Dematerialization: Variety, caution, and persistence

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Contributed by Paul E. Waggoner, June 28, 2008 (sent for review June 7, 2008)

Dematerialization, represented by declining consumption per GDP of energy or of goods, offers some hope for rising environmental quality with development. The declining proportion of income spent on staples as affluence grows, which income elasticity <1.0 measures, makes dematerialization widespread. Further, as learning improves efficiency of resource use, the intensity of environmental impact per production of staples often declines. We observe that combinations of low income elasticity for staples and of learning by producers cause a variety of dematerializations and declining intensities of impact, from energy use and carbon emission to food consumption and fertilizer use, globally and in countries ranging from the United States and France to China, India, Brazil, and Indonesia. Because dematerialization and intensity of impact are ratios of parameters that may be variously defined and are sometimes difficult to estimate, their fluctuations must be interpreted cautiously. Nevertheless, substantial declining intensity of impact, and especially, dematerialization persisted between 1980 and 2006.

carbon | cropland | energy | fertilizer | impact

If consumers dematerialize their intensity of use of goods and technicians produce the goods with a lower intensity of impact, people can grow in numbers and affluence without a proportionally greater environmental impact (1). For example, the intensity of energy use equals joules per GDP, and intensity of impact equals carbon emission per joule. If the combined intensities of use and impact decline, an economy decarbonizes.

Are dematerialization and declining intensity of impact unfortunately ending, or more fortunately, can they continue ameliorating worries about humanity's impact on the environment, especially changing climate? We test whether dematerialization and declining intensities of impact can be depended on to alleviate anxiety about carbon from energy use, concerns about farming, fertilizer, and forestry. Dare humanity project that consumers will promote sustainability by dematerialization, and project that technologists will promote it by lowering the intensity of impact?

Recent Chinese and American statements about carbon emission exemplify the arrival of the intensities of use and impact at the crux of affairs. Rather than emitting fewer tons of carbon, "[China] reiterated the target that it set a year ago of reducing *energy consumption per unit of economic output* by 20% between 2006 and 2010." (2). The U.S. target combined dematerialization and decarbonization: "Reducing U.S. *emissions intensity* by 18% between 2002 and 2012." (3). Asian-Pacific nations wrote the Sydney Declaration on climate change in terms of *lower energy intensity* (4). (Italics added).

At the same time that the complementary intensities of use and of impact define national goals, they also indicate progress toward sustainability. The World Commission on Environment and Development defined sustainable development with the dual dimensions of 1) meeting the needs of the present and 2) not compromising the ability of future generations to meet their own needs (5). Consistent with these dual dimensions, intensities also have twin dimensions. One dimension of the intensity of use is the GDP that measures economic development or affluence that the present generation enjoys. The other dimension is the consumption of a quantity that may either subtract from resources or harm the environment that future generations will inherit. Thus, stating a national goal in terms of intensity of use suits it to map sustainability. Similarly, the intensity of impact has twin dimensions: An environmental impact like carbon emission divided by a consumption like energy use. Combined, intensity of use and impact can, for example, map carbon emission intensity, whose dimensions are emission divided by GDP. Mapped as functions of affluence measured by per capita GDP, the intensities of use and of impact chart journeys of economic development and sustainability on two-dimensional planes.

During past years, dematerialization and declining intensity of impact have ameliorated a range of humanity's environmental impacts, from the carbon emission attending energy use to the cropland and fertilizer attending food production, and the use of wood (6). Now, the elevation of dematerialization and decarbonization to the crux of affairs plus a fear that "The carbon intensity of the world's economy has stopped decreasing (after 100 years of doing so)." (7–9) sharpen the need for a reassessment. Accordingly, we examine the variety of intensities, the caution needed when interpreting their change, and the evidence that their improvement may persist.

Our assessment employs the ImPACT identity (6), which relates an environmental impact Im to four parameters: Population P, affluence A as GDP per person, consumers' intensity of use C per GDP, and technologists' intensity of impact T per goods used, Table 1. If lowercase symbols represent annual percentage changes, affluence changes by a, intensity of use by c, and intensity of impact by t %/yr. When, for example, a nation increases its GDP 4% and consumers use only 1% more joules of energy, the ratio of joules to GDP falls, making c equal to minus 3%/yr.

