

Prospects for Reconciling the Conflict between Economic Growth and Biodiversity Conservation with Technological Progress

BRIAN CZECH

Virginia Polytechnic Institute and State University, National Capital Region, 7054 Haycock Road, Room 411, Falls Church, VA 22043, U.S.A., email czech@vt.edu

Abstract: *The conflict between economic growth and biodiversity conservation is understood in portions of academia and sometimes acknowledged in political circles. Nevertheless, there is not a unified response. In political and policy circles, the environmental Kuznets curve (EKC) is posited to solve the conflict between economic growth and environmental protection. In academia, however, the EKC has been deemed fallacious in macroeconomic scenarios and largely irrelevant to biodiversity. A more compelling response to the conflict is that it may be resolved with technological progress. Herein I review the conflict between economic growth and biodiversity conservation in the absence of technological progress, explore the prospects for technological progress to reconcile that conflict, and provide linguistic suggestions for describing the relationships among economic growth, technological progress, and biodiversity conservation. The conflict between economic growth and biodiversity conservation is based on the first two laws of thermodynamics and principles of ecology such as trophic levels and competitive exclusion. In this biophysical context, the human economy grows at the competitive exclusion of nonhuman species in the aggregate. Reconciling the conflict via technological progress has not occurred and is infeasible because of the tight linkage between technological progress and economic growth at current levels of technology. Surplus production in existing economic sectors is required for conducting the research and development necessary for bringing new technologies to market. Technological regimes also reflect macroeconomic goals, and if the goal is economic growth, reconciliatory technologies are less likely to be developed. As the economy grows, the loss of biodiversity may be partly mitigated with end-use innovation that increases technical efficiency, but this type of technological progress requires policies that are unlikely if the conflict between economic growth and biodiversity conservation (and other aspects of environmental protection) is not acknowledged.*

Keywords: biodiversity conservation, competitive exclusion, economic growth, economies of scale, research and development, technological progress, thermodynamics, trophic levels

Perspectivas para la Reconciliación del Conflicto entre Crecimiento Económico y Conservación de la Biodiversidad Mediante Progreso Tecnológico

Resumen: *El conflicto entre crecimiento económico y conservación de la biodiversidad es entendido en porciones de la academia y a veces es reconocido en círculos políticos. Sin embargo, no hay una respuesta unificada. En los círculos políticos, se postula que la curva ambiental Kuznets resuelve el conflicto entre crecimiento económico y protección ambiental. Sin embargo, en la academia se ha estimado que la curva ambiental Kuznets es falaz en escenarios macroeconómicos e irrelevante para la biodiversidad. Una respuesta más convincente al conflicto es que puede ser resuelto con progreso tecnológico. Aquí reviso el conflicto entre crecimiento económico y conservación de la biodiversidad en la ausencia de progreso tecnológico, exploro las perspectivas del progreso tecnológico para reconciliar ese conflicto y proporciono sugerencias lingüísticas*

para describir las relaciones entre el crecimiento económico, el progreso tecnológico y la conservación de la biodiversidad. El conflicto entre crecimiento económico y conservación de la biodiversidad se basa en las dos primeras leyes de la termodinámica y en principios de ecología como los niveles tróficos y la exclusión competitiva. En este contexto biofísico, la economía humana crece a costa de la exclusión competitiva de especies no humanas. La reconciliación del conflicto mediante el progreso tecnológico no ha ocurrido y no es viable por la estrecha relación entre el progreso tecnológico y el crecimiento económico en los niveles actuales de tecnología. Se requiere la producción de excedentes en los sectores económicos existentes para realizar la investigación y desarrollo necesarios para traer nuevas tecnologías al mercado. Los regímenes tecnológicos también reflejan metas macroeconómicas, y si la meta es el crecimiento económico, es menos probable que se desarrollen tecnologías reconciliadoras. A medida que crece la economía, la pérdida de biodiversidad puede ser mitigada parcialmente con innovaciones que incrementen la eficiencia técnica, pero este tipo de progreso tecnológico requiere políticas que no funcionarán si no se reconoce el conflicto entre el crecimiento económico y la conservación de la biodiversidad (y otros aspectos de la protección ambiental).

Palabras Clave: conservación de la biodiversidad, crecimiento económico, economías de escala, exclusión competitiva, investigación y desarrollo, niveles tróficos, progreso tecnológico, termodinámica

Introduction

The basic conflict between economic growth and biodiversity conservation is generally understood among ecologists and ecological economists. The conflict tends to resonate with the general public and is occasionally reflected by political representatives. For example, the 93rd U.S. Congress expressed an understanding of the conflict in the first sentence of the Endangered Species Act, in which it found that “various species of fish, wildlife, and plants in the United States have been rendered extinct as a consequence of economic growth and development untempered by adequate concern and conservation” (16 U.S.C. 1531[a][1]). The phrase “untempered by adequate concern and conservation” left a theoretical door open to reconciling economic growth with biodiversity conservation. Reconcilable or not, the basic conflict is not well understood in broader society (Czech & Krausman 1999) and therefore is seldom accounted for in public policy, especially macroeconomic policies that influence rates of economic growth. Perhaps nothing prevents public understanding and acceptance of the conflict more than the belief that technological progress may reconcile economic growth with biodiversity conservation (Weizsäcker et al. 1997).

