

The debt of nations and the distribution of ecological impacts from human activities

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Communicated by Kirk R. Smith, University of California, Berkeley, CA, October 19, 2007 (received for review February 3, 2007)

As human impacts to the environment accelerate, disparities in the distribution of damages between rich and poor nations mount. Globally, environmental change is dramatically affecting the flow of ecosystem services, but the distribution of ecological damages and their driving forces has not been estimated. Here, we conservatively estimate the environmental costs of human activities over 1961–2000 in six major categories (climate change, stratospheric ozone depletion, agricultural intensification and expansion, deforestation, overfishing, and mangrove conversion), quantitatively connecting costs borne by poor, middle-income, and rich nations to specific activities by each of these groups. Adjusting impact valuations for different standards of living across the groups as commonly practiced, we find striking imbalances. Climate change and ozone depletion impacts predicted for low-income nations have been overwhelmingly driven by emissions from the other two groups, a pattern also observed for overfishing damages indirectly driven by the consumption of fishery products. Indeed, through disproportionate emissions of greenhouse gases alone, the rich group may have imposed climate damages on the poor group greater than the latter's current foreign debt. Our analysis provides *prima facie* evidence for an uneven distribution pattern of damages across income groups. Moreover, our estimates of each group's share in various damaging activities are independent from controversies in environmental valuation methods. In a world increasingly connected ecologically and economically, our analysis is thus an early step toward reframing issues of environmental responsibility, development, and globalization in accordance with ecological costs.

ecological degradation | ecosystem change | ecosystem services | external cost

Humanity is transforming ecosystems around the globe at an unprecedented speed and scale (1–4), but the distribution of the drivers and costs, both past and future, is uneven among nations. Many of these ecosystem changes have led to substantial benefits in terms of food security and economic development but at a growing cost to ecosystems and humanity's future (1–5). The Millennium Ecosystem Assessment (MA), which reported that ≈60% of ecosystem services surveyed are being degraded or used unsustainably (1), did not assess the worldwide costs of this degradation, but for habitat loss in 2000 alone, a net cost of (2000 United States) \$250 billion for that year and all subsequent years was estimated in ref. 6. In many ways, humanity is already in *terra incognita* regarding the extent of current ecological degradation and more so in predicting the future impacts of our past and ongoing actions. Indeed, our awareness of the risks of future climate catastrophes (e.g., collapsing ice sheets and changes in ocean circulation) is growing, although the probabilities and costs of such events are unknowable (7–9).

Accountability for climate change among nations and regions has been estimated by using a variety of indices (10–12). Still, our understanding of whose actions are driving ecological degrada-

tion in general and who is paying the costs remains limited. Here, we use a simple accounting framework to link activities over 1961–2000 by low-, middle-, and high-income nations with ecological damages borne by these groups. Although a complex interplay of direct and indirect drivers cause this degradation, our analysis begins to shed light on crucial issues. In a world tightly knit by phenomena such as climate change and globalization, much ecosystem change is driven by activities beyond a nation's borders or within its borders but beyond its control (13). This raises equity concerns over the global atmospheric commons and the displacement of damages by global trade (10, 11, 13–15). Our analysis highlights the distribution of impacts across income groups, with important implications for “ecological debts” (10, 14, 16, 17) between groups.

Results and Discussion

Our empirical analysis focuses on external costs or externalities, the negative or positive side-effects of economic activity not included in market prices (18). Because of the quality of available data, we cover human activities over 1961–2000 that have contributed to six major classes of ecological damage (Table 1). Two broad, widely recognized drivers of environmental damage—global population and average per capita gross world product—approximately doubled during this time.[§]

The valuations we present are based on estimates in the peer-reviewed literature and United Nations (UN) reports. Because valuing environmental and human health impacts is “conceptually, ethically, and empirically” fraught (8, 19), the particular values we present should be taken as more indicative than literal. Our estimates represent changes in ecosystem services due to human activities rather than total economic values of ecosystems as in previous efforts (20). We calculate net present value (NPV) impacts over the time scales in Fig. 1 using a discount rate to weight the yearly impacts. To give some consideration to potentially large impacts on future generations, we use a discount rate at the lower end of the spectrum (2%). The choice of a discount rate, a great uncertainty in climate change economics (9), is ethical, and even a sensitivity analysis [supporting information (SI) Table 3] cannot fully address the issues of intergenerational rights and obligations (21).

