FORUM

The IPAT Equation and Its Variants

Changing Views of Technology and Environmental Impact

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Summary

In the early 1970s Ehrlich and Holdren devised a simple equation in dialogue with Commoner identifying three factors that created environmental impact. Thus, impact (*I*) was expressed as the product of (1) population, (*P*); (2) affluence, (*A*); and (3) technology, (*T*). This article tracks the various forms the IPAT equation has taken over 30 years as a means of examining an underlying shift among many environmentalists toward a more accepting view of the role technology can play in sustainable development. Although the IPAT equation was once used to determine which single variable was the most damaging to the environment, an industrial ecology view reverses this usage, recognizing that increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems.

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Introduction

In a provocative article, Rockefeller University researcher Jesse Ausubel asks: "Can technology spare the earth?" (Ausubel 1996a). It is a modern rendering of an epochal question concerning the relationship of humanity and nature, and, especially since Malthus and Darwin, of the effect of human population on resources. Surely, technology does not offer, on its own, the answer to environmental problems. Sustainability is inextricably linked with economic and social considerations that differ across cultures. This article, however, discusses the imperative of technological change and the role it can play in human and environmental improvement, particularly in the United States.

The vehicle used to begin the discussion of technological change, though phrased mathematically, is largely a conceptual expression of what factors create environmental impact in the first place. This equation represents environmental impact, (I), as the product of three variables, (1) population, (P); (2) affluence, (A); and (3) technology, (T). The IPAT equation and related formulas were born, along with the modern environmental movement, circa 1970. Although first used to quantify contributions to unsustainability, the formulation has been reinterpreted to assess the most promising path to sustainability. This revisionism can be seen as part of an underlying shift among many environmentalists in their attitudes toward technology. This article examines the conversion of the IPAT equation from a contest over which variable was worst for the planet to an expression of the profound importance of technological development in Earth's environmental future.

A Historical Perspective

In many ways, the modern environmental movement itself was a reaction to unbridled faith in technology, especially over the last 50 years. On the one hand, contemporary researchers converge around World War II as the starting point of a generation of unprecedented technological development springing from governmental policies supporting scientific advance (Brooks 1987; Freeman 1982; Smith 1990; Spiegel-Rosing and Price 1977). On the other hand, the result of this development was a quantum leap in environmental impact. Prior to World War II, "smoke, sewage, and soot were the main environmental concerns" (Heaton et al. 1991, 5). In 1972, the revolutionary thinker Barry Commoner opined: "Most United States pollution problems are of relatively recent origin. The postwar period, 1945–46, is a convenient benchmark, for a number of pollutants—man-made radioisotopes, detergents, plastics, synthetic pesticides, and herbicides—are due to the emergence, after the war, of new productive technologies" (1972a, 345).

Commoner conclusively assigned blame, asserting that his evidence "leads to the general conclusion that in most of the technological displacements which have accompanied the growth of the United States economy since 1946, the new technology has an appreciably greater environmental impact than the technology which it has displaced; and the postwar technological transformation of productive activities is the chief reason for the present environmental crisis" (1972a, 349).

Commoner's contemporaries, eminent environmentalists Paul Ehrlich and John Holdren, writing in the same set of conference proceedings as Commoner, disagree that technology is the dominant reason for environmental degradation, emphasizing the importance of population size and growth, noting "if there are too many people, even the most wisely managed technology will not keep the environment from being overstressed" (Ehrlich and Holdren 1972a, 376).

Commoner, Ehrlich, and Holdren have been extremely influential environmental thinkers for a generation. Following their work came an unprecedented barrage of regulatory activity in the United States, initiated to alter human degradation of the environment. First, the National Environmental Policy Act of 1970, followed by the Clean Air Act, the Clean Water Act, the Toxic Substances Control Act, the Resource Conservation and Recovery Act, and more than a dozen other less-well-known statutes, focused America's attention on a range of threats to human and ecosystem health. Interestingly, the regulation of the 1970s relied to a large extent on technology and engineered solutions to control and manage end-of-pipe pollution.[1] The solution to dirty technology was, through the force of law, to use more technology to clean it up.

In the pre–Earth Day period, when Americans were coming to grips with the unintended consequences of rapid technological development, blame tended to be placed on what Commoner referred to as "ecologically faulty technology." With twenty years more data to examine, Ausubel sees Earth Day 1970 to be a possible inflection point in a number of trends, including population, and finds the message from history to be "that technology, wisely used, can spare the earth" (Ausubel 1996a, 177).

This move toward technological optimism, as discussed later in this article, has gained ground in environmental circles. Although there are notable extremes in any distribution, and serious limits to what scholars and practitioners often refer to as "technological fixes," a better understanding exists of how technology, combined with improved design, can greatly aid the quest for sustainability. Indeed, the notion that technological choice is crucial for environmental improvement lies at the core of industrial ecology. Such thinking revises the informal mantra of U.S. technology policy from simply "cheaper, faster" in the flow of innovations to the marketplace to, at a minimum, "cheaper, faster, cleaner" and, to some visionaries, it offers the transformative mechanism for achieving sustainability.

Origins of the IPAT Equation

The relationship between technological innovation and environmental impact has been conceptualized mathematically, as noted above, by the IPAT equation. IPAT is an identity simply stating that environmental impact *(I)* is the product of population *(P)*, affluence *(A)*, and technology *(T)*.

$$I = PAT \qquad (1)$$

Generally credited to Ehrlich, it embodies simplicity in the face of a multitude of more complex models, and has been chosen by many scholars (Commoner et al. 1971a; Dietz and Rosa 1994, 1997, 1998; Turner 1996; Wernick et al. 1997) as a starting point for investigating interactions of population, economic growth, and technological development.

The IPAT identity has led, in turn, to the master equation in industrial ecology (Heaton et al. 1991; Graedel and Allenby 1995). These have been followed by two concepts in sustainability research: the Factor 10 Club (1994) and Factor Four (von Weizsäcker et al. 1997). The first two references, IPAT and the master equation, state relationships about technology and environmental impact, whereas the use of Factor Four, Factor 10, and even the Factor *X* debate described later, are attempts to quantify potential impacts.