Regarding affluence rather than mere passage of years to be the lever that moves intensities, we chart intensity versus affluence rather than versus years. To show how affluence sometimes worsens, sometimes improves the environment, the World Bank also graphed indicators versus affluence (10). On a chart of intensity of use C versus affluence A, dematerialization appears as a downward slope of (c/a). The graph of 4%/yr more affluence and 3%/yr less use per GDP slopes downward at the dematerialization rate (c/a) of minus ¾. This definition connects dematerialization to the income elasticity b that economists have long calculated. Dematerialization (c/a) equals $(b\text{-}1)$, which equates the dematerialization of -¾ to an income elasticity of ¼ that represents a staple rather than a luxury. In rich and poor countries, approximate income elasticities for food are 0.3 and 0.7 (11) and for energy are 0.4 and 0.6 (12), which foreshadow dematerializations of −0.7 to −0.3. Where income elasticity is 0.3, a 10% increase in per capita affluence increases the per capita demand for food only 3% because the intensity of use dematerializes by 7%.

Author contributions: J.H.A. and P.E.W. designed research; J.H.A. and P.E.W. performed research; P.E.W. analyzed data; and J.H.A. and P.E.W. wrote the paper.

The authors declare no conflict of interest.

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Table 1. Variables of the ImPACT identity, their percentage change per year, in lower case, and the corresponding dematerialization rate and income elasticity

Variable	Name	Dimension
Im	Impact	Impact = $P \times A \times C \times T$
P, p	Population	Capita
A, a	Affluence	GDP/Capita
C, c	Intensity of use	Use/GDP
T, t	Intensity of impact	Impact/Use
c/a	Dematerialization rate	Dimensionless
b	Income elasticity	*c/a*+1, Dimensionless

Charts that show consumers' dematerialization and income elasticity can also show how fast technologists change the intensity of the impact of producing the consumed goods. Consider an example of income elasticity 0.3 for food, 10% more affluence, 7% less intensity of use, and 3% more consumption per GDP. Technology could forestall the impact of plowing more land per capita by lowering the intensity of impact with 3% higher yields. Our goal is testing how much the world can depend on dematerialization and declining intensity of impact to help its journey of sustainability as affluence grows, especially by curbing carbon emissions and the impacts of farming, fertilizer, and forestry.

Results

Variety. Declining curves of energy per GDP in Fig. 1 show the falling global and Chinese intensity of energy use that exemplify dematerialization. Showing variety, Brazilian intensity of use instead rose. Because Chinese affluence per person multiplied 8-fold from 1980–2006, its journey from left to right on the chart extends farther than the global journey to a 1.4-fold, and farther than the Brazilian journey to 1.3-fold multiplication of affluence. During the 26-year span, Chinese intensity of use declined to 0.4 and the global to 0.8, whereas Brazilian rose to 1.3 times their 1980 levels. Without the dematerialization from 1980–2006 by Chinese consumers, actual national energy use in 2006 would have been 180% greater. Reversing China's 26-year dematerialization would increase the entire global energy consumption by fully 28%.

Three goods illustrate the variety of declining intensity of impact in Fig. 1. Although global affluence multiplied 1.4-fold from 1980–2005, global farmers raised yields and lowered the cropland per crop production to only 0.6 of the 1980 level. In 1980, world farmers grew 64 of the FAO units of crop production on 1,440 million ha. At the 1980 rate, they would have used 2,584 million ha to grow the 113 units grown in 2005. Instead, they grew the greater 2005 crop on only 1,537 million ha, a savings of a billion ha, slightly more than all of the land and 6 times the cropland of the 50 US states. Global farmers learned to use fertilizer more skillfully and lowered fertilizer per crop production to 0.8 of the 1988 level. The introduction of inexpensive fertilizer in approximately 1950 caused a rapid increase of its intensity of impact until its availability induced plant breeders to develop varieties that responded to it more fruitfully, farmers learned to tailor its application, and its intensity of impact began a steady decline (18). With nuclear power plants, the French lowered carbon emission per energy use to 0.6 whereas affluence grew 1.5 times from 1980–2005. In 2005 a French consumer enjoyed 50% more affluence but used only 20% more energy. In addition, the improved intensity of impact charted in Fig. 1 *lowered* each consumer's emission by a ton of carbon.