Our estimates of the ecological external costs are given in Table 1. To balance different currencies' purchasing power for

Author contributions: U.T.S. and J.H. designed research; U.T.S., S.P.C., A.C.K., A.B.S., and R.W. performed research; U.T.S., S.P.C., E.H., P.A.T.H., A.C.K., L.E.K., A.B.S., and R.W. analyzed data; and U.T.S. and R.B.N. wrote the paper.

The authors declare no conflict of interest.

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[¶]The World Bank Group, World Development Indicators Database, <http://publications.worldbank.org/WDI/indicators>. Accessed September 28, 2006.

This article contains supporting information online at www.pnas.org/cgi/content/full/0709562104/DC1.

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Table 1. NPV of environmental externalities associated with human activities undertaken over 1961–2000, PPP-adjusted

| Category | Direct or indirect driver | <i>b</i> , driver of costs | Income group <i>a</i> , bearer of costs (2005 international \$ × 10 ⁹) | | | |
|--|--|----------------------------|--|----------------|---------------|-----------------|
| | | | Low | Middle | High | World |
| Climate change | Greenhouse gas emissions (carbon dioxide, methane, nitrous oxide) | Low | (50)–740 | (1,300)–1,100 | (180)–640 | (1,600)–2,500 |
| | | Middle | (170)–2,500 | (4,500)–3,800 | (620)–2,100 | (5,300)–8,500 |
| | | High | (160)–2,300 | (4,200)–3,600 | (580)–2,000 | (5,000)–7,900 |
| | | World | (370)–5,500 | (10,000)–8,600 | (1,400)–4,800 | (12,000)–19,000 |
| Stratospheric ozone-layer depletion | Chlorofluorocarbon emissions | Low | 0.58–1.3 | 5.3–9.8 | 15–23 | 21–34 |
| | | Middle | 10–23 | 94–170 | 260–420 | 370–610 |
| | | High | 25–57 | 230–430 | 660–1,000 | 910–1,500 |
| | | World | 36–81 | 330–610 | 930–1,500 | 1,300–2,200 |
| Agricultural intensification and expansion | Consumption of agricultural goods | Low | 2,100 | 27 | 4.8–16 | 2,100 |
| | | Middle | 13 | 15,000 | 51–170 | 15,000 |
| | | High | 29 | 580 | 870–3,000 | 1,500–3,600 |
| | | World | 2,100 | 15,000 | 930–3,200 | 18,000–21,000 |
| Deforestation | Consumption of agricultural goods and wood-related goods, weighted equally | Low | 310–1,600 | 0.27–4.8 | — | 310–1,600 |
| | | Middle | 5.9–30 | 180–3,300 | — | 190–3,300 |
| | | High | 7.3–37 | 12–220 | (17) | 3–240 |
| | | World | 320–1,600 | 200–3,500 | (17) | 500–5,100 |
| Overfishing | Consumption of fish and fisheries products | Low | 0.027–0.061 | 0.029–0.091 | 0.0086–0.041 | 0.064–0.19 |
| | | Middle | 0.52–1.6 | 65–210 | 0.82–4.0 | 66–220 |
| | | High | 1.2–2.3 | 12–36 | 4.3–21 | 17–59 |
| | | World | 1.8–3.9 | 76–250 | 5.1–25 | 83–280 |
| Mangrove loss | Consumption of farmed shrimp | Low | 39 | 0.18 | 0.0021 | 40 |
| | | Middle | 1.5 | 90 | 0.22 | 92 |
| | | High | 34 | 71 | 9.1 | 110 |
| | | World | 75 | 160 | 9.4 | 250 |
| Totals | | Low | 2,400–4,400 | (1,300)–1,200 | (160)–680 | 940–6,300 |
| | | Middle | (140)–2,500 | 11,000–22,000 | (300)–2,700 | 10,000–27,000 |
| | | High | (60)–2,500 | (3,300)–4,900 | 950–6,000 | (2,400)–13,000 |
| | | World | 2,200–9,500 | 6,000–28,000 | 480–9,400 | 8,700–47,000 |