In reviewing the literature, an interesting history emerges. The original formulation presented by Ehrlich and Holdren (1971, 1972a,b) was intended to refute the notion that population was a minor contributor to the environmental crisis.[2] Rather, it makes population—which the authors call "the most unyielding of all environmental pressures"—central to the equation by expressing the impact of a society on the ecosystem as:

$$I = P \times F \qquad (2)$$

where I = total impact, P = population size, and F is impact per capita. As the authors explain, impact increases as either P or F increases, or if one increases faster than the other declines. Both variables have been growing rapidly and are much intertwined. To show that the equation is nonlinear and the variables interdependent, Ehrlich and Holdren then expanded their equation as follows:[3]

$$I = P(I, F) \times F \qquad (3)$$

This variant shows that F is also dependent on P, and P depends on I and F as well. For example, rapid population growth can inhibit the growth of income and consumption, particularly in developing countries. On the other hand, cornucopians such as Julian Simon maintain that greater population is the key to prosperity (Simon 1980). Ehrlich and Holdren comment extensively on the tangled relationship of these factors and note that almost no factor has been thoroughly studied (1972a).

Technology, at this stage, is not expressed as a separate variable, but is discussed in relationship to F, per capita impact. First, F is related to per capita consumption—of, for example, food, energy, fibers, and metals. Then, it is related to the technology used to make the consumption possible and whether that technology creates more or less impact. The authors note that "improvements in technology can sometimes hold the per capita impact, *F,* constant or even decrease it, despite increases in per capita consumption" (1972a, 372). Although this statement recognizes the positive role technology can play, Ehrlich and Holdren generally conclude that technology can delay certain trends but cannot avert them.

Commoner also plays an important role in the formulation of the IPAT equation. Commoner's work in his popular 1971 book *The Closing Circle*, and much of his scientific analysis during the period of 1970–1972, were concerned with measuring the amount of pollution resulting from economic growth in the United States during the postwar period. To do so, he and his colleagues became the first to apply the IPAT concept with mathematical rigor. In order to operationalize the three factors that influence *I,* environmental impact, Commoner further defines *I* as "the amount of a given pollutant introduced annually into the environment." His equation, published in a 1972 conference proceedings (Commoner 1972a), is:

$$I = Population \times \frac{Economic\ good}{Population} \times \frac{Pollutant}{Economic\ good} \quad (4)$$

Population is used to express the size of the U.S. population in a given year or the change in population over a defined period. *Economic good* is used to express the amount of a particular good produced or consumed during a given year or the change over a defined period and is referred to as "affluence." *Pollutant* refers to the amount of a specific pollutant released and is thus a measure of "the environmental impact (i.e., amount of pollutant) generated per unit of production (or consumption), which reflects the nature of the productive technology" (Commoner 1972a, 346). Used in this way, the equation takes on the characteristics of a mathematical identity. On the right-hand side of the equation, the two *Populations* cancel out, the two *Economic goods* cancel out, and what remains is: *I = Pollutant.*

$$I = \cancel{Population} \times \frac{\cancel{Economic\ good}}{\cancel{Population}} \times \frac{Pollutant}{\cancel{Economic\ good}}$$

Thus, for Commoner, environmental impact is simply the amount of pollutant released rather than broader measures of impact; for example, the amount of damage such pollution created or the amount of resource depletion the pollution caused.[4] His task, then, is to estimate the contribution of each of the three terms to total environmental impact.

Much to the consternation of Ehrlich and Holdren, Commoner's effort to measure impact as amount of pollution released leads to the conclusion that technology is the culprit in almost every specific case he examines. Commoner goes on to compare the relative contributions of the three IPAT variables arithmetically: Population, affluence *(Economic good/Population)*, and technology *(Pollutant/Economic good)*, in examples such as detergent phosphate, fertilizer nitrogen, synthetic pesticides, tetraethyl lead, nitrogen oxides, and beer bottles. He concludes that the contribution of population and affluence to present-day pollution levels is much smaller than that of the technology of production. He calls for a new period of technology transformation to undo the trends since 1946 in order "to bring the nation's productive technology much more closely into harmony with the inescapable demands of the ecosystem" (1972a, 363).

Following the publication of *The Closing Circle* (Commoner et al. 1971a), full-scale academic war erupted between Ehrlich and Holdren on the one hand and Commoner on the other. In a fierce Critique and Response published in the *Bulletin of the Atomic Scientists* in March 1972, Ehrlich and Holdren reject the mathematical basis through which Commoner finds population a modest contributor to environmental impact. In their piece, "One-Dimensional Ecology," Ehrlich and Holdren charge that Commoner, in his zeal to blame faulty technology, overemphasizes pollution, misconceives certain aspects of demography, understates the growth of "affluence," and resorts to "biased selection of data . . . and bad ecology." Their evident fear comes from "the possibility that uncritical acceptance of Commoner's assertions will lead to public complacency concerning both population and affluence in the United States" (1972b, 16).

Commoner (1972b), in his Response published in the same issue of the *Bulletin*, offers a spirited defense of his mathematical and ecological competence and evokes supporting reviews by Sir Eric Ashby and Rene Dubos to the "intemperate onslaught" by Ehrlich and Holdren. Commoner reminds the reader that it was Ehrlich who first wrote: "Pollution can be said to be the result of multiplying three factors; population size, per capita consumption, and an 'environmental impact' index that measures, in part, how wisely we apply the technology that goes with consumption" (Commoner 1972b, 42). Commoner originally quoted this in an April 1971 article in *Environment* written with colleagues Michael Corr and Paul Stamler. Commoner's interest in the *Environment* piece and in a follow-up piece for a symposium held by the U.S. think tank Resources for the Future was to try to operationalize the relationship "first proposed by Ehrlich and Holdren, that is, to find a way of entering the actual values for the several factors and thus computing, numerically, their relative importance" (Commoner 1972b, 42). Commoner's team paraphrased this relationship, introducing the terms "consumption" and "production" into the variant as follows as:

$$\textit{Population size} \times \textit{per capita consumption} \times \textit{environmental impact per unit of production} = \textit{level of pollution} \quad (5)$$

At this stage Commoner brought to light a letter Ehrlich and Holdren sent to colleagues in which they reveal that they had urged Commoner not to engage in debate about which of the factors was most important because it would be counterproductive to achieving environmental goals. Commoner takes great umbrage at the idea of avoiding public discussion of scientific findings in favor of private agreements that, in turn, erode democracy and "the survival of a civilized society" (1972b, 56). Commoner identifies what he believes to be behind the debate: that "Ehrlich is so intent upon population control as to be unwilling to tolerate open discussion of data that might weaken the argument for it" (1972b, 55).