In the charts, the general increase of affluence moved the data points rightward. Booms pulled the points farther apart, stagnation pushed them together, and recession during the 1980s placed a few points left of 1980 affluence. The recessions did not clearly reverse dematerialization.

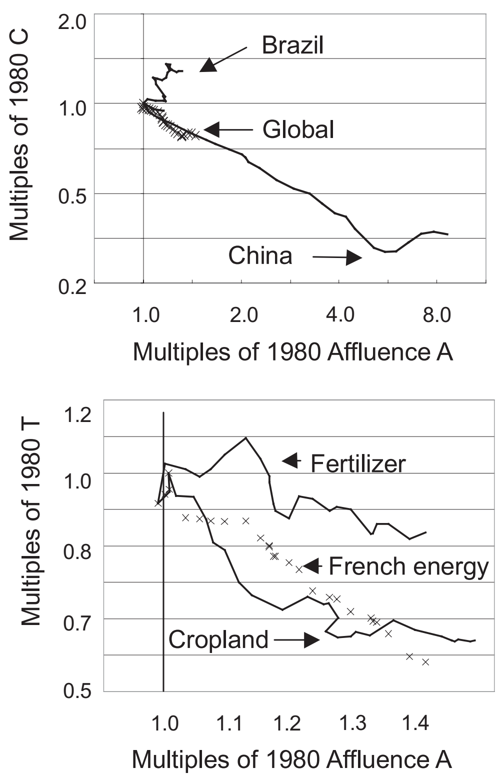

Fig. 1. A variety of change as affluence *A* increased. (*Upper*) From 1980 to 2006, the declining energy intensity globally and in China, and its rise in Brazil, illustrate the variety and wide spread of dematerialization of *C*. The U.S. Dept of Energy Information Agency (DOE) reports were extended from 2005 to 2006 with British Petroleum (BP) reports. (*Lower*) From 1980 to 2005, the declining intensities of impact *T* of fertilizer and cropland per crop production index and of emission per French energy (13–17).

Caution. Divergent 1980–2004 paths of energy dematerialization and intensity of impact in India teach cautionary lessons, Fig. 2. During the 24 years, Indian affluence multiplied 2.4-fold. Because DOE reported that per capita energy and carbon emission multiplied about the same as affluence during the same period, it implied the steady intensities of use and impact in Fig. 2. However, because the International Energy Agency (IEA) included energy from renewables and waste (19, 20), they implied only a 1.5-fold increase in energy use, and hence the dematerialization during the 2.4 multiplication of affluence plotted in Fig. 2.

Although IEA included energy from renewables and waste, they did not include the corresponding carbon in estimating emission and so reported about the same emissions as DOE. Dividing the same change in emission by a smaller change in energy use changed IEA's implied intensity of impact 1.6-fold along the rising path seen in the chart. One set of data implied neither dematerialization nor changing intensity of impact, whereas the other implied steady dematerialization but emitting 60% more carbon to produce a joule of energy in 2004 than in 1980.

Chinese dematerialization and intensity of impact calculated from energy and emission estimates by DOE and IEA demonstrate the caution needed concerning brief changes, Fig. 2. The 2005 DOE and 2006 British Petroleum (BP) estimates show some renewed dematerialization after a 2-year hiatus, a renewed dematerialization not reported by the IEA reports that ended in 2004. Because IEA included energy from combustible renew-

