Supporting Information

Srinivasan *et al.* "The Debt of Nations and the Distribution of Ecological Impacts from Human Activities"

I. Methods

Here we provide further details on our estimation of the 2005 net present values (NPV) of ecosystem degradation as linked to activities among income-based groups of countries. To avoid double-counting, we only consider the local external costs of deforestation and agriculture, leaving the climate impacts of the land-use emissions of greenhouse gases to the climate analysis. Where possible, we apply region-relevant valuations to each of the three income groups.

Adapting valuations made in one locale for a specific population to other countries is risky since the characteristics of the study and transfer sites and populations nearly always differ. For this reason, benefits transfer across national borders is rarely done. Climate change models have adjusted valuations by income (1, 2), although equity-conscious critics argue that this produces vastly different values for ecosystem services as well as human mortality and morbidity around the world. On the other hand, while it is appealing to ascribe a common global value to an ecosystem service flow and human life, there are many who reject this approach as it can result in valuations that exceed available income (1, 3). Equity weighting, which takes into account the different value of marginal income for people with different incomes, has been offered as a possible remedy (1, 2). Values of ε, the elasticity of the marginal utility of income, that range from 0.5-1.2 have been proposed (2), with $\varepsilon = 1$ used in (4). Here we use $\varepsilon = 1$.

For income-group classification of countries, we use the categories designated by the World Bank based on countries' 2005 GNI per capita (World Development Indicators WDI database), and we categorize the former Soviet Union and Yugoslavia based on the 2005 population-weighted income grouping of the countries formed from these countries. We adjust costs to 2005 US$ using the U.S. Consumer Price Index (U.S. Department of Labor Bureau of Labor Statistics, Consumer Price Indexes) unless otherwise noted. We further adjust costs to 2005 international $ using purchasing power parity (PPP) rates from the WDI Database.

A. Overfishing

Estimation of External Costs

We estimate the NPV of one type of external cost to fisheries from unsustainable fishing over 1961-2000, the foregone catch, using data from the Sea Around Us Project (SAUP, http://www.seaaroundus.org) and the Northeast Fisheries Science Center (NEFSC) of the U.S. National Oceanic and Atmospheric Administration (NOAA) (http://www.nefsc.noaa.gov/sos/). We consider species only if both catch and price data are available from SAUP. Normalizing each species' catch data over 1961-2000 with maximum catch = 1, we label the fish stock as potentially overexploited if the normalized catch fell to ≤ 0.30 for either an uninterrupted succession of at least 10 yr or 15 yr in total subsequent to the year in which maximum catch occurred. Investigating all 64 large marine ecosystems (LMEs) and 18 Food and Agriculture Organization (FAO) designated areas, we identify 77 species with sufficient data that fit the above pattern of decline.

We estimate the long-term sustainable catch, or maximum sustainable yield (MSY), for these species in each LME or FAO area by devising simple, conservative guidelines based on the species' lifespans t_{max} (from refs. 5, 6 and the following databases: FishBase, http://www.fishbase.net/; the FAO Fisheries Global Information System (FIGIS), http://www.fao.org/figis/servlet/static?dom=root&xml=index.xml; and ARKive's Images of Life on Earth, http://www.arkive.org/species/ARK/) and the maximum catch over the period C_{max} (SAUP), and selected MSY and catch estimates from the NEFSC. Reported catch is by necessity lower than the biomass of a stock upon which most detailed stock assessments are based. For a lower bound estimate, we take the following approach. Assuming that the maximum catch of a stock is directly proportional to its spawning biomass and that 10-30% of spawning biomass should be preserved for stock sustainability (7-9), we conjecture up to 30% of C_{max} may be fished sustainably for species with high breeding capacity and young breeding age (SI Table 5). We use a species' t_{max} as a measure of its stocks' intrinsic production rate and replacement ability, revising MSY designations using age to maturity t_m where appropriate. For species with long lifespans and late maturation ($t > 30$), we assume no level of catch may be maintained sustainably (10).

For an upper estimate of the foregone catch, we compile NEFSC's estimates of MSY and C_{max} for the 10 species covered by NEFSC also on our list. For each of these species, we calculate from NEFSC data the MSY level as a percentage of C_{max}, taking averages where data for multiple stocks were available. We multiply these values by C_{max} from SAUP data for stocks of the same species to estimate MSY. For the remaining species, we double our lower bound percentages (SI Table 5) on the basis of the linear regression slope between the NEFSC MSY percentages (y) and our original MSY-from-lifespan percentages (x) ($y = 2.25x + 0.30$, $R^2 = 0.66$, $P < 0.05$). SI Table 6 lists the lower and upper bound MSY percentages that we use.