Herein, I describe the basic conflict between economic growth and biodiversity conservation, explore the prospect of technological progress to reconcile that conflict, and provide linguistic suggestions for describing the relationships among economic growth, technological progress, and biodiversity conservation. The phrase *basic conflict* refers to the conflict between economic growth and biodiversity conservation in the absence of technological progress. Only when the basic conflict is well understood can the potential for technological progress to alleviate that conflict be explored rigorously.

Basic Conflict between Economic Growth and Biodiversity Conservation

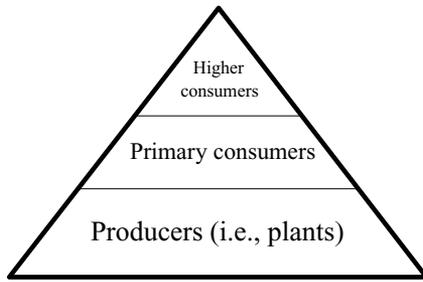
Economic growth is an increase in the production and consumption of goods and services, and it occurs with increasing population or increasing per capita production and consumption. An increasing gross domestic product (GDP) indicates a growing economy. Gross domestic product is a measure of the production of goods and services, income derived from that production, and expenditure thereon (Abel & Bernanke 2003). Increasing real GDP (i.e., adjusted for inflation) is sometimes considered synonymous with economic growth (Goodwin et al. 2007).

The basic conflict between economic growth and biodiversity conservation is rooted in principles of physics and ecology. An economy has a structure that resembles the trophic structure of an ecosystem. In an ecosystem surplus production by producers (i.e., plants) supports the existence of primary-, secondary-, and higher-level consumers. In the human economy surplus production by agricultural and extractive agents is required to support the existence of manufacturing sectors (Boulding 1993) (Fig. 1).

Some species escape easy classification among the standard trophic levels of producers or consumers. For example, detritivores consume decayed biomass and thus help maintain the ecosystem and its other species. They may be described as service providers in the economy of nature. In the human economy, too, there are service providers that interact with the agricultural, extractive, and manufacturing sectors (e.g., janitors, waiters, and information providers).

A convenient way of envisioning the basic conflict between economic growth and biodiversity conservation is by integrating the economy of nature and the human economy, with *Homo sapiens* comprising the highest

(a) Ecosystem Trophic Structure



(b) Human Economy

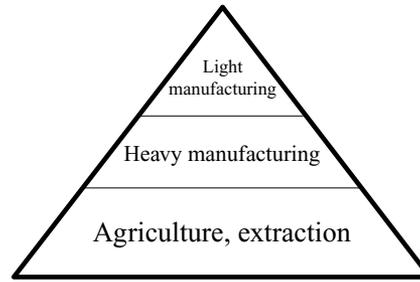


Figure 1. Trophic structures of (a) ecosystems and (b) human economies. The amount of area representing each trophic level is indicative primarily of biomass (a), material volume of product (b), and natural capital allocation (a and b). Service providers interact throughout ecosystems and human economies.

trophic level. Humans have the unique, omnivorous ability to identify, harvest, and consume virtually all other edible species. When the human economy grows, the effect is a trophic compression of nonhuman species (Fig. 2). This view is consistent with the history of species that have become endangered or gone extinct as a result of direct human consumption or displacement (Matthiessen 1987). A related concept is competitive exclusion (Pianka 1974), which establishes that species with overlapping niches compete for scarce resources—the quintessential subject matter of economics. Humans have a very broad niche; thus, humans proliferate at the competitive exclusion of nonhuman species (Czech et al. 2000). A modicum of physics is also required to understand the basic conflict. For example, if the human-inclusive economy of nature could expand indefinitely, then theoretically the human economy could grow without displacing nonhuman species. Nevertheless, the laws of thermodynamics preclude the prospect of perpetual growth in any economy (Georgescu-Roegen 1971). The first law, or the law of conservation of energy, establishes a limit to the amount of energy and (via $E = mc^2$) matter available for comprising the ecosystem. The second law, or the entropy law, establishes that the disorder or randomness of energy and matter always increases in an isolated system; in other words, no production process may achieve absolute efficiency (Georgescu-Roegen 1971). The application of the entropy law to trophic theory is known to ecologists as the concept of ecological efficiency, expressed as the proportion of energy or biomass converted from one trophic level to the next (Ricklefs 1990). For example, a thousand kilograms of plant biomass (or a thousand kilojoules embodied therein) will not produce