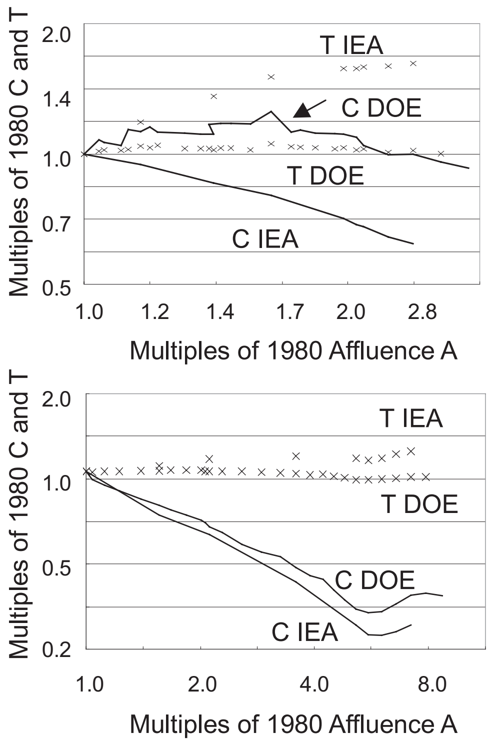

Fig. 2. Two charts illustrating the need for caution about changes in energy and carbon emission as affluence *A* increased. (*Upper*) The differing Indian courses of dematerialization of *C* and change of intensity of impact *T* calculated with (IEA Reference method) and without (DOE) combustible renewables and waste. (*Lower*) The Chinese courses of *C* and *T* calculated with DOE and IEA reports. IEA reference method used and DOE data extended from 2005 to 2006 with BP reports (13–16, 19).

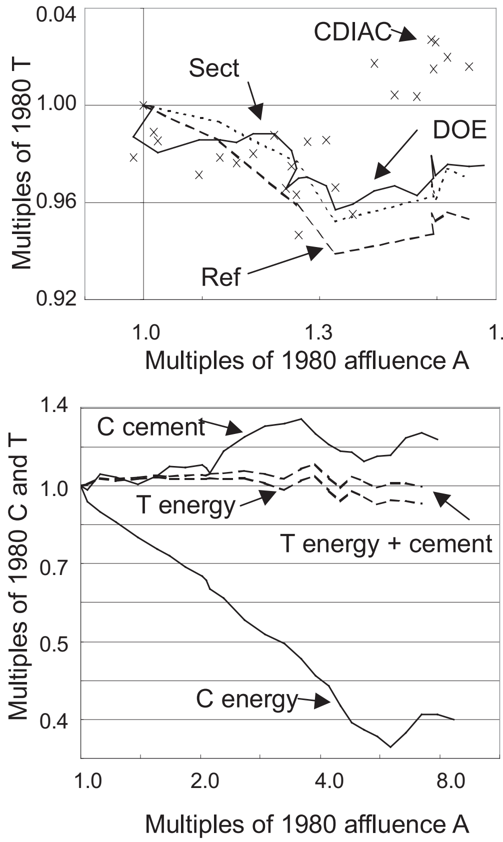

Fig. 3. Two charts illustrating the need for caution about changes in energy and carbon emission as affluence *A* increased. (*Upper*) The differing U.S. courses of energy intensity of impact *T* calculated from CDIAC, IEA Reference (Ref) and Sectoral (Sect) reports (1980 to 2004), and from DOE reports (1980 to 2005). (*Lower*) For China after 1980, the courses of energy intensities of use *C* to 2006 and of cement intensities to 2005 and of intensity of impact *T* to 2004 calculated, with and without emission from cement production. DOE data extended 2005/2006 with BP reports (13–16, 19–22).

ables and waste in estimating energy use but DOE did not, IEA implied a steeper dematerialization. As in the preceding example of India, IEA's faster dematerialization and omission of emissions from renewables and waste produced an apparent rise of Chinese intensity of impact.

Even in a developed nation, the intensity of impact from 1980 to 2004 or 2006 implied by reports from different methods and agencies requires caution (Fig. 3). The IEA estimates of U.S. emission by its reference method are more than but increase less than the estimates by its sectoral method. Thus, when the two IEA estimates of emission are divided by the same IEA estimate of energy use, the consequent intensities of use differ from each other. They also differ from DOE intensities of impact. The Carbon Dioxide Information Analysis Center's (CDIAC) estimates labeled "Total emissions from fossil-fuels" (21) include ≈1% from cement production and gas flaring and imply that intensity of impact rises instead of falls as other reports imply.

Comparisons of Chinese intensity of use and of impact implied by CDIAC reports of emission reports and DOE of energy clarify the effect of cement. In China in 2004, 36 Tg of China's so-called "total emissions from fossil-fuels" came from cement. The 36 Tg from cement exceeded the Italian or South Korean emission from fossil fuel. As Fig. 3 shows, the intensity of Chinese use of cement increased (22), whereas its energy dematerialized. Consequently, although the intensity of impact calculated from energy decreased slightly, the CDIAC estimate of emissions from energy plus cement implied no decrease.