Each entry C_{ab} represents the share of the externalities borne (or predicted to be borne) by income group b that may be linked to emissions or consumption by income group a , where a and b refer to rows and columns, respectively. We use a discount rate of 2% for all analyses, and consider impacts over 2000–2100 for climate change, 1985–2100 for ozone layer depletion, and 1961–2000 for the other topics. All climatic impacts are counted under the climate change category and are not divided among the other categories that contribute to emissions such as deforestation or agriculture. We do not distribute the high-income group's external benefits from net afforestation based on consumption but do include the value in the world sums. For overfishing, net rather than total revenues from foregone catch are listed, and catch from the high seas is allocated per capita among the world's citizens. We use income groupings as designated by the World Bank (low income: India, Pakistan, Bangladesh, Nigeria, Vietnam, etc.; middle income: China, Indonesia, Brazil, Russian Federation, Mexico, etc.; high income: United States, Japan, Germany, France, United Kingdom, etc.).

comparable goods, we present estimates in international dollars, United States dollars translated for national per capita income groups at their purchasing power parity (PPP) exchange rates.[§] The total costs are distributed such that low-income (L), middle-income (M), and high-income (H) groups bear up to 20%, 60%, and 20%, respectively, of the total damages. The upper bound value of external costs experienced by each group is comparable with or greater than that group's year-2000 gross domestic product (GDP) (PPP-adjusted), with ratios of 1.9, 1.5, and 0.30 (LMH). Predictably, equity weighting, which seeks to address the disparity in burden to poor and rich persons bearing the same monetary costs (see *Methods*), shifts the distribution dramati-

cally so that LMH groups each bear 45%, 52%, and 3.1%, respectively, of the total damages (SI Table 4). In the remainder of this article, we will refer to the non-equity-weighted estimates in Table 1 unless noted.

Compared with world NPV revenues over 1961–2000, the external costs from four classes of degradation—agricultural change, deforestation, overfishing, and mangrove loss—represent up to 16% of agricultural revenue,^h 52% of industrial roundwood and fuelwood revenue (22), 12% of fisheries revenue,ⁱ and 63% of aquaculture fisheries revenue,^j respectively (non-PPP values used for comparisons). For climate change, the NPV of external costs in the 21st century from emissions over 1961–2000 alone may represent up to one-third of year-2000 world GDP (PPP). We also estimate health impacts from ozone depletion in disability-adjusted life years (DALYs), which combine years lost from premature mortality with those lost from disability. The NPV range of years of life lost from ozone depletion (110–220 million) is comparable with the global

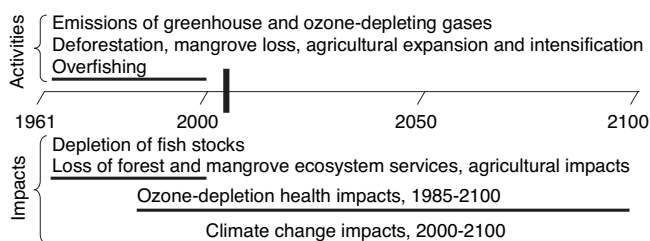


Fig 1. Time periods of ecologically damaging activities and impacts considered here. NPV sums D are taken at 2005.

^hWorld Resources Institute, EarthTrends, <http://earthtrends.wri.org>. Accessed March 20, 2006.

ⁱFisheries Centre, University of British Columbia, Sea Around Us Project, [www.seararoundus.org](http://seararoundus.org). Accessed June 5, 2006.

^jUnited Nations Food and Agriculture Organization, Statistical Databases, <http://faostat.fao.org>. Accessed March 20, 2006.

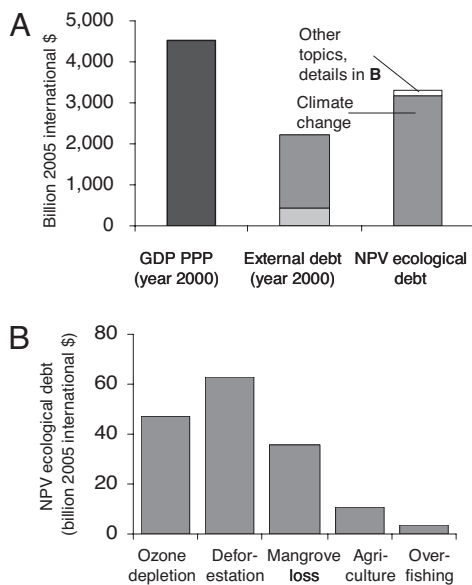


Fig. 2. Upper bound values of NPV net “ecological debt” to low-income nations from middle- and high-income nations in 2000, calculated as $C_{ML} + C_{HL} - C_{LM} - C_{LH}$ (PPP-adjusted, discount rate 2%). In A, year-2000 PPP-adjusted levels of both GDP and external debt for the low-income group are provided for comparison, with external debt PPP-adjusted to reflect its different value to debtor low-income (dark gray) and creditor high-income (light gray) groups.