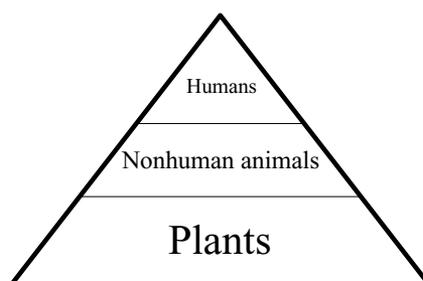
a thousand kilograms of animal biomass (or a thousand kilojoules embodied therein) because energy is lost in the transformation process. Similarly, a thousand kilotons of raw iron will not yield a thousand kilotons of steel beams, and energy will be dissipated during the transformation into steel.

The Economic Production Process and Biodiversity Conservation

The foundation of the human economy is agricultural and extractive activity that directly impacts nonhuman species. For example, agriculture, mining, logging, and domestic livestock production are all prominent causes of species endangerment (Czech et al. 2000). The production of crops, ores, logs, and livestock require the conversion of natural resources into human goods. Natural resources may be considered “natural capital,” stocks of which are drawn out of the economy of nature so that goods may flow into the human economy (England 2000). In the absence of *Homo sapiens*, natural capital is allocated entirely to nonhuman species. The level of human economic activity determines how much natural capital is available for biodiversity (Fig. 3).

If natural capital stocks are drawn on faster than they can be replenished, the drawdown enters the phase of liquidation (Daly & Farley 2003). This occurs, for example, when a forest is harvested at a rate exceeding its sustainable yield. For nonrenewable resources such as minerals, drawdown is essentially synonymous with liquidation, although some minerals may be recycled (with <100% efficiency). There are numerous examples

(a) Human-inclusive economy of nature



(b) Growth of human economy

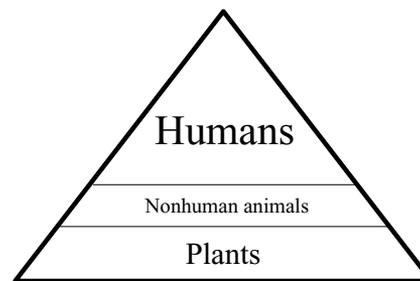


Figure 2. Human economy (a) embedded in nature and (b) with economic growth.

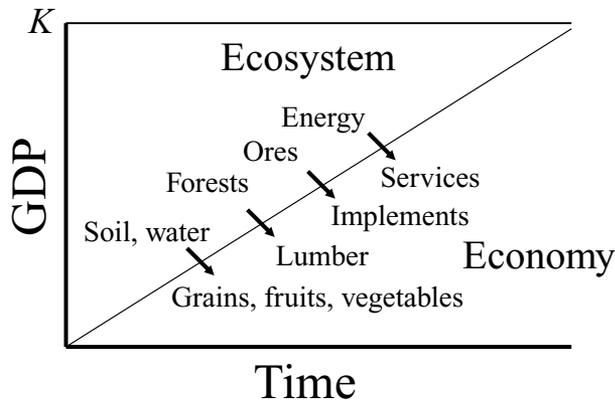


Figure 3. Reallocation of natural capital from the ecosystem and its nonhuman species to the human economy, with representative examples of natural capital stocks and human goods and services. The K (top line on graph) symbolizes the ecological carrying capacity of the economy. The general buildup of the economic trophic structure over time from agricultural and extractive sectors to manufacturing and service sectors is also indicated. Energy is a factor of production for all goods and services but is noted here particularly as an input for the production of services.

of species endangerment resulting from the liquidation of natural capital. For example, liquidation of old-growth forests has endangered the Spotted Owl (*Strix occidentalis*) (Yaffee 1994), and, more directly, liquidation of Atlantic cod (*Gadus morhua*) has endangered the cod (Kurlansky 1997).

Manufacturing also entails a drawdown of natural capital because the elements of manufactured goods and manufactured capital are procured or derived from nature. Service sectors, on the other hand, are often portrayed as less dependent on natural capital (Heiskanen & Jalas 2000). Nevertheless, many service sectors require copious amounts of natural capital, especially energy. For example, the transportation sector requires a continuous drawdown of petroleum stocks. Other service sectors such as banking, insurance, and computational services, appear less directly involved in natural capital drawdown, especially after the required infrastructure and equipment are in place. When such services become prominent, the economy may be referred to as an “information economy,” the growth of which has been portrayed as environmentally benign on the grounds that information substitutes for material resources as a factor of production (Coyle 1999).