Some of the issues raised between the two sides of this debate reflect the formative nature of the ideas. Note that across the several different articles and books mentioned, there is not one single way of stating the variables or even consistency as to whether we are attempting to measure I, environmental impact or P, Pollution. The very first time the reference $I = P \times A \times T$ appears in writing is as part of the Critique and Response in 1972, in which Ehrlich and Holdren take Commoner's equation from a footnote from *The Closing Circle*:

$$\textit{pollution} = (\textit{population}) \times (\textit{production/capita}) \times (\textit{pollution emission/production}) \quad (6)$$

and, say, "for compactness, let us rewrite this equation":

$$I = P \times A \times T \quad (7)$$

From this basis Ehrlich and Holdren dissect Commoner's mathematics. They point out that Commoner uses his definitions of P, A , and T as independent variables such that their effects on I are independent of each other. Ehrlich and Holdren are careful to describe them as interdependent as in formula (3) above. Ehrlich and Holdren also emphasize the multiplicative nature of population. In a 1974 piece, they identify how population acts as a multiplier of consumption and environmental damages associated with human activity such that even if no one of the IPAT terms goes up very much, it is the simultaneous increases in all the factors that cause extensive environmental impact. They make the case that using them as independent variables tends to underestimate the impact of population.[5]

In another article, Holdren and Ehrlich (1974) offer yet another formulation of what they term the "population/environment equation":

$$\textit{environmental disruption} = \textit{population} \times \textit{consumption/person} \times \textit{damage/unit of production} \quad (8)$$

First, environmental disruption substitutes for I, impact, and damage, in the third term, is a presumed outcome of each unit of consumption. Note, also, the cross-substitution among the many formulations of consumption and production. Sometimes production and consumption cancel each other out, and sometimes they do not. Sometimes the affluence term is used for one or the other or for both as in the form "production/consumption" or "production (consumption)." In Commoner's original paraphrase of Ehrlich (equation (5)), in which he makes consumption part of affluence and production part of technology and the terms do not cancel out, he goes on to make the now outdated statement that "since imports, exports, and storage are relatively slight effects, total consumption can be taken to be approximately equal to total production" (Commoner et al. 1971b, 4). Today, imports and exports are not slight effects, so we would not even try to equate U.S. production with U.S. consumption. Even so, the relationship of production to consumption is not a focus of these early articles. In fact, only in the late 1990s did an analytic discussion of consumption begin to take shape in the scientific community (Stern et al. 1997; Berkhout 1998).

Apples and Oranges

In comparing Commoner with Ehrlich and Holdren, there are often differences in time and spatial scale. Commoner tends to write about the present deteriorating environmental conditions in the United States, and sometimes focuses more locally on a given pollutant. He gives light attention to resource use with his heavy focus on pollution. Ehrlich and Holdren have a broader sweep and are less specific in space and time. They write in several of their articles about the underestimated role of diminishing returns, threshold effects, and synergisms, as well as the relation between ecosystem complexity and stability. They suggest that direct effects of environmental damage such as lead poisoning and air pollution are likely to be less threatening, ultimately, than the indirect effects on human welfare from interference with ecosystem structure and function. They note numerous examples of the "public services" of nature (Holdren and Ehrlich 1974), today better known as ecosystem services (Daily 1997).

Commoner and Ehrlich and Holdren even differ on a common meaning of affluence. Ehrlich and Commoner generally consider a per capita output measure. Commoner does not see "true affluence" as the culturally prescribed accumulation of television sets and fancy cars, more akin to consumption. Rather, he attempts to differentiate the technology used to deliver goods from the actual contribution of those goods to human welfare as a means of separating consumption from "true affluence." For example, although the consumption of nonreturnable beer bottles went up almost 600 percent in the period 1950–1967, actual consumption of beer per capita increased a mere five percent. Thus, the affluence gain to the beer drinker has been slight, whereas the technology chosen to package and deliver the beer, which is of no use to the consumer, has changed dramatically at the expense of the environment.

Despite some differences in orientation between Commoner and Ehrlich and Holdren, the chicken-and-egg nature of this debate—whether population or technology is a bigger contributor to environmental damage—is revealing. Does an increased population call for improved technology, or does improved technology increase carrying capacity?[6] (Boserup 1981; Kates 1997). Even our latter-day technology optimist, Jesse Ausubel, is stymied by the technology/population link (1996a, 1996b). Just as he demonstrates a revolution in factor productivity in energy, land, materials, and water, especially since the time of the Commoner/Ehrlich debate, he goes on to describe how the new technologies serve to make "the human niche elastic. If we solve problems, our population grows and creates further, eventually insurmountable problems" (1996a, 167). Would technology that is not, in Commoner's phrase, "ecologically faulty," (1972a, 362), but rather ecologically wise, merely delay the inevitability of environmental destruction, or is better technology our best horse in the race toward sustainability?

In a review of several models of anthropogenic driving forces of environmental impact, Deitz and Rosa single out the IPAT equation because it "is easily understood, frequently used for illustrative purposes and can discipline our thinking" (Deitz and Rosa 1997). They draw this conclusion despite their finding that the effects of population and economic growth on environmental degradation have not been extensively researched and are thus uncertain.