products have been more stark: *M* and *H* groups consumed $\approx 85\%$ of products fished in their waters, whereas *L* countries retained only $\approx 15\%$. Furthermore, fishing in the high seas was almost completely done by *M* and *H* countries, who captured $\approx 32\%$ and 68% of the catch from these waters, respectively. In fact, several food-deficit countries in West Africa collect only modest access fees and allow distant fleets to land significant catches in their waters, and other *L* and *M* countries are major exporters of high-value fish products (1). Thus, our estimate of the toll of overfishing on fisheries belies its significance to food security. A more pronounced case of disconnect between suppliers and consumers concerns shrimp aquaculture, a main driver of mangrove destruction (24). Over 1980–2000, *L* and *M* countries have sent 96% of their shrimp exports to the *H* group. Although the trade is voluntary, shrimp-exporting countries bear undue environmental harm because mangroves mostly occur within 16 miles of cities of $\geq 100,000$ people (1) and key storm protection is lost.

Our distributional framework adds a layer to the understanding of human impacts on ecosystem services and accountability, complementing insights from the MA (1), ecological footprint (17, 37), natural debt (10, 14), consumption (38), IPAT (39), and other analyses. The imbalance of activity and harm is most pronounced for low-income countries. It has been argued that ecological damages from disproportionate emissions or consumption patterns contribute to ecological debts between countries (10, 11, 14, 16, 17). Recognizing that the values we estimate are uncertain, they nevertheless provide important information on the general magnitude and direction of these debts. If we assume that the direct and indirect drivers used here are the sole causes of the damages, we can approximate the net ecological debt owed by rich and middle-income nations to poor nations (Fig. 2), with climate and ozone depletion impacts accounting for 97% of the debt. As expected, equity weighting magnifies this debt, by nearly six times (SI Table 4). Although emissions and consumption patterns are not uniform within each income group, our analysis highlights the ecological harm poor countries bear to indirectly

enable the living standards of wealthier nations. Given current data availability and the difficulty of addressing interactions between drivers, our estimates are provisional but can be reevaluated as researchers continue to document ecosystem change and its drivers, value human impacts to ecosystem service flows, and extend techniques to transfer valuations made in different contexts (40).

Given that we parity-adjust valuations across income groups to account for different standards of living, as is commonly done, the distribution patterns we show here raise crucial questions regarding the division of responsibility for environmental harm. The actual distribution of future costs will depend primarily on how climate change is mitigated. By distorting world prices, subsidies are another important factor that shapes the distribution. Annually, global subsidies to energy and fisheries are currently \$200 billion (34) and \$17–50 billion (1), the upper bound of the latter being approximately equivalent to annual global fisheries revenue (1). At more than \$300 billion per year, support to agriculture within rich nations is comparably high (34). Our results suggest that acting in accordance with “truer” costs can affect the distribution of ecosystem damage at all levels: (i) at the local level, where emissions have global impacts, and where the changes in land use and land cover that drive ecosystem service losses are hidden from distant consumers; (ii) at the institutional level, in cost-benefit analyses of environmental regulations and the promotion of green accounting (40); and (iii) at the multilateral level, in negotiating and supporting international conventions to reduce ecosystem degradation. In particular, our analysis helps explain why efforts to curb GHG emissions equitably across countries from different income groups have been so thorny. Our work suggests how globalization and economic development, particularly that fueled by fossil fuels, may deepen the uneven distribution of ecological burdens. With pressure on ecosystem services expected to intensify in the next half-century (41), the framework and results described here may contribute to an emerging discussion of the distribution of ecological drivers and impacts, and the relationship of these issues with the responsibilities and debts between nations.