This brings us to the closely related subject of technological progress, but first the role of information in the production process should be noted. For information to be relevant in economic terms, it must be demanded in the market, which is populated by users from other, noninformation sectors (i.e., agricul-

tural, extractive, manufacturing, and capital-intensive service sectors such as transportation). The information is typically purchased to increase production in those sectors, resulting in more drawdown of natural capital (Ruttan 2001). Just as economic production requires a flow of natural capital at stable rates of production, economic *growth* (i.e., growing rates of production) in the absence of technological progress ultimately requires the liquidation of natural capital (Daly & Farley 2003). Prior to liquidation, the natural capital stocks comprised habitats for nonhuman species.

The Environmental Kuznets Curve

Although ecology and physics are required for a thorough understanding of the basic conflict between economic growth and biodiversity conservation (i.e., sans technological progress), the basic conflict is readily observed and therefore is sometimes acknowledged in public policy circles. Nevertheless, the “basic” nature of the conflict exists in a world of increasing intellectual complexity and sophisticated political rhetoric, and the conflict has been deemed malleable and amenable to reconciliation. The ultimate prospect for reconciliation is technological progress (Weizsäcker et al. 1997). The role of technological progress in environmental affairs is complex, and political approaches to invoking technological progress for environmental protection redound to a simple concept called the “environmental Kuznets curve” (EKC) (Stern 2004).

The EKC represents the hypotheses that (1) there is a basic conflict between economic growth and environmental protection, but (2) the basic conflict is resolved when enough economic growth occurs. The logic is that when enough financial wealth accumulates, especially in per capita terms, society successfully refocuses on solving environmental problems (Fig. 4).

There is clearly a grain of truth to the EKC. In impoverished societies, little attention and fiscal resources are available for environmental programs. There is empirical evidence for Kuznets curves in microeconomic scenarios. For example, sulfur dioxide emissions have

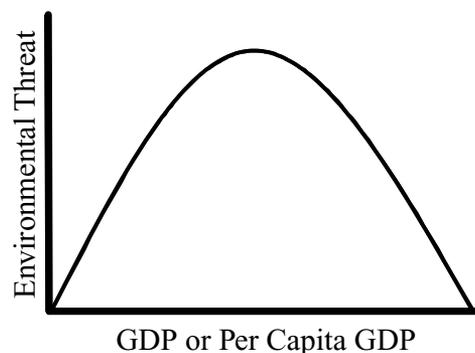


Figure 4. Generic environmental Kuznets curve.

declined in nations that have accumulated enough fiscal resources to ascertain the problem, develop technological alternatives, and replace the problematic infrastructure (Begun & Eicher 2007).

Here, however, the subject is economic growth, that is, increasing production and consumption of goods and services in the aggregate. There is no evidence for a macroeconomic EKC. Many environmental problems have been created and exacerbated as a function of economic growth—few have exhibited a Kuznets curve (Stern 2004).

The subject is also biodiversity conservation, and the prospect for a biodiversity Kuznets curve has several unique features. First, biodiversity loss has a particularly macroeconomic aspect, with the human (macro) economy growing at the competitive exclusion of the (macro)economy of nature. Second, most environmental problems (e.g., pollution) stemming from economic growth are problematic for nonhuman species as well as humans. Therefore, biodiversity should decline not only directly pursuant to the principle of competitive exclusion, but also as an indirect function of economic growth. Third, an extinct species cannot be resurrected to function with ecological and evolutionary integrity regardless of how much money is expended. Similarly, it is exceedingly difficult to restore wholly transformed habitats for the purposes of species recovery. For example, a metropolis could not be returned to a state of ecological integrity with a full complement of species, even if it were to be abandoned by humans (Weisman 2007). Furthermore, abandonment of a metropolis would contribute not to economic growth, but to recession, a condition in which the EKC is inapplicable.

The few studies designed to detect a biodiversity Kuznets curve have not done so (Asafu-Adjaye 2000; Naidoo & Adamowicz 2001; Clausen & York 2008). Naidoo and Adamowicz (2001) did find that “[b]irds were the only taxonomic group in which numbers of threatened species decreased throughout the range of developed countries’ per capita gross national product.” Naidoo and Adamowicz (2001) refer to *per capita* gross national product, not gross national product (GNP) or GDP. In other words, Naidoo and Adamowicz (2001) did not detect a reconciliation of economic growth (as indicated by GDP or GNP) with bird conservation; rather, they detected a reconciliation of prosperity (as indicated by per capita GNP) with bird conservation. All the other taxa declined even with increased prosperity.

Regarding the data on birds, Naidoo and Adamowicz (2001) expressed the need to “see whether this knowledge can be applied to conservation of other taxa.” Using a system for classifying policy targets devised by Schneider and Ingram (1993) and data on public opinion, political support, and fiscal expenditure, Czech and Krausman (2001) found that birds were “clearly the most advantaged type” among nonhuman taxa. These authors

posited that biodiversity would be lost as a function of economic growth, beginning with the less advantaged taxa and ultimately including birds.