B. L. Turner (1996) finds the IPAT equation useful as a macro-scale assessment, noting that regional and local scale assessments generally highlight other drivers of environmental changes such as policy, institutions, and complexity of social factors. Meyer and Turner point out that the IPAT equation is largely the product of biologists and ecologists and uses terms undefined in social science. They comment that neither *A* (affluence) nor *T* (technology) is associated with a substantial body of social science theory (Meyer and Turner 1992).

Conceptually as well as numerically, *P*, population, and *A*, defined as a per capita measure of wealth, consumption, or production, have generally been more accessible to researchers than the *T* term. The product ($P \times A$) represents an aggregate measure of total economic activity, such as total GDP. In this case, $T = I/P \times A$ or T = unit of environmental impact per unit of economic activity. Here, *T*, technology, becomes the residual of an accounting identity; it represents everything that affects the environment that is not population or affluence. As Deitz and Rosa observe, "most social scientists are frustrated by the truncated visions of the rest of the world offered by the *T* in the IPAT model" (1994, 287). In this sense, whether technology, through the *T* term, is truly endogenous to the master equation could be questioned (Grubler 2001). Thus, Deitz and Rosa recommend that an independent measure of *T* be used and that researchers be required to specify *T* rather than solve for it.

The notion of *T* as residual is a reminder of an important antecedent to the IPAT quest to disaggregate the elements of environmental impact. Macroeconomists have been involved since the 1930s with efforts to disaggregate factors of economic growth and productivity in the economy (Griliches 1996). Robert Solow's Nobel Prize in economics, for example, was associated with his statistical explanation of the causes of U.S. manufacturing growth from 1909–1949 (Clark 1985). He found that labor and capital, the traditional factor inputs of neoclassical economics, explained only about 10 percent of this growth. The rest, some 90 percent, was "residual"—a factor representing all other contributions to growth such as education, management, and technological innovation. Later research identified about 30–40 percent of the explanation for income growth to be attributable to technological change, with the poorly understood interdependence of the variables being the most difficult challenge (Stoneman 1987; Abramovitz 1993). Although there is no clear evidence that the IPAT progenitors were exposed to growth accounting in economics, we see that poor definition of a residual term is not unique to the environmental field.

Another critique leveled by Deitz and Rosa is that although the IPAT equation does allow for some disaggregation of the forces of environmental change, including human impacts, the disaggregation is too simple and does not allow for interactions among population, affluence, and technology (Deitz and Rosa 1998). As it stands, a direct relationship is formed such that a 10 percent increase in *P*, *A*, or *T* creates a 10 percent increase in environmental impact. Deitz and Rosa cite several studies that build upon the IPAT model to enable it to capture more complexity and interaction among the variables. They actually reformulate the IPAT equation as STIRPAT—meaning "Stochastic Impacts by Regression on Population, Affluence and Technology"—to be able to disaggregate *P*, *A*, and *T* and to be able to use regression methods to estimate and test hypotheses. Their reformulation is $I = aP^bA^cT^de$, where the variables a–d can be either parameters or more complex functions estimated using standard statistical procedures and e is the error term (Deitz and Rosa 1994, 1997, 1998). They have used the STIRPAT model to bridge the social and biological sciences in, for example, studies of global climate change.

The IPAT equation has also been a source for the development of the literature on energy decomposition analysis, which disaggregated energy intensity and extended and refined the mathematics of IPAT (Greening et al. 1998, 1999; Gurer and Ban 1997). The use of the IPAT equation in research related to climate change, specifically energy-related carbon emission studies, may be the most enduring legacy of IPAT. Such formulations are typically stated as (Holdren 2000): Energy use = Population × GDP/person × energy/GDP; and Carbon emissions = Population × GDP/person × carbon energy. In this way IPAT has played a prominent role, particularly in the Intergovernmental Panel on Climate Change assessments (IPCC 1996).

Ultimately, the evidence presented suggests that the IPAT equation can be used to support many different points of view. Ehrlich and Holdren show how it supports the population view. Commoner demonstrates how it supports the harmful technology or Faustian view. Economist Julian Simon, representative of the cornucopian view, believes that increasing population and wealth is the driving force for new technological development (Simon 1981). That the IPAT formulation can be interpreted in so many ways represents a weakness and a strength: on the one hand, it may simply be too broad and general to account for the interrelationships among the variables. On the other hand, it has not revealed a bias and need not be definitive to be extremely useful as a thought model. There really has been no underlying disagreement that each of the terms belongs to the equation in some way and so, as a conceptual analytic approach, IPAT provides readily identifiable common ground.

The technology factor is also subject to multiple interpretations. Ehrlich and Holdren cite a fundamental problem associated with reliance on technology by recognizing that no technology can completely eliminate the environmental impact of consumption. They choose the example of recycling, which always results in some loss of materials, if for no other reason than the "sad but unavoidable consequences of the second law of thermodynamics" (1972a, 370). Commoner is the harshest on "ecologically faulty technology" and its singular environmental impact, but, on the other hand, is quite receptive to "developing *new* technologies which incorporate not only the knowledge of the physical sciences (as most do moderately well), but ecological wisdom as well" (1972a). Because IPAT factors take us well beyond technological choice, we quickly cross from the realm of technologists, especially scientists and engineers, into the realm of social scientists, politicians, and the needs, wants, and desires of people. The ubiquity of C. P. Snow's "two cultures" problem is especially evident in the IPAT realm because organizing the relationships of population, environmental impact, and social welfare puts analysts at the juncture of the scientific and humanistic realms. As cultural historian Leo Marx points out, we often name environmental problems after their biophysical symptoms, such as soil erosion or acid rain, and thus address them to scientists. Naming practices reflect the dominant outlooks of the culture. For example, Marx points out that if we, as a society, were less technology-friendly, we might have avoided the flowery "greenhouse effect" in favor of "the problem of global dumpsites" or "the celestial emphysema syndrome" (Marx 1994, note 3). The root cause of each of these problems, however, does not come from nature, but rather the human behavior and the complex practices that go along with it (Marx 1994). We lean to technologists in part because of an "inadequate understanding of the part played by ideological, moral, religious, and aesthetic factors in shaping response to environmental degradation" (1994, 18).