To encompass more reports of energy and emission than can practically be charted, Tables 2–4 display annual average changes in the world and in five exemplary nations. The annual changes of the ImPACT parameters are symbolized by lowercase letters *c* and *t*, and the rate of dematerialization by (c/a), which equals (b-1). The reference years of 1980 and 2004 fit reports for all agencies, the midpoint of 1995 fits IEA reports, and the early and recent spans of 1980–1995 and 1995–2004 extend long enough to minimize brief fluctuations. The differing rates of change implied by different agencies and methods show the caution required in interpretation. Nevertheless, some general conclusions merit later discussion.

Persistence. Instances of dematerialization slowing and of the intensity of impact accelerating from the earlier to the later period are evident in Tables 2–4. Nevertheless, instances of continued dematerialization and a few instances of falling intensity of impact can also be found. The sum ($c + t$) of intensities of use plus impact equals the annual change in emission, which indicates decarbonization when negative.

What evidence supports or denies the persistence of other declining intensities of use and impact? Fig. 4 shows consumers caused an unflagging dematerialization of global intensity of use measured as crops per GDP. Although the average global consumer enjoyed 45% more affluence in 2006 than in 1980, each only consumed 22% more crops and 13% more energy. The richer consumer actually used 20% less wood, a saving of 0.67 minus 0.53 m^3 per person or 39 board feet. The evidence in Fig. 1 also shows persistently declining intensity of the impact of crop

Table 2. Rates of changing intensity of use and impact and dematerialization during an early period of 1980/1995 and a recent period of 1995/2004

	Intensity of use, change c %/yr					
	Early period, 1980/1995			Recent period, 1995/2004		
Region	DOE	BP	IEA	DOE	BP	IEA
World	−1.1%	−1.1%	−1.2%	−0.7%	−0.9%	−0.8%
USA	−1.9%	−1.9%	−2.0%	−2.2%	−2.2%	−2.1%
China	−5.2%	−4.5%	−6.0%	−2.6%	−3.7%	−3.9%
India	1.5%	0.6%	−1.5%	−2.5%	−1.4%	−2.9%
Brazil	1.7%	1.2%	0.1%	0.5%	0.6%	0.8%
Indonesia	0.6%	0.1%	−1.4%	2.7%	2.2%	1.2%

The rates for the world and five nations were calculated from reports by the DOE, BP, and CDIAC, and by the Reference and Sectoral methods of the IEA. Sources: World Bank (GDP), and named agencies.

production on land and fertilizer use and persistence of declining French carbon emissions per energy production.

For energy and carbon, the world, including rapidly growing China, did interrupt the global dematerialization and declining intensity of impact in 2001, shown in Fig. 4. Including China, the average global consumer increased affluence by 45% but used only 13% more energy in 2006 than in 1980. Without China, the average consumer increased affluence by 34% while changing energy use little. Outside China, the world persistently dematerialized energy use at 10% per 10% more affluence, corresponding to income elasticity near 0. The world without China retained the smaller intensity of impact of energy production attained during the earlier years.

Discussion

Variety. Because the consumption of many things does not rise as fast as income, the variety of dematerialization should not surprise. A century after this phenomenon was noticed, Houthakker (23) wrote, "Few dates in the history of econometrics are more significant than 1857. In that year Ernst Engel (1821–1896) published a study on the conditions of production and consumption, in which he formulated an empirical law that the proportion of income spent on food declines as income rises. Similar laws have also been formulated for other items of expenditure." Consumption that follows Engel's law has an income elasticity $b < 1$, dividing staples from luxuries with $b > 1$. Given the generality of Engel's law, it is no surprise that a variety of energy use, crop production, and wood obey it in Figs. 1 to 4. The Brazilian exception of rising intensity of energy use seen in Fig. 1 accompanied discovery of petroleum followed by a 10-fold increase of Brazilian oil production from 1980 to 2006 (16). However, when global, Chinese, or U.S. affluence rose 10%, energy consumption dematerialized >5%, shown in Fig. 1. Because dematerialization equals (b-1), these correspond to income elasticity of <0.5, signifying that energy is a staple.