Using a nonlinear regression model to investigate relationships among population, GDP, and environmental impact, Dietz et al. (2007) concluded, “Contrary to the expectations of the EKC [environmental Kuznets curve], increased affluence apparently exacerbates rather than ameliorates impacts.” Their findings are especially relevant to biodiversity conservation given the macroeconomic nature of the analysis. Dietz et al. (2007) also found that “the proportion of GDP in the service sector. . . [has] no net effect on environmental impact.”

Although the grain of truth in the EKC will not find fertile soil in the field of biodiversity conservation, there remains the hope that technological progress can reconcile economic growth with biodiversity conservation. This prospect is related to the EKC insofar as a threshold level of wealth may provide the financial resources for problem-solving technologies, as opposed or in addition to fiscal resources for public conservation programs.

Innovation and Technological Progress

In economic terms technological progress results in increasing technical efficiency (productivity) (i.e., greater production of output per unit input [Perelman 1995]). Engineers may view such an increase primarily in physical terms (e.g., an increase in steel production from the same amount of iron and energy). Economists level the field by using monetary units, such as dollars, to measure inputs and outputs (Fried et al. 1993). They also distinguish between product innovation and process innovation (Li et al. 2007). Product innovation is synonymous with invention, and process innovation pertains to reconfiguring the production process. Paying particular attention to the prospects for alleviating environmental impact, Wils (2001) suggests a classification system with three categories of innovation: explorative, extractive, and end-use innovation.

Explorative innovation allows the user to locate stocks of natural capital that were not previously detectable, and extractive innovation allows the user to extract known resources that were previously inaccessible. Explorative and extractive innovations contribute to economic growth by increasing the amount of natural capital reallocated from the economy of nature to the human economy (Wils 2001).

This leaves end-use innovation as the lone source of technological progress that could conceivably reconcile economic growth with biodiversity conservation. End-use innovation is essentially synonymous with increasing technical efficiency (Wils 2001). A good example for our purposes is increasing fuel efficiency of fishing vessels. Product innovation such as vessel design, or process

innovation such as optimizing fishing schedules, may increase the amount of fish caught per unit of fuel consumed. Two basic scenarios may follow: (1) the same amount of fish are caught and sold, but less fuel is purchased, and *ceteris paribus*, economic growth does not result, and (2) the same amount of fuel is purchased, more fish are caught and sold, and, *ceteris paribus*, economic growth results. In the first scenario, economic growth is not reconciled with biodiversity conservation because economic growth does not occur. In the second scenario, economic growth is not reconciled with biodiversity conservation because more fish are reallocated from the economy of nature to the human economy.

In an intermediate scenario, somewhat less fuel is purchased by the fishing fleet and somewhat more fish are caught and sold. In other words, theoretically the economy may grow somewhat, with somewhat less natural capital reallocated from the economy of nature to the human economy, at least relative to the amount of natural capital that would have been allocated pursuant to the same amount of economic growth in the absence of the end-use innovation. Nevertheless, this theoretical outcome is based on the assumption that different forms of natural capital (fuel and fish in this case) are substitutable; an assumption not conducive to fish conservation (Daly & Farley 2003). It is also based on the assumption that the fish harvest has not reached the stage of liquidation.

These theoretical considerations say nothing quantitatively about the technical efficiency gains required to reconcile the conflict between economic growth and biodiversity conservation. Nevertheless, to the extent that biodiversity is a function of intact landscapes, or lands from which natural capital has not been liquidated for human economic production, studies pertaining to growth of the ecological footprint are highly relevant. Dietz et al. (2007) estimated "an annual growth rate in the global footprint of 2.12% per year" and surmised that "the requisite technological improvement needs to exceed 2% per year" for environmental protection. Annual productivity gains exceeding 2% typified the "advanced capitalist economies" during the third quarter of the 20th century (Maddison 1987), but gains falling well below 2% have befuddled growth theorists and national income accountants ever since. In countries with less-advanced economies, much of the recent economic growth has resulted from increases in factor inputs (land, labor, and capital), not from the efficiency with which those factors were used (Oguchi 2005).

The only solid conclusion to be drawn from this section (i.e., prior to considering the following sections) is that, in theory, the possibility of reconciling economic growth with biodiversity conservation via technological progress cannot be ruled out. Nevertheless, reconciliation is not occurring and does not appear likely, partly because much innovation is not end use but rather explorative and extractive (Wils 2001). Even end-use in-

novation does not appear to offer a sure prospect for reconciling economic growth with biodiversity conservation, although it does appear to offer a clear prospect of lessening the impact of economic growth (at any rate) on biodiversity. Both of these prospects are eventually limited by the entropy law, which establishes limits to technical efficiency (Georgescu-Roegen 1971). In other words, any prospective reconciliation or mitigation via end-use innovation would be temporary in nature and not a fundamental aspect of the relationship between economic growth and biodiversity conservation.

