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

U. Thara Srinivasan[a,b], Susan P. Carey[c], Eric Hallstein[d], Paul A. T. Higgins[d,e], Amber C. Kerr[d], Laura E. Koteen[d], Adam B. Smith[d], Reg Watson[f], John Harte[c,d], and Richard B. Norgaard[d]

[a]Pacific Ecoinformatics and Computational Ecology Laboratory, Berkeley, CA 94703; [d]Energy and Resources Group, 310 Barrows Hall, University of California, Berkeley, CA 94720-3050; [c]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720-3114; [e]American Meteorological Society, 1120 G Street NW, Washington, DC 20005-3826; and [f]Sea Around Us Project, Fisheries Centre, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

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

SUSTAINABILITY SCIENCE

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 degradation 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.[g]

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.

[b]To whom correspondence should be addressed. E-mail: utharas@gmail.com.

[g]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.

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

Category	Direct or indirect driver	b, driver of costs	Income group a, 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.[g] 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 dramatically 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.

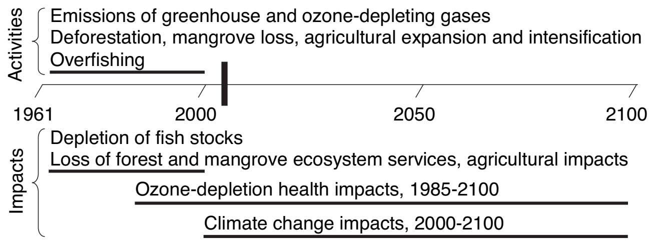

Fig 1. Time periods of ecologically damaging activities and impacts considered here. NPV sums D are taken at 2005.

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

[h]World Resources Institute, EarthTrends, http://earthtrends.wri.org. Accessed March 20, 2006.

[i]Fisheries Centre, University of British Columbia, Sea Around Us Project, www.seaaroundus.org. Accessed June 5, 2006.

[j]United Nations Food and Agriculture Organization, Statistical Databases, http://faostat.fao.org. Accessed March 20, 2006.

burden from all cancers and respiratory infections for the single year, 2002.[k]

Up to 53%, 22%, and 36%, respectively, of these PPP-adjusted costs borne by *LMH* groups are linked to activities by other groups. To avoid overlap between classes of damage, we count all climate impacts including those from deforestation and agricultural land use change in the climate change category. Although cross-category comparisons must be made carefully for this reason as well as uncertainties within each analysis, our results show that agricultural impacts may rival those from climate change over the next half-century (23). The results also underscore the importance of rare habitats. Although mangroves comprise only a small fraction of the world's coastline area, the loss since 1980 of 35% of mangrove area (24) may have caused a loss of ecosystem services (mainly storm protection) on par with the revenue of all aquaculture fisheries, 1980–2000.

We account for both positive and negative externalities of climate change but only for negative externalities for the other topics, even though positive externalities have also resulted. The doubling of agricultural production over 1965–2000 surely improved the health and well being of many (23), but we are unaware of comprehensive estimates of such aggregate external benefits (refs. 1, 25, and 26, but see ref. 27). Nevertheless, as an estimate of the true ecological costs incurred over 1961–2000, we judge ours to be conservative for several reasons:

(*i*) We do not account for degradation that occurred before 1961. For example, we use the 1961 level of forest area as a sustainable baseline, even though much forest conversion occurred previously (1).

(*ii*) We base each analysis on what we believe are conservative assumptions (*SI Methods*). While climate impact projections in the Stern Review (8) currently represent the high end of literature values (9), socially contingent impacts were not fully accounted for, and our understanding of potentially abrupt climate change is still developing (7).

(*iii*) We estimate externalities from all activities undertaken over 1961–2000 only. For climate change and ozone depletion into the next century, we present the portion of impacts attributable to emissions over this 40-year period, assuming intermediate emissions projections until 2100. Because of inertia in the atmospheric and global economic systems, however, we may have already committed to the bulk of the projected impacts (8, 28).

(*iv*) We do not count continued losses of ecosystem services into the future for the four categories of land and ocean use we consider, and our estimate of NPV climate impacts, up to 40% of the total external costs, extends to 2100 even though climate damages may increase beyond 2100 (8, 29).