A variety of substantial decreases in intensity of impact is also evident in Fig. 1. Although rapid introduction of nuclear power in France occurred in the 1970s, intensity of impact still improved during 1980–2005. The scarcity of other declining intensities of impact for energy and negative t in Table 3 shows that the French performance is exceptional. Nevertheless, the intensity of energy impact for the world outside China is not discouraging, shown in Fig. 4. The evidence of experience and learning decreasing the intensity of impact for food production (Fig. 1) is encouraging, and after its peak, the course for fertilizer on crops is also encouraging, shown in Fig. 1.

Caution. The fortunate lack of recessions and retreats from left to right in the charts requires an overarching warning. Unlike the above abundant evidence of the effect of increasing affluence, evidence of the effect of economic recession is brief. The little evidence in Figs. 1 and 4 shows that decreasing affluence in the 1980s did not markedly change intensities. In the Russian Federation, affluence contracted to 0.7 and then rose to 1.2-fold the 1992 level. The Russian intensity of use of energy rose slightly during the economic downturn but has dematerialized since 1999. The intensity of impact fluctuated irregularly. The evidence of behavior during retreating affluence is, fortunately, brief. Russian performance was calculated from references 14–16.

The dramatically different performances of intensities implied for India and illustrated in Fig. 2 caution about the definition of variables. When IEA included the energy from combustible renewables and waste, a steady dematerialization was evident in the developing Indian nation. When, however, DOE omitted combustible renewables and waste, they implied first Indian materialization and then dematerialization. The behavior of the intensity of impact shows the need for further caution. Because IEA includes the energy but not the emission from renewables and waste, they implied a steady growth of intensity of impact.

The effect on intensity of impact when emissions from cement production are included or omitted reinforces the warning about

Table 3. Intensity of impact, change t %/yr

	Early period, 1980/1995				Recent period, 1995/2004			
Region	DOE	CDIAC	Reference	Sectoral	DOE	CDIAC	Reference	Sectoral
World	−0.5%	−0.4%	−0.5%	−0.4%	0.1%	−0.1%	0.1%	0.1%
USA	−0.3%	−0.2%	−0.4%	−0.3%	0.2%	0.6%	0.2%	0.2%
China	−0.1%	0.6%	0.8%	1.3%	−0.3%	−1.0%	0.4%	0.4%
India	0.4%	−0.5%	2.7%	2.6%	−0.4%	0.9%	0.8%	0.8%
Brazil	−0.8%	−1.6%	−0.3%	−0.2%	−0.5%	−0.1%	−0.2%	0.3%
Indonesia	−1.1%	0.6%	2.0%	1.8%	0.2%	−2.5%	1.5%	2.3%

See Table 2 for details.

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Table 4. Rate of dematerialization (*c*/*a*) = (*b*−1), (changing intensity of use/changing affluence)

	Early period			Recent period		
Region	DOE	BP	IEA	DOE	BP	IEA
World	−0.99	−0.97	−1.04	−0.41	−0.55	−0.50
USA	−1.01	−1.02	−1.05	−0.99	−0.97	−0.93
China	−0.61	−0.53	−0.71	−0.33	−0.47	−0.50
India	0.46	0.18	−0.45	−0.60	−0.34	−0.69
Brazil	12.53	8.90	0.97	0.64	0.72	0.99
Indonesia	0.12	0.03	−0.29	2.75	2.27	1.27

See Table 2 for details.

definition. Because CDIAC included them, the curve for intensity of impact of energy production in the U.S. rose whereas other reports implied an improvement in the emission per energy consumption, shown in Fig. 3. In China, the intensity of energy use generally dematerialized, whereas that of cement use rose. So, the intensity of impact calculated from CDIAC reports did not improve as implied by other reports (Fig. 3).

The behavior of Chinese intensities for energy calls for caution about interpreting fluctuations. Whereas the reports of intensity of use to 2005 by IEA rose menacingly in Fig. 2 *Lower*, the 2005 DOE and 2006 BP estimates show a leveling of the 2002–2004 rise. In another cautionary lesson, IEA's inclusion of energy from combustible renewables plus wood for energy raised China's 1980 intensity of use and thus sped its fall compared with the fall implied by DOE reports. For India, IEA's combination of a slower rise in energy use without reporting emission from combustible renewables plus waste lifted its recent rise of the intensity of impact apparent in Fig. 2 *Upper*.

