0.522)	(0.464)	(0.651)
Region: Midwest		0.060	−0.642	−0.653	−0.644	−0.704
		(0.325)	(0.296)	(0.271)	(0.251)	(0.411)
Region: South		1.498	1.136	1.724	0.922	−0.576
		(0.339)	(0.288)	(0.287)	(0.253)	(0.423)
Region: West		−0.447	−0.126	1.332	−0.005	0.442
		(0.334)	(0.304)	(0.384)	(0.271)	(0.430)
Rural		0.536	0.767	−0.670	0.049	−0.487
		(0.353)	(0.367)	(0.319)	(0.338)	(0.489)
Constant	5.015	−5.553	−4.393	−4.985	−2.898	2.655
	(0.305)	(0.879)	(0.845)	(0.893)	(0.769)	(1.168)
Income elasticity at median	0.510	0.335	0.286	0.335	0.281	
	(0.020)	(0.026)	(0.022)	(0.023)	(0.018)	
F-test of income coefficients	483.4	165.5	147.5	153.3	188.5	
Observations	3,184	3,184	2,923	3,703	3,538	
R^2	0.407	0.520	0.459	0.381	0.410	

Robust standard errors in parentheses. Household pollution calculated by multiplying itemized household consumption with the 2002 pollution intensity of production for each type of good and summing for each household. Includes upstream pollution based on a Leontief input-output calculation. Nominal incomes adjusted using the CPI for all items; nominal expenditures are adjusted using the corresponding core, food and beverage, gasoline, electricity, and fuel oil CPIs. Income elasticities calculated at the annual median value of after-tax income, with all other variables fixed at their annual means.

education of the household head, and regional indicators that control for relative price differences.[12] Nearly all covariates are statistically significantly correlated with total PM10. Overall, the results suggest that households that are larger, older, married, more educated, nonblack, and located in the South were indirectly responsible for more pollution. The estimated EEC is still upward sloping, but it is less steep and not concave.

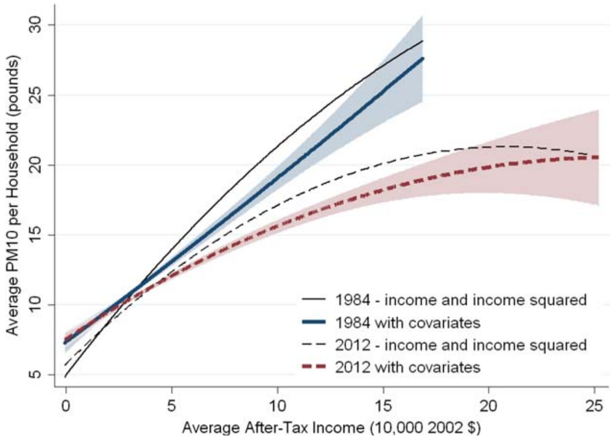
The change in the EECs between columns 1 and 2 of table 2, with the addition of covariates, raises concerns about omitted variable bias. To address this, in what follows, we estimate all of our results two ways: first, with only income and income squared as in column 1, and second, with a full set of covariates as in column 2. As we will show, adding the extra observable covariates does not change our fundamental conclusions about the shapes of the curves, how they change over time, or the decomposition of pollution changes into movements along and shifts in EECs between 1984 and 2012.[13]

To compare these parametrically estimated EECs across time, columns 3 through 5 of table 2 repeat the regression

[12] For now we include only the four Census regions. Later, we discuss adding state indicators.

[13] To formalize this, we also estimated a version using Altonji, Elder, and Taber (2005) as refined by Oster (2017). Under some restrictive assumptions about the relationship between observed and unobserved covariates, the short and long regressions in columns 1 and 2 of table 2 can be used to approximate the true coefficients from a hypothetical regression using a full set of observed and unobserved covariates. In our case, the results suggest that column 2 provides a reasonable estimate of the causal effect of income on pollution, even after taking into account other observed and unobserved household characteristics.