(*v*) We leave out many critical drivers (e.g., excessive freshwater withdrawals, waterway modifications, introduction of invasive species, war, dispersal of persistent pollutants, and destruction of coral reefs) (1).

(*vi*) We exclude impacts to critical ecosystem functions including nutrient cycling, soil formation, and pollination. In addition, we do not count the substantial externalities incurred worldwide from acute and chronic pesticide poisoning, which result annually in three million cases of poisoning, 750,000 new cases of disease, and 20,000 deaths (30). The latter we estimate were unevenly divided by income group: 46%, 47%, and 7.1% (*LMH*).

(*vii*) Because valuing biodiversity presents a great challenge (1, 31, 32), economic valuations of biodiversity losses scarcely figure into our total estimates.

(*viii*) We exclude all non-use values of nature that might address its intrinsic worth or existence value (31).

More important than the particular values we derive is the framework we provide for allocating externalities by direct and indirect drivers (see *Methods* and *SI Methods*). This simple approach provides quantitative links between populations who experience ecological damage and those whose activities drive or contribute to the damages. Because the causal linkages between damages and drivers vary by category, entries in Table 1 should be interpreted within the context of each category. The impacts of climate change and ozone depletion are mediated by a globally well mixed atmosphere, and the emissions we analyze are direct drivers of these phenomena (1, 28). Thus, we allocate responsibility for the climate and ozone external costs according to emissions activity among the groups.

In contrast, the direct drivers of land use and land cover change are the local activities of agricultural expansion and intensification and deforestation themselves, often undertaken with consent or awareness of governments. Hence, the externalities we estimate for these topics were primarily caused by the nations that bore them. The situation for overfishing is less clear because exclusive economic zones (EEZs) were only given binding recognition midway into our time period (33). Still, for distributional insights into issues of land and ocean use, understanding the indirect drivers of environmental change is critical. Generally, many indirect drivers that interact over different temporal, spatial, and organizational scales are involved (34, 35). Given the lack of quantitative data on particular combinations and the incomparability of drivers (e.g., economic, sociopolitical, and cultural), we allocate external costs from agriculture, deforestation including mangrove loss, and overfishing on the basis of consumption patterns. Although this is a simplification, consumer demand for goods combined with producer access to markets is a key factor enabling environmental change (34–36). Globalization is a unifying theme underlying land cover and land use change (35, 36). Overfishing, too, has been spurred by the increase in demand from population and income growth and changing preferences, along with technological advances and price supports (33).

Informative patterns arise when impacts and drivers are analyzed in this manner. Over 1961–2000, the *LMH* groups each represented 32%, 50%, and 18% of the world population on average yet were responsible for 13%, 45%, and 42% of greenhouse gas (GHG) emissions weighted by global warming potential and may bear up to 29%, 45%, and 25% of the resulting climate damages. On a per capita basis, we estimate that high-income citizens were responsible for 5.7 times more GHG emissions than their low-income counterparts, but the low-income group is charged climate damages for more than two times its own emissions. If we exclude land use emissions and allocate responsibility by fossil CO_2 emissions only as in ref. 10 and elsewhere, industrialized nations would bear an even greater share of liability (11, 12). The use of ozone-depleting substances was distributed even more unequally. While the groups (*LMH*) were responsible for 1.6%, 28%, and 70% of chlorofluorocarbon emissions, the *L* and *M* groups may suffer up to 15% and 44%, respectively, of the ensuing health burden in terms of DALYs, a more meaningful metric for health impacts than dollars (SI Table 3).

In contrast, agricultural goods and wood products were largely consumed within the groups in which they were produced (94–98%). Hence, external costs from agricultural change and deforestation are concentrated along the diagonals in the Table 1 matrices, although the other entries remain significant given the scale of these enterprises. Consumption patterns for fishery

[k] World Health Organization, Original Global Burden of Disease (GBD) 2002 Estimates, www.who.int/healthinfo/bodgbd2002original/en/index.html. Accessed September 18, 2006.