To develop more reliable conclusions about the prospect for reconciling economic growth with biodiversity conservation, even temporarily, one must explore the economic origins of technological progress.

Empirical Trends in Research and Development

Technological progress results primarily from research and development (R&D) (Romer 1994). Some technological progress also results from "learning by doing" (i.e., on-the-job innovation), but learning by doing is subject to diminishing returns and is temporary for a given technology (Lucas 1993). Research and development is conducted by industry, governments, colleges and universities, and nonprofit organizations. Among nations, the United States (governmental and nongovernmental entities) invests in approximately 30% of the global R&D (Duga & Stadt 2005). Given the leading role played by U.S. R&D, I scrutinized U.S. R&D data to gain insights into the nature of R&D with regard to technical efficiency and biodiversity conservation.

In the United States approximately \$299 billion of R&D was conducted in 2006, 71% of which was conducted by industry, 17% by colleges and universities, 7% by the federal government, and 5% by nonprofit organizations (National Science Foundation 2007a). Similar proportions apply in other nations with substantial R&D expenditures (Table 1). Research and development in the United

Table 1. Research and development conducted by industry, government, and academia or others in representative nations, abbreviated from Duga and Stadt (2005).

<i>Nation</i>	<i>Industry (%)</i>	<i>Government (%)</i>	<i>Academia or others (%)</i>
Australia	47.5	22.9	29.5
China	61.2	28.7	10.1
Germany	69.1	13.8	17.1
Japan	74.4	9.5	16.1
Mexico	30.3	39.1	30.6
Poland	21.4	44.9	33.8
Russia	69.9	24.5	5.6
Spain	54.6	15.4	30.0
Sweden	77.6	2.8	19.5
United Kingdom	67.0	8.9	24.1

Table 2. Research and development expenditures (billions of U.S.\$) in the United States in 2006 (National Science Foundation 2007a).*

<i>Entity</i>	<i>Funded (%)</i>	<i>Conducted (%)</i>	<i>Basic (%)</i>	<i>Applied (%)</i>	<i>Development (%)</i>
Industry	194 (65)	213 (71)	8 (15)	47 (68)	158 (91)
Colleges, universities	8 (3)	50 (17)	35 (64)	11 (16)	3 (2)
Federal government	84 (28)	21 (7)	4 (7)	7 (10)	10 (6)
Nonprofits	10 (3)	15 (5)	8 (15)	4 (6)	3 (2)
Other governments	3 (1)				
Total	299	299	55	69	174

*Percentages pertain to columns. Rounding errors occur. All figures except in column 2 (Funded) refer to research conducted regardless of funding source.

States consisted of 19% basic research, 23% applied research, and 58% development (Table 2). These figures reflect who conducted the R&D, not the funding source. For example, the federal government provides funding for R&D conducted by industry, colleges and universities, and nonprofit organizations. Conversely, colleges and universities receive most of their funding for R&D from federal and state governments, industry, and nonprofit organizations.

Whether viewed in terms of who is conducting the R&D or who is providing the funds, the R&D landscape is dominated by the United States and by corporations. Of the world's 100 largest economic units, 51 are corporations and 49 are countries (Anderson & Cavanagh 2000). Corporations are chartered for the primary purpose of generating profits and seldom deviate from that purpose in their investment decisions (Bakan 2005). Likewise, the vast share of global R&D is conducted for the purpose of generating profits, not for biodiversity conservation. This observation is not intended to reflect the level of environmental concern among corporate personnel and shareholders but rather to illuminate the financial exigencies of corporations.

One might assume that any R&D that increases technical efficiency has the potential to reconcile the basic conflict between economic growth and biodiversity conservation, as long as enough such R&D is conducted. Nevertheless, much of the technological innovation is explorative and extractive and tends to increase the drawdown of natural capital (Wils 2001). The National Science Foundation does not categorize R&D among explorative, extractive, and end-use innovation, but the categories it does use provide clues about the nature of R&D expenditures. "Basic research" connotes scientific investigation for the general benefit of society, "applied research" is designed to answer specific questions for particular users, and "development" refers to the innovations required to bring the answers into practice. Given the corporate focus on profits, it is not surprising that the lowest proportion of basic research (4%) and the highest proportion of development (74%) are conducted by corporations (Table 2). Conversely, the highest proportion of basic research (70%) and the lowest proportion of development (6%) are conducted by colleges and universities.

Trends have been away from basic research, conducted by universities and governments, and toward development, conducted by industry (Ruttan 2001).