Tables 2–4 teach other cautionary lessons. For example, the 1980–1995 annual change of intensity of use in Indonesia calculated from the reports of three agencies ranged from an annual increase of 0.6% to a decrease of 1.4%. Divided by the 4.9% annual rise of affluence during the same period, these correspond to rates (*c*/*a*) as different as a materialization of 1% versus a dematerialization of 3% when affluence rises 10%. Although differences among reports, like that of India examined above, may be explained by the inclusion, or not, of renewables and waste, caution is warranted.

In the future, the subtraction of the carbon sequestered in forests will add another need for caution. In 2007 at the climate change meetings in Bali, the World Bank announced the Forest Carbon Partnership Facility (FCPF) to reduce deforestation and degradation and provide a fresh source of financing for the sustainable use of forests (24). Thus, the acute uncertainty about the increase or loss of carbon in forests (25) can add another cause for caution to the present ones about fuel emissions.

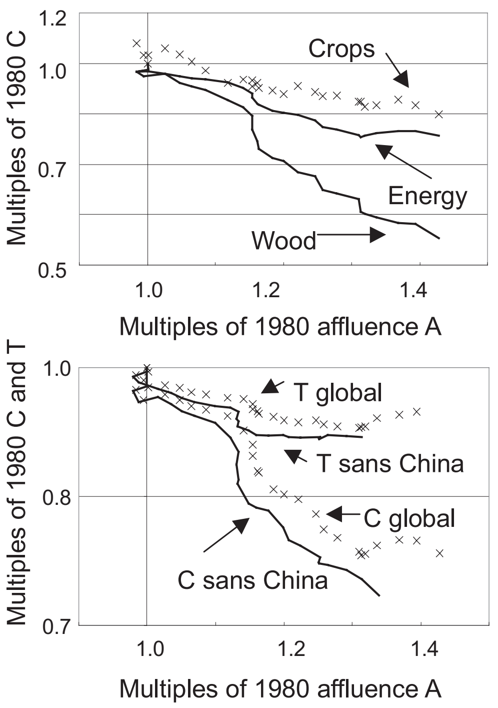

Fig. 4. Two charts illustrating persistent dematerialization or intensity of impact as *A* increased. (*Upper*) The persistence of dematerialization of *C* global crop production index, energy use, and wood production. (*Lower*) For the world or the world without China, the changes of energy use *C* and intensity of impact *T*. Energy extended 2005 to 2006 by BP reports (13–17).

Persistence. Generally, as century-old Engel's law predicts, consumers increase their use of staples more slowly than their affluence grows. Also, producers generally learn to get more from less (26). Thus, rising intensity of use or impact is exceptional, and the examples of their fall seen in our Figs. are prevalent. In an analog to regression toward the mean, the tendency of exceptional cases to regress toward the prevalent ones encourages continuing dematerialization and falling intensity of impact.

If an elasticity $b < 1$ defines staples and $b > 1$ defines luxuries, then because the rate of dematerialization (*c*/*a*) equals (*b*-1), saying staples will cause dematerialization is a tautology. By this logic, the end of dematerialization means that a staple has become a luxury. The persistent dematerializations of energy, crops, and wood evident in the four figures show staples remaining staples. The exceptional materialization of Brazilian energy use is better explained by the extraordinary increase in oil consumption from a new supply (16) rather than by energy becoming a luxury. The late rise of Chinese energy intensity evident in several Figs. was evidently passing rather than caused by energy becoming a luxury. Even when China's energy and emission are included in the global sum, the recent regression in Fig. 4 toward the evident trend of falling intensity of use persisted. In the Indian example of a switch from materialization to dematerialization calculated from DOE reports (Fig. 2), the omission of energy from renewables and waste is a simpler explanation than a luxury becoming a staple.

More advantageous than persistent dematerialization would be its acceleration. Acceleration is hard to find in Tables 2–4.