SUSTAINABILITY SCIENCE

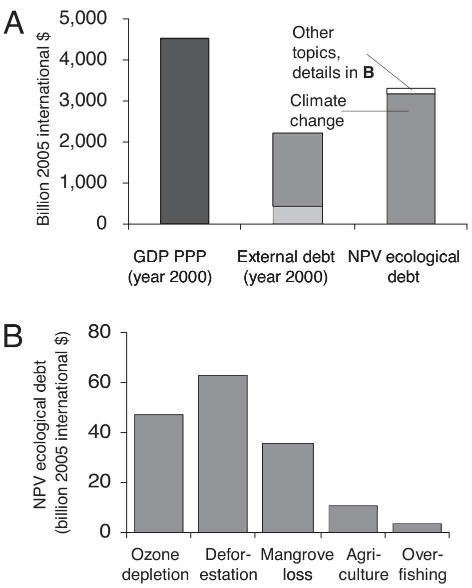

Fig. 2. Upper bound values of NPV net "ecological debt" to low-income nations from middle- and high-income nations in 2000, calculated as $C_{ML} + C_{HL} - C_{LM} - C_{LH}$ (PPP-adjusted, discount rate 2%). In *A*, year-2000 PPP-adjusted levels of both GDP and external debt for the low-income group 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 ≈85% of products fished in their waters, whereas *L* countries retained only ≈15%. Furthermore, fishing in the high seas was almost completely done by *M* and *H* countries, who captured ≈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 ≥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* (≤\$875), *M* (\$876–10,725), and *H* (≤\$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,[g] 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

Table 2. Environmental externalities considered and summary of all valuations applied here

	Externalities considered in this study	Sources of valuations applied here	Valuation methods
Climate change	Agriculture, forestry, water resources, and energy use impacts (with and without human adaptation); increased weather disturbances; loss of wetlands, drylands, and coastal protection; increased/decreased heat/cold stress; increased incidence of infectious diseases; human migration; disruption to unmanaged ecosystems; risk of climate catastrophes.	*LMH*: global impact assessment models by Pearce *et al.* (43), Nordhaus and Boyer (44), Mendelsohn *et al.* (45), Tol (46) [version described in Link and Tol (29)], and Stern *et al*. (8) used with IPCC scenarios IS92a, IS92e, and A2 (temperature rise in 2100: 1.2–3.9°C). Lower and upper bounds derived from Tol and Stern *et al.*, respectively.	*LMH*: mp, p, r; impacts as percentages of sector GDP; VSL and VLYL.
Agricultural intensification and expansion	Contamination of drinking water by pesticides, fertilizers, soil, and microorganisms; eutrophication; pollution incidents and fish mortality; soil fertility loss and erosion (water and wind); waterlogging, salinization; biodiversity loss, landscape damage.	*LM*: FAO South Asia study (55). *H*: U.S. and U.K. studies by Pretty *et al.* (25), with U.K. valuation updated in Pretty *et al.* (26) and U.S. valuation reassessed in Tegtmeier and Duffy (57). *H*: lower and upper bounds from valuation in ref. 57.	*LM*: p, r, re. H lower and upper: mp, p, t, r, pr, rec; VSL.
Stratospheric ozone depletion	Increased incidence of human skin cancers and cataracts.	*LMH*: Health impacts from Smith *et al.* (28). Costs from U.S. EPA (48); VSL, VLYL guidelines in Tol (46) and Eyre *et al.* (58). DALY guidelines and parameters in Mathers *et al.* (59, 60), Murray and Lopez, eds (62), and WHO (30).	*LMH*: COI, WTP; VSL, VLYL.
Deforestation	Loss of NTFPs; decreased flood prevention, water regulation, and protection of offshore fisheries; soil erosion; loss of recreation.	*L* lower: Cameroon study by Yaron (62); *M* lower: Malaysia study by Kumari (63); *LM* upper: Amazonian metavaluation by Torras (17); *H*: Nordic study cited in Turner *et al.* (31).	*L* lower: mp, p. *M* lower: mp, p, tr. *LM* upper: mp, tr, h, r, p. *H*: mp, p, t.
Overfishing	Fisheries catch foregone due to overexploitation of fish stocks.	*LMH* lower: our MSY estimates based on fish species' lifespan, age to maturity, and historical maximum catch. *LMH* upper: our estimates based on aforementioned factors as well as MSYs from NOAA.	*LMH*: mp to estimate foregone net revenue.
Mangrove loss	Loss of storm protection, timber, NTFPs, and nursery support for offshore fisheries; damages to rice farming from saltwater pollution.	*LMH*: Thailand study by Sathirathai (64).	*LMH*: mp, p, r, re.