For each species i in SI Table 6 and for years t in which the species' normalized catch fell below our assumed long-term sustainable catch level MSY, the 2005 NPV of its foregone catch D_{it} over all LME and FAO areas is estimated as:

$$D_{it} = \sum_{t = t_{Y_{it} < MSY}} (MSY - Y_{it})(p_i)(1+r)^{2005-t} \quad \text{(SA.1)}$$

where Y_{it} is the actual catch or yield recorded for the species in the relevant year, p_i is the average real price per metric ton for the species' foregone catch, and r is the discount rate. SI Fig. 1 provides a graphical example of the foregone catch calculation in one LME for *Gadus morhua*, Atlantic cod. To account for effects on price of scarcity and the availability of substitutes, p_i in each area is taken as the average of the species' actual price per ton (SAUP) for all years 1961-2000 when the catch was within 10% of our designated MSY. For ten species fished in Antarctic waters, we do not count foregone catch since 1990, as fishing pressure on Antarctic stocks is known to have declined dramatically following the disassociation of the former Soviet Union (11).

Assignment of External Costs

For the species for which we calculate D_{it}, we analyze spatially disaggregated fishing statistics over 1961-2000 (SAUP) to determine the likely fishers of the foregone catch among the three income groups of nations (low L, middle M, and high H) and also the likely bearers, those who might have benefited from the lost catch, among these groups. We assume that the portion of each species' foregone catch caused by an income group's fishing is the share of the species' actual catch taken by the group's nations over the time period. Likewise, the portion of each species' foregone catch borne by an income group is set as the share of the species' actual catch taken in its countries' waters. (A country's waters refer to its exclusive economic zone (EEZ), or before the adoption of EEZs, its territorial waters.) For each species i, we multiply coefficients $f_{ab,i}$ representing the fraction of that species' catch taken by each of the income groups, a, in each of the groups' waters, b, by the total foregone catch of the species. Summing over all species, we calculate F_{ab}, the share of the foregone catch fished by group a and borne by group b:

(SA.2) $$F_{ab} = \sum_i f_{ab,i} D_{i,1961-2000} \,.$$

We divide the foregone catch fished from the high seas equally among all people of the world according to each income group's share of world population over 1975-2000, in which ~90% of the foregone catch would have occurred.

To distribute the foregone catch as an external cost to consumption among the income groups, we modify the F_{ab} matrix using export statistics for fish and fisheries products (FAO Statistical Databases (FAOSTAT), http://faostat.org/; UN Commodity Trade Statistics Database (Comtrade), http://unstats.un.org/unsd/comtrade/). We define C_{ab} as the share of the foregone catch borne by income group *b* that may be linked to consumption by income group *a*. Using FAO statistics over 1975-2000 we calculate a weighted mass fraction of each group's total fishery output Pr_a that was exported to other income groups, E_a/Pr_a. Next, we analyze UN bilateral export data from the Comtrade database over 1990-2000 to estimate the monetary value fractions of each group's exports that were exported to all other groups, $E_{a\to b}/E_a$. We use these export statistics in the formulas listed in SI Table 7 to generate C_{ab} entries. As shown below, $e_{a\to b}$ represents the fraction of production by group *a* exported to group *b*, and $e_{a\to a}$ accounts for goods that were not exported as well as those that were traded within an income group:

(SA.3) a) $$e_{a\to b} = \frac{E_a}{Pr_a}\frac{E_{a\to b}}{E_a}$$ b) $$e_{a\to a} = 1 - \left(\frac{E_a}{Pr_a}\right) + \left(\frac{E_a}{Pr_a}\right)\left(\frac{E_{a\to a}}{E_a}\right).$$

To subtract the operating costs and thus estimate the net revenue lost from the foregone catch, we refer to data in a cost survey of 108 types of fishing vessels in 15 countries (12). The ratios of net profits to total earnings (NP/TE) for profitable vessels ranged from 0.1-76%. Counting ratios for each vessel equally, we derive a mean NP/TE of 16% (SE 1.7%), which we apply to C_{ab} values to give approximate net values.