The Transition to Technological Optimism

If the approach of the environmental movement of the 1970s was to juxtapose the gains of economic growth with the devastating reality of pollution, this approach changed in the 1980s. The Brundtland Commission report in 1987 concluded that if humanity were to have a positive future, then economy and environment had to be made more compatible. "Sustainable" was paired with "development" to describe this state, and since that time there has been increasing acceptance that economy and environment can be mutually compatible (World Commission on Environment and Development 1987).

At the same time, the IPAT equation makes us keenly aware of our limited choices. The year following the Brundtland report, one environmental chieftain, under the heading "A Luddite Recants," conceded that "economic growth has its imperatives; it will occur . . . seen this way, reconciling the economic and environmental goals societies have set for themselves will occur only if there is a transformation in technology—a shift, unprecedented in scope and pace, to technologies, high and low, soft and hard, that facilitate economic growth while sharply reducing the pressures on the natural environment" (Speth 1988). Here, James Gustave Speth, then president of the World Resources Institute, converts the 1970s suspicion, as expressed by Commoner's condemnation of "ecologically faulty technology," into an expression of hope for transformed technology (see also Speth 1990, 1991).

This line of argument is presented in a publication of the World Resources Institute called

"Transforming Technology: An Agenda for Environmentally Sustainable Growth in the 21st Century" (Heaton, Repetto, and Sobin 1991). Heaton and colleagues recite a variant of the IPAT equation resurrected by Speth in a background paper a year earlier (Speth 1990) and explain its critical importance to the future of the environment in a section of their article titled "Why Technological Change Is Key." They write:

> Human impact on the natural environment depends fundamentally on an interaction among population, economic growth, and technology. A simple identity encapsulates the relationship:
>
> $$Pollution = \frac{Pollution}{GNP} \times \frac{GNP}{Population} \times Population \quad (9)$$
>
> Here, pollution (environmental degradation generally) emerges as the product of population, income levels (the GNP per capita term) and the pollution intensity of production (the pollution/GNP term).
>
> In principle, pollution can be controlled by lowering any (or all) of these three factors. In fact, however, heroic efforts will be required to stabilize global population at double today's level, and raising income and living standards is a near-universal quest. Indeed, economic growth is a basic goal for at least 80 percent of the world's population. These powerful forces give economic expansion forward momentum. In this field of forces, the pollution intensity of production looks to be the variable easiest to manipulate, which puts the burden of change largely on technology. In fact, broadly defined to include both changes within economic sectors and shifts among them, technological change is essential just to halt backsliding: Even today's unacceptable levels of pollution will rise unless the percentage of annual growth in global and economic output is matched by an annual *decline* in pollution intensity (Heaton, Repetto, and Sobin 1991, 1).

Thus, whereas the IPAT equation can send us in several directions, recent interpretations cast the *T* term in a very positive light. In essence, a new generation of technological optimists finds that experiments in changing human behavior to vary the course of *P* and *A* are highly uncertain. Stated another way, Walter Lynn, while Dean of the Cornell University faculty, cited the lack of progress in "social engineering," and the success, even if temporary, of technological fixes. He observed: "Currently, technology provides the only viable means by which our complex interdependent society is able to address these environmental problems" (Lynn 1989, 186).

Enter Industrial Ecology

The concepts of the IPAT equation are at the core of the emerging field of industrial ecology. Industrial ecology has been described as the "marriage of technology and ecology" and examines, on the one hand, the environmental impacts of the technological society, and, on the other hand, the means by which technology can be effectively channeled toward environmental benefit. According to the first textbook in this new field (Graedel and Allenby 1995), industrial ecology has adopted the following IPAT variant as its "master equation":

$$Environmental\ impact = Population \times \frac{GDP}{person} \times \frac{Environmental\ impact}{unit\ of\ per\ capita\ GDP} \quad (10)$$

This master equation incorporates the same relationships as the WRI equation, with some changes in terminology. Once again we see the variation between defining pollution, *P,* as WRI has done, in contrast to defining environmental impact, as in the master equation. WRI states the equation as an identity—the populations cancel and the GNPs cancel—so that *Pollution* = *Pollution*. The master equation is not strictly stated as an identity. Also, Graedel and Allenby use gross domestic product (GDP) for the affluence term rather than WRI's gross national product (GNP), which reflects a shift by the United States in 1991 to the use of GDP in order to conform to the practices of most other countries. Although GNP is defined as the total final output produced by a country using inputs owned by the residents of that country, GDP counts the output produced with labor and capital *located* *inside* the given country, whoever owns the capital (Samuelson and Nordhaus 1998).

WRI's technology term is a measure of the pollution intensity of production (the pollution/GNP term). Graedel and Allenby define their third term, qualitatively, as the degree of environmental impact per unit of per capita gross domestic product, which they call "an expression of the degree to which technology is available to permit development without serious environmental consequences and the degree to which that available technology is deployed" (Graedel and Allenby 1995, 7). Although it is interesting to observe the back and forth of the use of *I*, impact versus *P*, pollution in the history of the IPAT equation, it is not surprising that such a macro view makes it difficult to capture true differences in types and dynamics of specific impacts that are difficult, if not impossible, to aggregate.