FIGURE 3.—EECs BASED ON PARAMETRIC ESTIMATES: PM10



All other covariates are fixed at their mean values. Inflation adjustments as in figure 1. Standard errors for pollution intensity of production are not estimated, so 95% confidence intervals (shaded) reflect variation in household spending.

from column 2 using the 1994, 2005, and 2012 CEX. Column 6 shows the difference between coefficients in 1984 and 2012. Household size and age had smaller effects on pollution in 2012 than in 1984, whereas household size squared, age squared, and race being black or other had larger effects.[14]

Figure 3 plots the predicted relationship between income and PM10 pollution based on the EECs estimated in table 2. The two thick lines—one solid and one dashed—are based on columns 2 and 5 of table 2. Each is drawn by fixing the other covariates aside from income at their average values for their respective years. These EECs plot income expansion paths holding other observable household characteristics constant. They have similar characteristics to the nonparametric EECs in figure 1: they are upward sloping, have elasticities less than 1, and shift down over time. In addition, the curves become increasingly concave in recent years.[15]

To demonstrate what adding covariates does to the EECs, the two thin lines in figure 3 plot regressions of pollution on income and income squared alone: column 1 of table 2 for 1984 and its analog (not shown) for 2012. Although adding the covariates does change their shape somewhat, the basic results remain. The EECs slope up, are increasingly concave, and shift down over time.

Table 3 shows coefficient estimates for quadratic EECs for four other common air pollutants—VOCs, NO_x, SO_2, and CO—using the 1984 and 2012 CEX. In all cases, the coefficient on after-tax income is positive and statistically significant. Similar to PM10, the effect of after-tax income squared is not significant in 1984 but becomes negative and significant by 2012. Further, the sign and significance of other covariates are consistent with the PM10 EEC. The hallmark attributes of the individual PM10 EECs—upward sloping, becoming more concave, and shifting down over time—are also exhibited by other common air pollutants.[16]

Out of concern that the four Census region indicators used in tables 2 and 3 might not sufficiently account for geographic differences, including relative prices, we have also estimated all of the models using state fixed effects. State indicators became available in the CEX only starting in 1993, so we lose the first nine years of data. The income coefficients for all pollutants can be found summarized in table A.2 in the online appendix. The coefficients on income and income squared are not notably different from those with the regional fixed effects, and the basic results remain. Engel curves become flatter and shift down over time.

The two approaches so far represent extremes of parameterization. Figures 1 and 2 plot means of pollution by income group, assuming no functional form. At the other extreme, figure 3 assumes pollution follows a quadratic function of income, controlling for other household characteristics. As an intermediate case, we have also estimated all of the EECs using restricted cubic splines, using five spline knots rather than the income quadratic. Graphs of the splines look similar to both the nonparametric and quadratic specifications: EECs are upward sloping, have elasticities less than 1, and shift down over time.[17]

Finally, some readers have observed that consumption choices made early in people's lives may persist, either because the goods purchased are long-lived durables or because people develop spending habits. In other words, EECs for individuals whose incomes grow over time may not be as flexible or concave as a hypothetical EEC comparing two identical individuals with different incomes. We address this in two ways. First, in all of the parametric specifications, we include the age and age squared of the household head. That way, our plotted EECs compare the consumption choices of people with identical ages but different incomes. Second, we repeated all of the analysis, parametric and nonparametric, limited to cases where the head of household is in the youngest fourth of the age distribution, less than 34.5 years old. Incomes are lower, unsurprisingly, but the basic results persist. EECS have positive slopes, elasticities less than 1, and shift down over time.[18]

V. An Application: Decomposing the Composition Effects

Movements along EECs depend on underlying preferences of richer households relative to poorer households, all

[14] Over the entire 29-year period, the income coefficient remains about steady, and slightly greater than 1.0 for PM10. The coefficient on income squared becomes more precisely estimated over time and is marginally significantly negative throughout the latter half of the period. See appendix figure A.11 for all 29 pairs of coefficients.

[15] Other nonlinear specifications (cubic polynomials and logarithms) yield similar results: EECs are upward sloping, have elasticities less than 1, and shift down over time.

[16] Figure A.16 in the online appendix depicts versions of this same relationship for these other air pollutants, with similar income expansion paths.

[17] Plots of the restricted cubic splines are in the online appendix figures A.13 and A.14.

[18] Available separately from the authors.