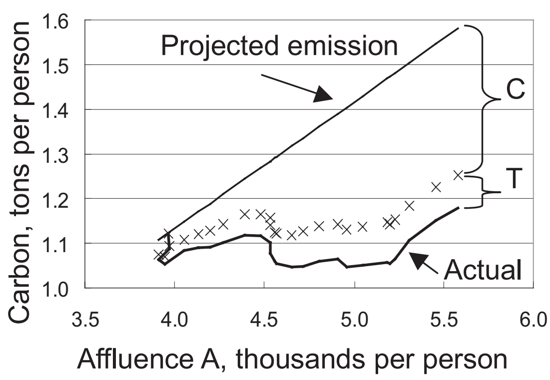

Fig. 5. Dematerialization and diminished intensity of impact of global carbon emission projected from 1980 to 2005 in step with global GDP, the product of population *P* times affluence *A*. Dematerialization cut the projected 10.3 emission in 2005 by 2.1 Pg (labeled *C*) and less intensity of impact cut it by a further 0.5 Pg (labeled *T*) to the actual emission of 7.7 Pg (13–15).

Nevertheless, during 1995–2004 dematerialization, as indicated by negative c %/yr or (c/a), continued globally and in three large emitters.

The declining intensity of impact expected from producers learning to get more from less is evident in the courses of T for global fertilizer application, cropland use and French energy (Fig. 1). Sans China, the global intensity of impact for energy remains steadily low (Fig. 4). For energy since 1980, Engel's law, nevertheless, has been more effective than learning to get more from less. Between the classic pair of consumer behavior and technical change that can preserve resource amenities (27), consumer behavior has so far excelled for energy and carbon. Some declining intensities of impact evident in Figs. 1 and 4 and in Tables 2–4 show technologists have sometimes curbed emission per energy. Energy engineers have decreased intensity of impact not only by switching fuel from coal to nuclear as in France but also by lifting efficiency across the span of the energy system from generators through transmission lines to devices used by end-users, such as windows and lamps, where resource productivity growth has persisted for >4,000 years (28).

If the intensities of use and impact had not changed for a quarter century from 1980 to 2005 as GDP increased along the horizontal axis of Fig. 5, global carbon emission would have increased relentlessly along the straight, projected emission line in the graph to a level of 10.3 Pg in 2005. If the intensity of impact had not changed, the actual dematerialization would have lowered the course of emission to the crosses in the graph, a lowering of 2.1 Pg in 2005 labeled C. Because the intensity of impact also declined, actual emissions in 2005 were still less, a lowering of 0.5 Pg labeled T in the graph. Monetizing the effects of dematerialization and lower intensity of impact of the C and T falling from 1980 to 2005 levels is imperfect but helps one comprehend their scale more keenly. At the June 2008 price of 27 euros per ton carbon dioxide or $151 per ton carbon, dematerialization by 2.1 Pg would be worth more than $300 billion, and 0.5 Pg lower intensity of impact be worth more than $70 billion. Although prices on the European Climate Exchange are surely transitory, the magnitude of these sums nevertheless merits precise reports and careful audits.

Cautiously amid conflicting reports in Tables 2–4, some national outcomes can be perceived.

Table 5. Sources of estimates

Variable	Agency	Ref.
Population	United Nations	13
GDP market rate deflated	World Bank	14
Energy and carbon emission	DOE	15
Energy	BP	16
Carbon emission	CDIAC	21
Energy and carbon emission	IEA	19, 20
Crops, land, fertilizer, wood	FAO	17
Cement	U. S. Geological Survey	22

- Indonesia materialized by all reports, and reports of changed intensity of impact were erratic.
- Brazilian materialization may have slowed, but how much depends on the statistics used.
- India, by several reports, changed from a worsening to an improving environmental performance.
- Chinese dematerialization slowed a bit, but did not cease by any report, and the rise of its intensity of impact either slowed or reversed.

Surprisingly, apparently unaffected by changes of government and with an income elasticity near 0, the USA dematerialized steadily near 2%/yr throughout the 25 years of Tables 2–4. Its intensity of impact did not decrease.

Firmly established, Engel's law is not failing. The dematerialization of crop, fertilizer and wood use plus the decarbonization of carbon emission per GDP continue. And although a declining intensity of impact is hard to find for energy, it continues for other phenomena. The declining intensities continue assisting the journey across sustainability's dual dimensions of present prosperity without compromising the future environment.

Materials and Methods

Waggoner and Ausubel (6) described the ImPACT identity. Table 5 displays the sources of estimates.

ACKNOWLEDGMENTS. We thank Arnulf Grubler, Vernon W. Ruttan, and Nadejda Victor. This work was supported by The Rockefeller University.

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