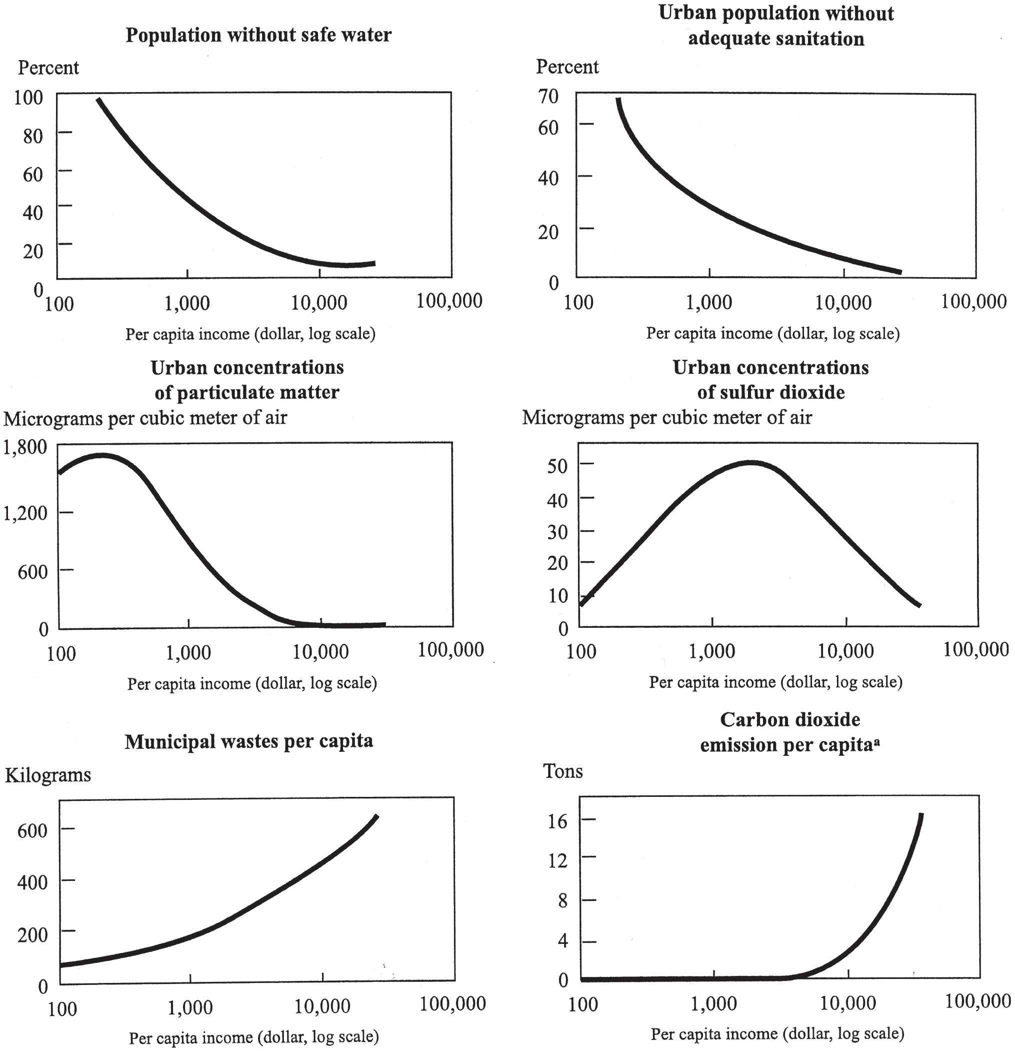
Characteristic of each *T* term is the assumption that the pollution it defines can be reduced. Curiously, this usage leaves room for being less bad, for example, through pollution reduction or eco-efficiency, but does not really express the potential human and environmental benefit that can come from technology (McDonough and Braungart 1998). All in all, WRI's formulation and that of the master equation are similar along the lines we have seen since the Commoner/Ehrlich and Holdren debate, but give further definition to A and T. A sense of progress exists in that Ehrlich and Holdren as well as Commoner, although using a multiterm equation, were really most interested in pursuing a single cause. Still, the more recent emphasis on pollution per unit GNP or GDP is not a satisfactory universal definition of technology, leaving room for continual reconsideration.

Let us examine the three terms of the master equation and IPAT more broadly. In practice, at the global level, there is strong upward pressure on the first term, population, even as we debate the range of those increases (Marchetti et al. 1996). Similarly, the common desire to improve quality of life translates into an increasing second term, affluence, as well. Affluence, as measured by gross domestic product (GDP) per person, spreads the worth of a country's economy over the population. Clearly, this, too, is a generalization. Per capita figures miss growing disparities between rich and poor in many countries. GDP has been criticized as distortionary for measuring only quantifiable transactions, leaving out harder-to-measure, but critical, assets such as an educated populace, healthy citizens, and a clean environment (Cobb, Halstead, and Rowe 1995).[7] Nonetheless, to the extent that, as a blunt measure, real GDP per person rises, it implies that wealth and, subsequently, quality of life are more likely to be improving. Therefore, as in the $I = PAT$ equation, both of the first terms presented here are headed upward, although estimates of how much vary widely.[8] In the emerging "industrial ecology" view, using technology to reduce environmental impact can, theoretically, not only compensate for the impact of *more* people, but also the impact of *more affluent* people. Increasing wealth without "backsliding" as described by WRI, or even while decreasing overall impact, is a worthy, if challenging goal. According to Graedel and Allenby:

> The third term, the amount of environmental impact per unit of output, is primarily a technological term, though societal and economic issues provide strong constraints to changing it rapidly and dramatically. It is this third term in the equation that offers the greatest hope for a transition to sustainable development, and it is modifying this term that is the central tenet of industrial ecology (Graedel and Allenby 1995, 8).

Until recently, the third term, technology, has been seen as a continuous source of pollution: technology, for example, to mine, manufacture, and drive with all the environmental harms such activities create. Other differences are concealed by the macro nature of the IPAT equation and its variants. In the master equation, the *T* term is defined as the amount of environmental impact each unit of a country's wealth creates averaged over the population as a whole. In reality, this is an oversimplification. Countries with clean, energy-efficient production have been able to produce greater wealth with less per-unit environmental impact. The poorest countries are least likely to have clean air, water, and sanitary systems. But even here anomalies exist, summarized in discussions of the environmental Kuznets curve, which considers a nuanced relationship between *A*, affluence, and *I*, impact, such that an environmental emission might rise as income increases until a particular level is reached, at which point emission levels begin to fall (Arrow et al. 1995).