Table 3.—Parametric EECs for Other Air Pollutants

	VOC		NO_x		SO_2		CO	
	1984	2012	1984	2012	1984	2012	1984	2012
Dependent Variable (pounds):	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
After-tax income ($10,000 in 2002 dollars)	2.281	1.857	6.720	6.020	10.450	9.527	5.961	4.622
	(0.337)	(0.161)	(0.838)	(0.470)	(1.479)	(0.840)	(0.685)	(0.417)
After-tax income squared	0.0034	−0.0349	−0.007	−0.125	0.036	−0.188	−0.040	−0.092
	(0.0256)	(0.0106)	(0.066)	(0.028)	(0.116)	(0.049)	(0.055)	(0.025)
Other regressors	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Income elasticity at median	0.402	0.382	0.311	0.270	0.308	0.254	0.437	0.393
	(0.035)	(0.023)	(0.023)	(0.016)	(0.025)	(0.017)	(0.030)	(0.027)
F-test of income coefficients	126.9	205	184.8	216.8	160.8	168.6	161.7	154.8
Observations	3,184	3,538	3,184	3,538	3,184	3,538	3,184	3,538
R^2	0.413	0.364	0.555	0.456	0.521	0.409	0.403	0.317

See notes for table 2. The full set of coefficients is available in online appendix table A.1.

else equal. They are independent of any particular environmental policy intervention. In this sense, movements along an 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.

The Oaxaca-Blinder decomposition provides a mechanism for separating these components while holding other demographic changes constant.[19] Define the average level of pollution in a given year based on the regressions from table 2:

$$\bar{P}_t = \alpha_t \bar{Y}_t + \beta_t \overline{Y_t^2} + \overline{\mathbf{X}}_t \boldsymbol{\delta}_t, \tag{2}$$

where $\bar{P}_t$ is average indirect pollution, $\bar{Y}_t$ and $\overline{Y_t^2}$ are average income and income squared, and $\overline{\mathbf{X}}_t$ is the average of other included covariates. The error term disappears because the average OLS error is 0 by construction.

The change in average pollution between 1984 and 2012 can then be written as:

$$\begin{aligned}\bar{P}_{12} - \bar{P}_{84} = {} & \alpha_{12}\bar{Y}_{12} + \beta_{12}\overline{Y_{12}^2} + \overline{\mathbf{X}}_{12}\boldsymbol{\delta}_{12} \\ & - \alpha_{84}\bar{Y}_{84} - \beta_{84}\overline{Y_{84}^2} - \overline{\mathbf{X}}_{84}\boldsymbol{\delta}_{84}\end{aligned} \tag{3}$$

By adding and subtracting $\alpha_{84}\bar{Y}_{12} + \beta_{84}\overline{Y^2}_{12} + \overline{\mathbf{X}}_{12}\boldsymbol{\delta}_{84}$ and grouping terms, we have

$$\begin{aligned}\bar{P}_{12} - \bar{P}_{84} = {} & \alpha_{84}(\bar{Y}_{12} - \bar{Y}_{84}) + \beta_{84}\left(\overline{Y_{12}^2} - \overline{Y_{84}^2}\right) \\ & + (\alpha_{12} - \alpha_{84})\bar{Y}_{12} + (\beta_{12} - \beta_{84})\overline{Y_{12}^2} \\ & + \bar{X}_{12}(\delta_{12} - \delta_{84}) + (\bar{X}_{12} - \bar{X}_{84})\delta_{84}.\end{aligned} \tag{4}$$

[19] Oaxaca (1973) and Blinder (1973).

The first two terms in equation (4) capture the effect of changing income on total point-source air 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 the changing coefficients on income and income squared. 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 entry 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, holding all else constant including technology. 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 PM10 embodied in the average household's consumption decreased by only 0.42 pound between 1984 and 2012 (from table 1). Changes in average after-tax income and income squared led to a hypothetical increase of 0.88 pound (0.82 increase from after-tax income and 0.06 increase from after-tax income squared). At the same time, changing demographics would have led to an additional increase of 0.12 pound. The remaining difference, 1.42 pounds, 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 after-tax income resulted in increases in emissions (1.71 pounds, 4.82 pounds, 8.09 pounds, and 3.84 pounds, respectively). As with PM10, these increases were augmented by demographic changes. The remaining portions of the changes for each pollutant were large, ranging from 5.74 pounds for VOC to 11.09 pounds for CO. For none of the pollutants, however, do the demographic changes other than income have substantial effects on total pollution, listed at the bottom of table 4; the pollution effects of the movements along and shifts in the EECs are much larger.