Furthermore, the profit motive (at the corporate level) and the macroeconomic goal of growth (at the government level) tend to redirect savings from any end-use innovation toward other activities that increase production and consumption in the aggregate, including capital investments to increase production, marketing to increase consumption, and further investments in R&D, including explorative and extractive R&D. In other words, there is a link between economic growth at current levels of technology and the technological progress that raises the bar for further economic growth, which I discuss in the next section.

First, however, as an indicator of the scale of R&D that may be motivated to some degree out of concern for biodiversity, approximately \$14 billion of R&D was expended on earth and biological sciences at U.S. colleges and universities in 2006 (National Science Foundation 2007b). Some of this R&D was probably designed to increase economic production too, as with much of the nearly \$3 billion of agricultural R&D (Table 3). Presumably some of the \$9 billion of R&D classified as "biological" was oriented toward conserving biodiversity. Even if a third of that amount was oriented toward biodiversity conservation (which conservation biologists would probably find a generous estimate), it would comprise approximately 1% of U.S. R&D.

Some government R&D may be focused on biodiversity conservation, but the amount is dwarfed by R&D devoted to defense and economic objectives in bellwether

Table 3. Research and development expenditures at U.S. colleges and universities in 2006 (National Science Foundation 2007b).

<i>Field</i>	<i>Expenditures (millions of U.S.\$)</i>
Atmospheric science	506
Earth sciences	897
Oceanography	839
Agricultural sciences	2,794
Biological sciences	9,044
Total	14,080

nations such as the United States, China, and the Russian Federation (Duga & Stadt 2005). For example, in China, the developing superpower with the second-highest R&D expenditures, most R&D is devoted to defense and economic growth (Duga & Stadt 2005). Conversely in Japan, a leading information economy where military objectives are limited, approximately 35% of R&D is devoted to economic objectives (AAAS 2002).

It is difficult to obtain data on the R&D expenditures of nonprofit organizations, but nonprofit R&D budgets reflect broad social concerns and funding sources. Nearly half of the funding for U.S. nonprofit R&D is provided by the federal government (39%) and industry (9%), whereas, somewhat paradoxically, the rest is provided by other nonprofit organizations (National Science Foundation 2007a). Of the 100 largest nonprofits in the United States, only four are devoted to biodiversity conservation or closely related aspects of ecological integrity: The Nature Conservancy (20th largest), Wildlife Conservation Society (52), Ducks Unlimited (55), and the Trust for Public Land (95) (Sinclair et al. 2005). These organizations, as with most environmental nonprofit organizations, focus on applied conservation mixed with small amounts of research.

Regardless of who funds or conducts it, most biodiversity R&D produces policy implications conducive to tempering economic projects or activities rather than conducting economic growth, so even biodiversity R&D cannot be assumed to contribute to reconciling the basic conflict between economic growth and biodiversity conservation. Research and development designed to increase technical efficiency among economic sectors appears to have more potential to reconcile the basic conflict, whereas R&D designed to ascertain the causes of biodiversity loss has more potential to raise awareness of the conflict.

Research and Development, Profit, and Economic Growth

Table 2 illuminates the central role of profits in R&D. The large proportion of R&D coming from corporations must be, by definition, a direct function of corporate profit. It is only after the factors of production (land, labor, and capital) are paid for and shareholder dividends distributed that any remaining corporate revenue may be allocated to R&D. A similar requirement applies to the next-largest funder, the federal government. Its revenue comes almost entirely from income taxes (individual and corporate) and social security payments (U.S. Department of the Treasury 2007). Taxes and social security payments are forthcoming only from solvent firms and individuals (i.e., those that have paid off maintenance and subsistence bills, respectively). In other words, federally funded R&D is a function of profits. Colleges and universi-

ties, nonprofit organizations, and state and tribal governments also depend on profits or, in more general terms that encompass all types of R&D funding, income above maintenance and subsistence costs. *Ceteris paribus*, increasing R&D requires increasing profits at the corporate level and increasing income at the national level (i.e., economic growth). The tight linkage of R&D to economic growth, and vice versa, is indicated by the fact that R&D comprises a distinct category of expenditure in the calculation of GDP. This reciprocal linkage was illuminated by the National Science Foundation's Panel on Research and Development Statistics: "the [R&D] data are sometimes used to measure the output of R&D, when, in reality, in measuring expenditures, they reflect only one of the inputs to innovation and economic growth" (Brown et al. 2004). Likewise, in economic growth theory, R&D and economic growth are modeled as mutually reinforcing processes (Romer 1994).