We treat all climatic impacts under the climate change category, avoiding double-counting greenhouse gas emissions from agriculture and deforestation. Although freshwater and temperate salt marshes have also undergone significant degradation recently, we single out mangrove loss as an illustrative example because mangroves provide particularly valuable storm protection services, and mangrove conversion is linked to a globally traded commodity, farmed shrimp. Income groups: *L*, low; *M*, middle; *H*, high—where "*L* upper" refers to valuation applied for upper bound costs for low-income group. Cost methods: DALY, disability-adjusted life year; VSL, value of a statistical life; VLYL, value of life years lost; MSY, maximum sustainable yield; mp, market price; p, productivity; r, replacement; re, restoration; t, treatment; rec, lost recreation; tr, travel; pr, prevention; h, hedonic price; NTFPs, nontimber forest products; COI, cost-of-illness; WTP, willingness-to-pay. For ozone health impacts, we use VSL = 200 × per capita GDP-PPP, and VLYL = 10 × per capita GDP-PPP × [(life expectancy at birth) − (age of onset)].

emissions[l,m] (CO_2, CH_4, and N_2O) from all sectors including fossil fuel burning and land use change, and ozone-depleting chlorofluorocarbons (CFCs).[n] Because we sought to value the externalities of activities undertaken over 1961–2000 only, for climate change and ozone depletion, we estimated the portion of the NPV projected impacts attributable to emissions during this period alone. For climate impacts, we used a published model (12) to calculate the contribution to future radiative forcing under three Intergovernmental Panel on Climate Change scenarios[o] from world GHG emissions over 1961–2000. For ozone-layer depletion, we used a general exponential model (49) to estimate the contribution to CFC concentration over 1985–2100 from emissions over 1961–2000. For every year t in which we assess these topic impacts, we multiplied the impacts by f_t, the fraction of radiative forcing or concentration for that year and scenario attributable to 1961–2000 emissions.

[l]World Resources Institute, Climate Analysis Indicators Tool, Version 3.0, http://cait.wri.org. Accessed October 3, 2006.

[m]Netherlands Environmental Assessment Agency, EDGAR-HYDE 1.4, www.mnp.nl/edgar/model/100_year_emissions. Accessed December 1, 2006.

[n]UNEP Ozone Secretariat, Frequently Asked Questions, http://ozone.unep.org/Data_Reporting. Accessed November 2, 2006.

[o]UNEP/Grid-Arendal, Climate Change 2001: Working Group I: The Scientific Basis www.grida.no/climate/ipcc_tar/wg1/353.htm#933. Accessed November 13, 2006.

Agriculture, deforestation, and mangrove loss. Given sparse valuation data, we used valuations from the peer-reviewed literature and reports by the United Nations cited by the MA and other reviews (1, 6, 31). Where possible, we applied region-relevant valuations to each of the income groups (Table 2). The incremental, or marginal, values of lost ecosystem services we employed for these three topics are in units of U.S. $\$\cdot ha^{-1}\cdot yr^{-1}$ and must be multiplied by forest area converted or agricultural area under cultivation in a particular year to give a dollar value of impacts. We used land area datasets from the United Nations Food and Agriculture Organization[j] and other prominent studies (24). For deforestation and mangrove loss, we took 1961 levels of forest area as our baselines when estimating losses (or gains) in ecosystem services over the period. We assumed $f_t = 1$ for all years because we only consider impacts from activities within the period, 1961–2000.

Overfishing. We formulated approximate thresholds of sustainable fishing for species (SI Table 6) using catch data[i] and maximum sustainable yield levels that we estimated as well as those we adapted.[p] We applied market prices to determine the value of fishery products lost to overfishing, estimating the net

[p]Northeast Fisheries Science Center, U.S. National Oceanic and Atmospheric Administration, Status of Fishery Resources off the Northeastern United States, www.nefsc.noaa.gov/sos. Accessed July 23, 2006.

SUSTAINABILITY SCIENCE

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 $\$\cdot ha^{-1}\cdot yr^{-1}$) 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 $(I_w/I_a)^{\varepsilon}$, 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 $\varepsilon = 1$ 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 *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 (CO_2, CH_4, and N_2O) 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 statistics[j,q] of relevant classes of goods (Table 2).

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

[q]United 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.

1. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group* (Island, Washington, DC).
2. Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) *Science* 297:999–1002.
3. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, *et al.* (2005) *Science* 309:570–574.
4. Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, Jackson JBC, Lotze HK, Micheli F, Palumbi SR, *et al.* (2006) *Science* 314:787–790.
5. Dasgupta P, Levin S, Lubchenco J (2000) *BioScience* 50:339–345.
6. Balmford A, Bruner A, Cooper P, Costanza R, Farber S, Green RE, Jenkins M, Jefferiss P, Jessamy V, Madden J, *et al.* (2002) *Science* 297:950–953.
7. Hall DC, Behl RJ (2006) *Ecol Econ* 57:442–465.
8. Stern N, Peters S, Bakshi V, Bowen A, Cameron C, Catovsky S, Crane D, Cruickshank S, Dietz S, Edmonson N, *et al.* (2006) *Stern Review* (HM Treasury, London).
9. Weitzman ML (2007) *J Econ Lit* 45:703–724.
10. Smith KR (1996) in *Climate Change: Developing Southern Hemisphere Perspectives*, eds Giambelluca T, Henderson-Sellers (Wiley, London), pp 423–448.
11. Baer P (2006) in *Fairness in Adaptation to Climate Change*, eds Adger WN, Paavola J, Huq S, Mace MJ (MIT Press, Cambridge, MA), pp 134–153.
12. Höhne N, Blok K (2005) *Clim Change* 71:141–173.
13. Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D (1999) *Science* 284:278–282.
14. Smith KR (1992) *Ambio* 20:95–96.
15. Baer P, Harte J, Haya B, Herzog AV, Holdren J, Hultman NE, Kammen DM, Norgaard RB, Raymond L (1999) *Science* 284:2287.
16. Martinez-Alier J (2002) *The Environmentalism of the Poor* (Elgar, Northhampton, MA).
17. Torras M (2003) *World Dev* 31:2161–2171.
18. Daly HE, Farley J (2004) *Ecological Economics* (Island, Washington, DC).
19. Jacobs M (1994) in *Social Theory and the Global Environment*, eds Redclift M, Benton T (Routledge, London), pp 69–91.
20. Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, *et al.* (1997) *Nature* 387:253–260.
21. DeCanio SJ (2003) *Economic Models of Climate Change: A Critique* (Palgrave Macmillan, New York).
22. Food and Agriculture Organization of the United Nations (2005) *Global Forest Resources Assessment 2005* (FAO, Rome), FAO Forestry Paper 147.
23. Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D (2001) *Science* 292:281–284.
24. Valiela I, Bowen JL, York JK (2001) *BioScience* 51:807–815.
25. Pretty JN, Brett C, Gee D, Hine R, Mason C, Morison J, Rayment M, van der Bijl G, Dobbs T (2001) *J Environ Plann Manage* 44:263–283.
26. Pretty JN, Lang T, Ball A, Morison J (2005) *Food Policy* 30:1–20.
27. Pretty JN, Noble AD, Bossio D, Dixon J, Hine RE, Penning de Vries FWT, Morison JIL (2006) *Environ Sci Technol* 40:1114–1119.
28. Smith D, Vodden K, Rucker L, Cunningham R (1997) *Global Benefits and Costs of the Montreal Protocol on Substances That Deplete the Ozone Layer* (Environment Canada, Ottawa).
29. Link PM, Tol RSJ (2004) *Port Econ J* 3:99–114.
30. World Health Organization (1990) *Public Health Impacts of Pesticides Used in Agriculture, 1990* (WHO, Geneva).
31. Turner RK, Cooper P, Farber S, Jessamy V, Georgiou S (2003) *Ecol Econ* 46:493–510.
32. Daily GC, Söderqvist T, Aniyar S, Arrow K, Dasgupta P, Ehrlich PR, Folke C, Jansson AM, Jansson B-O, Kautsky N, *et al.* (2000) *Science* 289:395–396.
33. Pauly D, Christensen V, Guénette S, Pitcher T, Sumaila UR, Walters C, Watson R, Zeller D (2002) *Nature* 418:689–695.
34. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Scenarios: Findings of the Scenarios Working Group* (Island, Washington, DC).
35. Geist HJ, Lambin EF (2002) *BioScience* 52:143–150.
36. Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, *et al.* (2001) *Global Environ Change* 11:261–269.
37. Wackernagel M, Schulz NB, Deumling D, Callejas Linares A, Jenkins M, Kapos V, Monfreda C, Loh J, Myers N, Norgaard R, Randers J (2002) *Proc Natl Acad Sci USA* 99:9266–9271.
38. Arrow K, Dasgupta P, Goulder L, Daily G, Ehrlich P, Heal G, Levin S, Mäler K-G, Schneider S, Starrett D, *et al.* (2004) *J Econ Perspect* 18:147–172.
39. Ehrlich PR, Holdren JP (1971) *Science* 171:1212–1217.
40. McComb G, Lantz V, Nash K, Rittmastera R (2006) *Ecol Econ* 60:461–472.
41. Alcamo J, van Vuuren D, Ringler C, Cramer W, Masui T, Alder J, Schulze K (2005) *Ecol Soc* 10:19.
42. Farber S, Costanza R, Childers DL, Erickson J, Gross K, Grove M, Hopkinson CS, Kahn J, Pincetl S, Troy A, *et al.* (2006) *BioScience* 56:121–133.
43. Pearce DW, Cline WR, Achanta A, Fankhauser S, Pachauri R, Tol R, Vellinga P (1996) in *Climate Change 1995: Economic and Social Dimensions Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, eds Bruce JP, Lee H, Haites EF (Cambridge Univ Press, Cambridge, UK), pp 183–224.
44. Nordhaus WD, Boyer JG (2000) *Warming the World: Economic Models of Global Warming* (MIT Press, Boston).
45. Mendelsohn R, Dinar A, Williams L (2006) *Environ Dev Econ* 11:159–178.
46. Tol RSJ (2002) *Environ Res Econ* 21:47–73.
47. Tol RSJ (2006) *Clim Change* 75:59–80.
48. U.S. Environmental Protection Agency (1992) *Regulatory Impact Analysis: Compliance with Section 604 of the Clean Air Act for the Phaseout of Ozone Depleting Chemicals* (U.S. Environmental Protection Agency, Washington, DC).
49. Rubin ES (2001) *Introduction to Engineering and the Environment* (McGraw–Hill, New York).
50. Tietze U, Prado J, Le Ry J-M, Lasch R (2001) *Techno-economic Performance of Marine Capture Fisheries* (FAO, Geneva), FAO Fisheries Technical Paper T421.
51. Wilson MA, Hoehn JP (2006) *Ecol Econ* 60:335–342.
52. Smith VK, Pattanayak SK (2002) *Environ Res Econ* 22:271–296.
53. Pearce D (2003) *Oxford Rev Econ Pol* 19:362–384.
54. Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: The Scientific Basis* (Cambridge Univ Press, Cambridge, UK).
55. Food and Agriculture Organization (1994) *Land Degradation in South Asia: Its Severity, Causes and Effects upon the People* (FAO, UNDP, and UNEP, Rome), World Soil Resources Reports.
56. Pretty JN, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD, van der Bijl G (2000) *Agric Syst* 65:113–136.
57. Tegtmeier EM, Duffy MD (2004) *Int J Agric Sustainabil* 2:155–175.
58. Eyre N, Downing T, Hoekstra R, Rennings K, Tol RSJ (1997) *Global Warming Damages* (ExternE : Externalities of Energy Project, European Commission, Brussels).
59. Mathers CD, Vos T, Lopez A, Salomon J, Ezzati M (2001) *National Burden of Disease Studies: A Practical Guide* (WHO, Geneva), Edition 2.0.
60. Mathers CD, Lopez AD, Stein C, Ma Fat D, Rao C, Inoue M, Shibuya K, Tomijima N, Bernard C, Xu H (2003) *Deaths and Disease Burden by Cause: Global Burden of Disease Estimates for 2001 by World Bank Country Groups* (WHO, Geneva), Working Paper 18.
61. Murray CJL, Lopez AD, eds (1994) *Global Comparative Assessments in the Health Sector. Disease Burden, Expenditures and Intervention Packages* (WHO, Geneva).
62. Yaron G (2001) *J Environ Plan Manage* 44:85–108.
63. Kumari K (1996) *Ambio* 25:459–467.
64. Sathirathai S (1998) *Economic Valuation of Mangroves and the Roles of Local Communities in the Conservation of Natural Resources: Case Study of Surat Thani, South of Thailand* (Economy and Environment Program for Southeast Asia, Singapore).