TABLE 4.—MOVEMENT ALONG PARAMETRIC EECS FOR AIR POLLUTANTS: 1984–2012 INCREASE IN POLLUTION DUE TO MOVEMENT ALONG AN EEC (POUNDS)

	PM10	VOC	NO_x	SO_2	CO
Dependent Variable:	(1)	(2)	(3)	(4)	(5)
After-tax income ($10,000 in 2002 dollars)	0.820	1.665	4.903	7.625	4.350
	(0.150)	(0.318)	(0.852)	(1.419)	(0.726)
After-tax income squared	0.058	0.043	−0.084	0.465	−0.509
	(0.154)	(0.329)	(0.847)	(1.495)	(0.703)
Household size	−0.500	−0.669	−3.047	−4.979	−1.487
	(0.110)	(0.171)	(0.667)	(1.101)	(0.383)
Household size squared	0.20	0.273	1.186	2.029	0.702
	(0.058)	(0.097)	(0.343)	(0.585)	(0.232)
Age	0.788	1.354	5.101	8.033	3.225
	(0.165)	(0.317)	(1.033)	(1.686)	(0.733)
Age squared	−0.661	−1.224	−4.139	−6.626	−2.896
	(0.147)	(0.295)	(0.906)	(1.491)	(0.677)
Married	−0.073	−0.176	−0.455	−0.749	−0.405
	(0.030)	(0.061)	(0.172)	(0.297)	(0.151)
Race dummies	−0.038	0.014	−0.273	−0.615	−0.133
Education dummies	0.304	0.485	2.140	3.433	0.905
Regional dummies	0.099	0.173	0.429	0.803	0.561
Total change due to income (movement along EEC)	0.88	1.71	4.82	8.09	3.84
Total change due to other demographics	0.12	0.23	0.94	1.33	0.47
Unexplained difference (shift in EEC)	−1.42	−5.74	−8.48	−8.25	−11.09

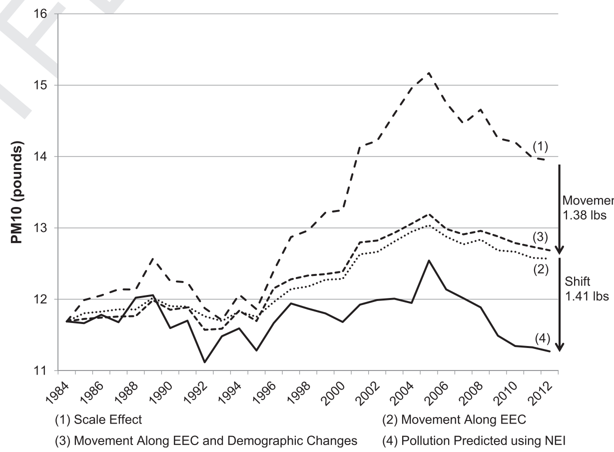
Estimates based on Oaxaca-Blinder decompositions. Robust standard errors in parentheses. Movement along each EEC calculated by multiplying the coefficients in tables 2 and 3 by the corresponding changes in table 1. Total changes calculated by summing the individual changes. Pollution based on 2002 production technology for all years. Values for race, education, and regional indicators are the combined effect for each category.

The increases in emissions due to changes in household income, such as the 0.88 pound increase in PM10, can be further decomposed into separate household-level scale and composition components. Along an EEC, richer households consume more goods and services but a less pollution-intensive mix of goods and services. The balance of these two effects depends on the shape of the EEC. To the extent that EECs are inelastic, the compositional component is stronger and households with higher incomes are responsible for proportionally less pollution. This effect becomes more pronounced as EECs become increasingly concave.