As indicated below, no universal rule exists: Impacts such as waste and carbon dioxide emissions increase with wealth, whereas other indicators, such as urban concentrations of particulate matter and sulfur dioxide, decline over specified income levels (see figure 1). Some indicators, such as urban concentrations of particulate matter or sulfur dioxide, as shown in figure 1, follow the environmental Kuznets curve hypothesis, worsening at first and then improving as income increases (Hosier 1996). Many researchers have been interested in the relationship of affluence and environmental impact and have determined that the condition of impact worsening and then improving with income is most typical of short-term, local indicators such as sulfur, particulates, and fecal coliforms, but not to accumulated stocks of waste or long-term dispersed indicators such as CO_2 (Rothman and de Bruyn 1998).



Note: Estimates are based on cross-country regression analysis of data from the 1980s.
a. Emissions are from fossil fuels.

Figure 1 Relationship of affluence (per capita income) to various environmental impacts.
Sources: Hosier (1996) from Shafik and Bandyopadhyay, background paper; World Bank data.

Earlier discussions of *T,* and IPAT in general from Ehrlich onward portray a curiously passive role for the technology producer. Either technology is used abstractly, as in Ehrlich and Holdren's writing, or it is assumed to be static in that the producers just keep on doing what they have done before. Interventions, then, are policies from above rather than revisions of the mindsets of the technologists. In contrast, industrial ecology has deep roots in engineering and the physical sciences, so it is not surprising that its practitioners would put stock in the *T* term, with which they are most familiar professionally. But neither is it easy to assure that any given technology, let alone *T,* technology collectively, will be beneficial rather than harmful. By offering a systems approach to environmental/technical interactions, industrial ecology research can provide an essential link between the episodic use of promising technology and the long-term, less defined goal of sustainable development.

Another critical component industrial ecologists have brought into the discussion of anthropogenic environmental impacts is the participation of private industry. In describing the "industrial" character of industrial ecology, the first issue of the *Journal of Industrial Ecology* notes that "it views corporate entities as key players in the protection of the environment, particularly where technological innovation is an avenue for environmental improvement. As an important repository of technological expertise in our society, industrial organizations can provide crucial leverage in attacking environmental problems by incorporating environmental considerations into product and process design" (Lifset 1997, 1).

The Factor *X*

Neither in the IPAT equation, nor in Commoner's quantitative work, nor in the master equation in industrial ecology is there an attempt to quantify the relationship of technology and environmental impact in a *prospective* way, although this has entered some of the global climate change work cited earlier. Still, a threshold for sustainability is that it "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). Therefore, using these equations predictively would enhance the theoretical basis of IPAT ideas, for example, determining how much technology versus how much increase in population and affluence would be reasonable goals for countries and for the global commons. Recently, two agendas have been established that set targets for technology and environmental impact.

F. Schmidt-Bleek, while with the Wuppertal Institute, presented the Carnoules Declaration of the Factor 10 Club in 1994. The Factor 10 Club has focused on the need to substantially reduce global material flows. Its advocates believe that the current productivity of resources used must be increased by an average of a factor of ten during the next 30 to 50 years. "This is feasible if we mobilize know-how to generate new products, services, as well as new methods of manufacturing" (Factor 10 Club 1994, 8). We see here reliance on "know-how" and "methods of manufacturing" that again emphasizes the *T* term of the IPAT equation, in this case to create a specific sustainability target.

Weizsäcker, Lovins, and Lovins (1997) state in their book, *Factor Four: Doubling Wealth, Halving Resource Use*, that the amount of wealth extracted from one unit of natural resources can quadruple. Their goal that we can "live twice as well—yet use half as much" might be expressed in IPAT terms as achieving $2(A)$ with only $.5(T)$. They define technological progress neither as a reduction in pollution nor as a gain in labor productivity, but, overall, as a gain in productivity of resources. Up until now, tremendous gains in productivity have come from substituting resources for human labor. They are concerned that such substitution has gone too far and been inconsiderate of overusing resources such as energy, materials, water, soil, and air. Their research is devoted to an "efficiency revolution" that shows the potential for fourfold gains in resource use.

Factor Four and the Factor 10 are specific, if ambitious, expressions of the potential impact of *T,* the technology term. They are also future-oriented, setting a goal for corporate and policy direction. The four- to tenfold increase in aggregate economic impact, *PA*, can also be thought of as a twofold increase in *P,* population, over the next 50 years, and a two- to fivefold increase in *A*, affluence. Picking up on Factor Four and the Factor 10, Lucas Reijnders of the University of Amsterdam writes of "The Factor *X* Debate" (Reijnders 1998), in which researchers have gone even further than a factor of four or ten to propose long-term reductions in resource use as high as 50 times. This would occur through dematerialization, eco-efficiency, or increased natural resource productivity relying mainly on the *T* of the IPAT equation. Of course, until environmental impact is defined with great specificity, the choice of different *X* factors, including the baseline of Factor Four and the Factor 10, is arbitrary. Reijnders notes that whereas the debate in the United States is still largely within the NGO community, the concept of Factor *X* and the importance of quantifying objectives has influenced policy in several European nations, including Austria, Germany, and the Netherlands.

Do Factor *X* policies put the entire onus for environmental improvement on the technology variable? Some would tag WRI and the industrial ecologists as implying that nothing can be done about population and increasing wealth. This is too pessimistic a reading. The effectiveness of population programs has been demonstrated in many parts of the world, for example, in China, Japan, and Thailand (Miller 1994). As a matter of basic fairness, few would want to deny the improvement in the standard of living for the world's peoples implied in the affluence term. Neither can the three terms be considered in isolation. Rather, interactive effects exist, as demonstrated by Ehrlich and Holdren. Still, as Reijnders concludes, "although there is no agreement on the relative importance of technology in achieving a Factor *X* for economies as a whole, one still may note that the Factor *X* debate is characterized by a remarkable technological optimism. This is especially so if one views this debate against the background of a widely held supposition that environmentalism has an antitechnological bias" (Reijnders 1998, 18).