These basic relationships among profits, R&D, technological progress, and economic growth must be grasped by conservation biologists who would add value to scholarly or public dialog about the prospects for reconciling economic growth with biodiversity conservation. Most of the value added, however, will come from their knowledge of the natural sciences because economists who have dominated discussions about economic growth already grasp the significance of economic factors. Economists have long agreed that profits dry up for the firm that fails to attain a competitive advantage (Heilbroner 1992). In macroeconomics the tendency for national income to stagnate has played a prominent role in economic growth theory since Keynes (1936) wrote the *General Theory of Employment, Interest, and Money*. The conventional solution offered in both cases (micro- and macroeconomics) is technological progress, which gives the firm an advantage over competitors and allows the economy to grow continually.

In other words, R&D is required to maintain profits—and economic growth—but profits are required to maintain R&D. This reciprocal requirement may be viewed alternatively as a virtuous spiral or an impossible catch-22. With a few notable exceptions such as E. F. Schumacher, economists have viewed it as a virtuous spiral (Rostow 1990). Recalling the discussion of trophic levels, competitive exclusion, and thermodynamics above, a reasonable view for the ecologically informed is that the reciprocation of R&D and profits is a largely beneficial spiral until economic growth causes more problems than it solves. The conservation biologist may add that biodiversity is continuously diminished along the way.

Economies of Scale and Technical Efficiency

There has been one other major source of increased technical efficiency and attendant profits: economies of scale. Economies of scale are reductions in the average cost

of a product resulting from an increased level of output. They are classified as internal or external (Ruttan 2001). Internal economies of scale operate within the firm, such as when the efficiency of a sawmill increases with a higher volume of timber moving through the mill. External economies of scale operate at broader scales, such as when the timber industry grows large enough to hire a public relations firm that provides advertising services at cheaper prices than would be paid by individual timber companies.

Economies of scale also operate macroeconomically. For example, Denison (1985) attributed the increased productivity (indicated by increased income per capita) of western European nations from the period 1950–1962 largely to economies of scale.

Economies of scale may arise independently of new technology. For example, increasing demand as a function of population growth may induce economies of scale. As with technological progress resulting from R&D, economies of scale result in increasing technical efficiency. Nevertheless, by definition economies of scale require a concomitant increase in aggregate production.

Combining economies of scale with R&D has clearly been the modus operandi of large corporations because of the dual benefits of increased efficiency and market share (Gordon 2004). Nevertheless, this combination forms another spiral that, for purposes of biodiversity conservation, has not been so virtuous. As economies of scale have contributed substantially to corporate profits, they have done so by increasing the reallocation of natural capital at current levels of technology and polluting ecosystems at increased rates. The best that can be hoped for is that the additional production attributable to new technology stemming from R&D will have less impact *per unit* than the impact of production with old technology. To the extent that R&D is financed from profits generated via economies of scale (as opposed to new technology), even that prospect is diminished.

Linguistic Clarifications

For purposes of informing the public policy dialog on the relationships among economic growth, technological progress, and biodiversity conservation, conservation biologists should exercise linguistic caution to avoid misleading individuals and to avoid being quoted out of context by individuals or organizations that promote economic growth. The argument that economic growth can be reconciled with biodiversity conservation given enough technological progress is congruent with principles of ecology and physics only if *reconciled* means that the rate of biodiversity loss decreases as the economy grows via technological progress, not that biodiversity ceases to be lost or is somehow regained. Nevertheless,

reconcile tends to connote a relatively thorough resolution to a problem, so *lessen* is more apt. The argument then is that the basic conflict between economic growth and biodiversity conservation may be lessened with technological progress. The phrase *may be lessened*, as opposed to *is lessened*, is also more appropriate because of the preponderance of R&D devoted not to conservation purposes but rather to increasing profits and economic growth.

Because *basic* describes the conflict in the absence of technological progress and given that technological progress does not reconcile but may only lessen the conflict, the word *fundamental* is a more telling adjective for *conflict*. *Basic* tends to connote simple or even simplistic, whereas *fundamental* indicates the conflict is founded in first principles and is congruent with a sophisticated analysis of the evidence. Furthermore, because the nature of R&D tends to reflect profit motives and the political economy of growth, additional information should be provided to clarify to the public and policy maker that there must be a systematic, intentional, and determined approach to lessening the impact of economic growth via technological progress. Therefore, one may accurately posit that the fundamental conflict between economic growth and biodiversity conservation may be lessened with technologies that increase technical efficiency, but this type of technological progress requires policy goals and tools that are conducive to increasing technical efficiency rather than exploration and extraction.

The fundamentality of the conflict should be emphasized and clarified to prevent undue optimism from being generated by the word *lessened*, to lower the probability of being quoted out of context, and to add clear macroeconomic policy implications. For example, at the end of the argument it should be noted that ultimately economic growth will continue to cause environmental problems, including biodiversity loss, whereas a stabilized or steady state economy may be reconciled with environmental protection and biodiversity conservation.

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