Figure 4 depicts the relative magnitude of these effects for PM10 over time by applying the same decomposition every year from 1984 and 2012. 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.[20] Line 2 captures the hypothetical effect of movements along the 1984 EEC. The gap between lines 1 and 2 is the offsetting compositional effect reflected in the inelastic shape of EECs. Line 3 shows the contribution of changing demographics in addition to changing income and falls slightly above the second line because the balance of other factors, such as household size, education, and geography, led to a slight net increase in the pollution intensity of consumption.

The bottom line of figure 4 shows the predicted pollution in each year calculated by pairing the 2002 emissions intensity coefficients with each year's CEX expenditures. This is the pollution that would occur if technology were fixed based on 2002 emissions intensities, but where we account for the actual mix of goods and services consumed by households. The vertical distance between lines 3 and (4) is due to downward shifts in the EEC over time.

FIGURE 4.—DECOMPOSITION OF PREDICTED POLLUTION FROM HOUSEHOLD CONSUMPTION



The scale effect is calculated by increasing pollution in proportion to real after-tax income growth. Movements along and shifts in the EEC are calculated by estimating pollution in each year using the 1984 EEC coefficients. Pollution predicted using NEI-based pollution coefficients is estimated by matching itemized consumption expenditure in each year with the corresponding industry's 2002 pollution intensity.

Table 5 presents the calculations behind figure 4, decomposing household consumption-related pollution changes between 1984 and 2012, into those due to the scale of income growth, movements along the EEC, shifts in the EEC, and other demographic changes. Column 1 repeats the predicted change in household pollution from table 1, holding technology fixed using 2002 emissions intensities.

[20] A curious feature of the CEX is that real household incomes did not grow between 1984 and 1995. Hence, all of the changes we describe in table 5 stem from income growth during the last half of the sample period. See the online appendix for a comparison of income measured in the CEX to that reported by the Congressional Budget Office and in the Current Population Survey.

TABLE 5.—POLLUTION OFFSET DUE TO COMPOSITIONAL CHANGES IN HOUSEHOLD CONSUMPTION: SUMMARY OF LOCAL AIR POLLUTANTS

				Offset by Movement along EEC		Offset by Demographic Changes		Offset by Shifts in EEC	
	Total Change (pounds)	Scale Increase (pounds)	Total Spread (2) – (1)	Pounds	Share of Spread	Pounds	Share of Spread	Pounds	Share of Spread
Pollutant	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PM10	−0.42	2.26	2.68	1.38	0.52	−0.12	−0.044	1.41	0.53
VOC	−3.80	3.79	7.59	2.08	0.27	−0.23	−0.030	5.74	0.76
NO_x	−2.72	13.95	16.67	9.13	0.55	−0.93	−0.056	8.47	0.51
SO_2	1.17	22.58	21.41	14.49	0.68	−1.33	−0.062	8.25	0.39
CO	−6.78	8.62	15.40	4.78	0.31	−0.47	−0.031	11.09	0.72

The total change in pollution is predicted using CEX and NEI data, based on 2002 production technology. The scale increase in pollution is calculated by multiplying pollution levels in 1984 by the proportional increase in after-tax income between 1984 and 2012. The total spread is calculated as the difference between the predicted change from the NEI-based pollution coefficients 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.

Four of the five pollutants decline, and SO_2 increases only slightly. For PM10, the decline is just 0.42 pounds, depicted as the bottom line of figure 4. The second column of table 5 describes the household-level scale effect. Between 1984 and 2012, average household after-tax income increased 19%. That is the top line of figure 4. With no compositional shift in consumption, we would expect emissions of each pollutant in table 5 to also increase by 19%. In the case of PM10, that means an increase of 2.26 pounds per household. The difference between columns 1 and 2—2.68 pounds 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 2.26 pound increase in PM10 and our movement-related estimate of 0.88 from table 4 represents the mitigating effect of compositional shifts along the 1984 EEC. Compositional changes in consumption along the EEC offset 1.38 pounds of PM10 from the scale effect, reported in column 4 of table 5. In total, the compositional offsets (−1.38 from movement along the EEC and −1.41 pounds from shifts in the EEC), together with the demographics (+0.12 pound) counteract the scale effect (2.26 increase) to equal the overall predicted change of −0.42 pound. Those changes are depicted in figure 4 as lines 2 and 3.