The Call of the Optimist

Just as all ecological problems are contextual, so too are the issues confronted by IPAT, which may shed light on why it has multiple interpretations. Since it was introduced in the early days of the environmental movement, much has changed, in large part because of the alarm sounded in the post–*Silent Spring* era by Ehrlich and Holdren, Commoner, and many other thoughtful researchers and policy makers. Still, much of the change was motivated by pessimism, captured in this statement of Holdren and Ehrlich at the end of their 1974 article:

> Ecological disaster will be difficult enough to avoid even if population limitation succeeds: if population growth proceeds unabated, the gains of improved technology and stabilized per capita consumption will be erased, and averting disaster will be impossible (Holdren and Ehrlich 1974, 291).

Indeed, these are still controversial issues. Environmentalists of the 1970s who were pessimistic continued to sound alarms in the 1990s (Ehrlich and Ehrlich 1990; Commoner 1992; Meadows et al. 1992). Deep ecologists will not wake to find themselves warm to technological optimism. But a great deal more consciousness about environmental issues exists internationally, especially among global institutions such as the United Nations, the World Bank, and other financial players (Schmidheiny and Zorraguin 1996). Indeed, the notion that environmental problems can be addressed and even advanced through technical and procedural innovation has achieved its own name in the European environmental sociology literature—"ecological modernization" (Hajer 1996; Mol and Sonnenfeld 2000). In the United States, environmental policy, for all its warts, has made an enormous contribution at the end of the pipe, and is slowly migrating toward more integrative policy. Similarly, in corporate environmental policy, researchers can now measure the early stages of a change in emphasis from regulatory compliance toward overall process efficiency (Florida 1996), even at the expense of sales in the traditional end-of-pipe environmental industry (U.S. Department of Commerce 1998).

Upon reflection, I believe that Commoner (1972a) anticipates the work defined by Ausubel, WRI, and industrial ecologists. He calls for a "new period of technological transformation of the [U.S.] economy, which reverses the counterecological trends developed since 1946"—a transformation that reconnects people and their ecosystems:

> Consider the following simple transformation of the present, ecologically faulty, relationship among soil, agricultural crops, the human population and sewage. Suppose that the sewage, instead of being introduced into surface water as it is now, whether directly or following treatment, is instead transported from urban collection systems by pipeline to agricultural areas, where—after appropriate sterilization procedures—it is incorporated into the soil. Such a pipeline would literally reincorporate the urban population into the soil's ecological cycle, restoring the integrity of that cycle . . . Hence the urban population is then no longer external to the soil cycle . . . But note that this rate of zero environmental impact is not achieved by a return to "primitive" conditions, but by an actual technological advance.

Conclusions

This article underscores that technology, although associated with both disease and cure for environmental harms, is a critical factor in environmental improvement. Thus, important reasons can be found to continue to develop frameworks such as industrial ecology, that focus on cures. The overall shift from pessimism to optimism, captured here through changing interpretations of the IPAT equation and its variants, is shown to be partly fatalistic, in that few alternatives exist to the imperative established by the Brundtland Commission; partly pragmatic, in that technological variables often seem easier to manage than human behavior; and partly a continued act of faith, at least in the United States, in the power of scientific advance.

Notes

1. Indeed, the very prescriptive laws of this period have been criticized by researchers for becoming so specific in their standards as to preclude technological innovation (NACEPT 1991; Heaton et al. 1991; U.S. Department of Commerce 1998).
2. A precursor to the IPAT formulation by sociologist Dudley Duncan in 1964 was the POET model (population, organization, environment, technology). According to Deitz and Rosa (1994), the model showed that each of these components are interconnected but did not specify quantifiable relationships.
3. To trace the origins of these equations accurately is challenging. The IPAT ideas emerged in 1970 and 1971. Particularly relevant was an exchange by Commoner and Ehrlich and Holdren in the *Saturday Review* during 1970 followed by a meeting at the President's Commission on Population Growth and the American Future held on November 17, 1970, the findings of which were not published until 1972. However, Ehrlich and Holdren and Commoner produced numerous publications in the meantime, which helped steer the IPAT debate in new directions. Ehrlich and Holdren used $I = P(I,F) \times F(P)$ in the 1972 findings, but a slightly different version, $I = P \times F(P)$ in their earlier article from *Science* in March of 1971, which is otherwise almost identical to the 1972 conference report. Both equations try to express a similar point, that P and F are interactive and can increase faster than linearly.
4. In fact, one of the reviewers of this article suggested that this use of the IPAT equation might better be called "EPAT," showing the emphasis on "*E*" for "Emissions" rather than the totality of *I* for all impacts.
5. The authors use the example of the impact of lead emissions from automobiles from 1946 to 1967 and find that population has increased 41 percent; consumption, measured as vehicle-miles per person, has doubled; and lead emissions per vehicle-mile increased 83 percent. Hence, $1.41 \times 2.0 \times 1.83 = 5.16$, or, subtracting 1.0, a 416 percent increase in total impact. This illustrates that although no variable more than doubled, the cumulative impact is multiplicative. Had population not grown but been held constant, then total impact would only have been $1.0 \times 2.0 \times 1.83$, or 3.66, reflecting a 266 percent increase, illustrating the multiplier effect (see Holdren and Ehrlich 1974, using corrections to the variables suggested by Commoner 1972b).
6. *Editor's note:* For an application of decomposition analysis to materials flows, see Hoffrén, Luukkanen, and Kaivo-oja, "Decomposition Analysis of Finnish Material Flows: 1960–1996," *Journal of Industrial Ecology,* this issue.
7. Further, these authors point out that the GDP measures socially and environmentally destructive behavior as an economic gain. Pollution, for

example, shows up as a double boost to the economy. The first boost comes when a polluting company makes a profit on the product they are selling and the second boost comes when the company spends large amounts of money on environmental cleanup.

8. Graedel, however, has some revisionist thinking about *A*, the affluence term (Graedel, 2000). Simply assigning it a financial measure such as GNP or GDP per capita may overemphasize the contribution of the market, and, as a result, deemphasize the opportunity for changing attitudes even as income rises. Graedel has suggested that the essence of the *A* term resides in its cultural and behavioral attributes, which he has called "the Madonna factor"—after the pop singer's well-known phrase "a material girl in a material world."

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