Methods

Valuation. We used the World Bank’s 2005 per capita income-based groupings of nations: *L* ($\leq \$875$), *M* ($\876 – $10,725$), and *H* ($\leq \$10,726$). For each topic, we estimate each group’s 2005 NPV costs of ecosystem degradation *D*:

$$D_a = \sum_{t=t_0}^{t_f} D_{at} f_t (1+r)^{2005-t},$$

where D_{at} is the impact experienced by the group *a* in year *t*, f_t is the fraction of the impact due to activity between 1961 and 2000, *r* is the discount rate, and t_0 and t_f are the start and end years, respectively, of the topic impact periods. For all topics except overfishing, we rely on published valuations based on willingness to pay for services or accept compensation for their loss, as determined using a range of accepted techniques (42). We adjusted all valuations using PPP measures,⁹ which permitted us to compare impacts across countries more accurately than would simple income measures.

Climate change and ozone layer depletion. We employed widely cited results from well known impact models for climate change (8, 29, 43–46) and ozone depletion (28) (Table 2). For NPV climate impacts over 2000–2100, we multiplied impact predictions given as percentages of GDP by projections of GDP PPP that we estimated (47) (SI Methods) from intermediate Intergovernmental Panel on Climate Change climate scenarios used in the source studies (Table 2). We then estimated the distribution of these PPP impacts among the groups using regional impact percentages provided for a particular year (43–45) or the whole period (8, 29, 46). For ozone depletion, we used a global model for estimates of a subset of human health impacts (28). We used income-based and geographically disaggregated data over the period to find the division of impacts among the groups. We estimated monetary costs by adapting United States valuations (48) and also estimated costs in DALYs using published disability-weighting factors.^k

To allocate impacts thus calculated, we used statistics from databases on GHG

revenue lost by subtracting fishing cost data (50). We took $f_t = 1$ for all years even though overfishing before 1961 may have contributed to stock declines.

Valuation Transfer and Aggregation. We transferred valuations for agriculture, deforestation, and mangrove loss between countries and over time, even though such “benefits transfer” are rarely done (51, 52). To translate both (i) a country-specific valuation to an income group and (ii) the resulting income-group valuation to other years in the time period, we used two simple ratios of per capita GDP PPP and an indicator of the intensity of ecosystem use over time (e.g., for forest services we use population per unit forest area) (*SI Methods*). The marginal costs we used for the year 2000 were (in U.S. 2005 \$·ha⁻¹·yr⁻¹) 12–68 for agriculture, 40–520 for deforestation, and 2,400–2,800 for mangrove loss.

We adjusted valuations further by using equity weighting (53) (*SI Table 4*), scaling each group *a*'s external costs D_a by a factor $(I_w/I_a)^{\epsilon}$, based on the average per capita GDP PPP for the world, I_w , and the income group, I_a , and ϵ , the elasticity of the marginal utility of income (53). We used $\epsilon = 1$ so that over 1961–2000, \$1 of marginal PPP-adjusted income for the *H* group translates into \$5.7 and \$14 for the *M* and *L* groups, respectively.

In addition to results for a discount rate of $r = 2\%$, we provide a sensitivity analysis to $r = 0$ –3% (*SI Table 3*).

Matrix Framework. We estimated C_{ab} as the share of externalities borne or predicted to be borne by group *b* that may be associated with activities by group

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a. We allocated the damages for each category based on a direct driver (emissions) or an indirect driver (consumption of related goods). For climate change, we calculated each group's share of GHG emissions (CO₂, CH₄, and N₂O) over 1961–2000 according to its share of cumulative emissions weighted by global warming potential (defined in ref. 54). For ozone depletion, we used CFC consumption data in units of mass ozone-depleting potential, assuming that all CFCs produced or consumed in a certain year are emitted into the atmosphere that year. For agriculture, deforestation, mangrove loss, and overfishing, we analyzed production and trade statistics¹⁹ of relevant classes of goods (Table 2).

SI Methods and *SI Discussion of Methods* contain additional details.

¹⁹United Nations Commodity Trade Statistics Database <http://unstats.un.org/unsd/comtrade>. Accessed September 5, 2006.

ACKNOWLEDGMENTS. For sharing data, models, and programs, we thank K. Vodden for the Environment Canada ozone depletion health impact model, D. Pauly for catch statistics from the Sea Around Us Project, R. Tol for output from the FUND 2.8 model, S. Dietz for regional output from the Stern Review's baseline climate scenario, and N. Höhne for programs on climate responsibility metrics. We also thank J. M. Heck and N. Srinivasan for invaluable insights throughout the project, and D. Svehla for edits.

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