All five major air pollutants exhibit similar patterns in table 5. Total emissions predicted by household consumption declined or increased only slightly (column 1), even though emissions would have grown substantially if they had increased one-for-one with household income (column 2). That difference (column 3) is partly offset by the fact that EECs are inelastic. Pollution predicted by consumption does not increase one-for-one with income (columns 4 and 5). The difference is mostly unaffected by demographic changes (columns 6 and 7). And the difference is partly explained by downward shifts in the EECs. Households with similar income and demographics consume a less pollution-intensive mix of goods and services in 2012 than they did in 1984 (columns 8 and 9).

A key conclusion from table 5 is that movements along EECs and shifts in EECs are roughly equally responsible for reductions in household pollution relative to a pure scale effect. 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 EEC, and column 8 contains the pollution reductions due to shifts in the EEC between 1984 and 2012. They are of roughly similar magnitudes. 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 27% to 68% of the overall compositional effect, and shifts in the EECs explain 39% to 76%. But the fundamental insight is similar across pollutants. Changes in the goods and services households consumed between 1984 and 2012 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 inelastic EECs and those due to downward shifts of EECs over time.

We have also estimated a version of table 5 and figure 4 where the "movement along" calculation is based on EECs estimated from the quadratic in income alone, as in column 1 of table 2. That line overlies lines 2 and 3 in figure 4, and we have included the figure in the appendix (figure A.10). Adding the demographic covariates does not change the conclusion that consumption-related changes in the composition of polluting goods in the United States can be divided about equally between movements along and shifts in EECs.

Figures analogous to figure 4 drawn for the other four pollutants in table 5 make the same point.[21] Shifts in the mix of goods and services consumed by the average household have more than offset any pollution increase due to growth in household income. About half of those composition changes come solely from the fact that richer households consume a less pollution-intensive mix of goods, and

[21] Figures A.4 through A.7 in the online appendix.

the other half comes from the fact that households at every income level consume a less pollution-intensive mix in 2012 than they did in 1984.

VI. Discussion

Half of the decline in indirect air pollution from U.S. household consumption comes from downward shifts in EECs. Can that be attributed to environmental regulations? Perhaps. It is not attributable to regulations' effects on emissions intensities, because throughout, we have held emissions intensities constant at their 2002 levels. This is in the spirit of Engel curves holding all else equal. But the downward shift we see over time might be the indirect effect of regulations through their effects on prices. If regulations increase the relative prices of goods whose production emits more air pollution and households respond by consuming less of those more expensive goods, that could account for part of why our estimated EECs shift down over time.

More generally, the EECs we estimate help put broad changes in the U.S. environment into context. Over the past thirty years, air pollution in the United States has declined despite increases in total production. Some of this improvement has come from employing cleaner technologies, but some has come from consuming a cleaner mix of goods and services. How much of this cleaner consumption has been a consequence of economy-wide trends, such as regulation-induced price changes, and how much comes from 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 comparing these two effects.

Whether estimated parametrically or nonparametrically, EECs display three key characteristics: they are increasing, have elasticities less than 1, and are shifting down and becoming more concave 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 2012, we find that compositional changes in consumption due to movements along EECs and downward shifts of EECs more than offset the 19% increase in real 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.

A few caveats deserve mention. We study only five air pollutants—the ones documented most thoroughly by the NEI and that have been the focus of most decomposition analyses. That focus omits pollution from nonpoint sources (such as vehicles), other media (water pollution), and all other types of air pollution. We cannot be sure other pollutants follow the patterns we observe for the criteria air pollutants, but we suspect similar conclusions would apply.

In the end, this decomposition of pollution changes into movements along and shifts in 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, but a significant fraction comes from the changing composition of production. If changing import composition does not account for that changing production, then it must come from consumption. Isolating the consumption-related compositional changes in pollution suggests that household-level composition changes have more than offset the increased pollution from growing incomes.

In understanding the offsetting effect of compositional changes, the distinction between movements along and shifts in 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. Richer households in any given year do consume a proportionally less pollution-intensive mix of goods. 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 reduction. But households with the same real incomes also consumed a cleaner mix of goods in 2012 than in 1984, an improvement that accounts for an approximately equal reduction and one that must come from changes to aggregate conditions such as prices, social norms, or environmental policies.

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