B. Deforestation

Estimation of External Costs

We calculate the NPV of selected local external costs from deforestation using an area-based approach and estimates of the marginal costs of forest ecosystem service losses reviewed in refs. (15-17) (see main article, Table 2). For a given income group *a*, the costs are as follows:

(SB.1) $$D_a = \sum_{t=1961}^{2000} (MC_{at})(A_{at})(1+r)^{2005-t}$$

with MC_{at} the annual marginal cost of deforestation per unit area adjusted for income group *a* in the year *t*, A_{at} the cumulative land area deforested at the end of year *t* with respect to 1961 levels within the income group's nations, and *r* the discount rate. We combine two datasets to create a profile on land area deforested over the time period 1961-2000: the FAO Statistics (FAOSTAT, http://faostat.fao.org/) Land Use database, and the World Resources Institute (WRI) EarthTrends database (http://earthtrends.wri.org/).

We adapt two marginal cost estimates (13, 14) identified in (15, 16) as methodologically rigorous as well as an estimate assembled from several sources in (17). We extract and use the local services accounted for in the original studies, excluding carbon sequestration to avoid overlap with the climate change analysis. Since forest ecosystems can yield significant flows of goods and services after conversion to other states (15, 16), we sought estimates of services lost upon conversion rather than flows from virgin forest. To convert Torras' estimate of the services from intact forests (17), we multiply his valuation by 72% which we estimate from (15, 16) (SE 10%) as the percentage of local external services lost from tropical forests upon conversion.

In order to apply the marginal costs to the income groups, we adjust the country-specific values in the study year t^* using ratios for that year of GDP PPP per capita (I) and population per unit area forest (P) for the country c and for the income group as a whole:

(SB.2) $$MC_{at^*} = MC_{ct^*}\left(I_{at^*}/I_{ct^*}\right)\left(P_{at^*}/P_{ct^*}\right).$$

We include the population adjustment to account for people's differing levels of interaction with forests between the study country and the overall income group and thus different potentials for damage due to loss of forests and forest services (17). Over time, we adjust the values using ratios of population-weighted average GDP PPP per capita and average population density for the year t and the study year t^*:

(SB.3) $$MC_{at} = MC_{at^*}\left(I_{at}/I_{at^*}\right)\left(P_{at}/P_{at^*}\right).$$

Here, we intend the population adjustment to account for the increasing levels of human interaction with forests and hence, the increasing potential for damages from loss of forest services over 1961-2000. As we include local external costs only in all marginal costs, we assume that the damages we calculate for an income group were borne fully by that income group's nations.

Assignment of External Costs

The most significant direct drivers of forest loss are agricultural expansion and commercial wood extraction (18, 19). As these and other indirect drivers generally work in tandem and are difficult to quantify and compare, we allocate costs according to an important indirect driver: consumption of both agricultural products and wood and wood-related products, equally weighted. (The drivers of deforestation and afforestation are wholly different, so we do not assign the external benefits from afforestation according to consumption.) For each income group a, total production Pr_a and exports E_a in metric tons of agricultural products are tabulated from the FAOSTAT Agricultural Data set. We exclude certain goods to avoid double-counting with comparable items and use monetary estimates of each group's exports to other groups ($E_{a\rightarrow b}/E_a$) over 1980-2001 from (20). For wood and wood-related products, the FAOSTAT Forestry Data database is used for Pr_a and E_a, and we estimate $E_{a\rightarrow b}/E_a$ from bilateral export data over 1965-1995 in the UN Comtrade database. Then we use the formulas in SI Table 8 to calculate C_{ab} terms. By using averages of the terms multiplying D_a, we allocate the costs by consumption of agricultural and wood products equally-weighted (SI Table 11 contains results for the distribution of damages according to either agricultural or wood products alone).

C. Mangrove Loss

Estimation of External Costs

To estimate the NPV of selected local external costs from mangrove loss, we take a similar approach as described for deforestation (**B**). Here, A_{at} in Eq. SB.1 represents the mangrove area lost in year t for countries of group a, which we estimate over 1980-2000 (for reasons of data availability) from (21, 22) with priority given to values from (22) where available. To obtain yearly rates of mangrove loss, we assume a constant rate of mangrove loss over the different time periods covered in the data.

We apply a local marginal cost of conversion of intact mangrove to shrimp farming (23), cited by (15, 16) (main article Table 2). We adjust the country-specific marginal costs as in Eq. SB.2 using ratios for the study country and the income groups, where P here is the coastal population density. We assume each country's P as proportional to its coastal population (within 100 km of the coast and available for 1995 (WRI EarthTrends database, World Bank WDI database) divided by its coastline length, and for the income groups we weight averages by mangrove area. The population adjustment is intended to account for peoples' different levels of involvement with coastal mangrove services and therefore different potentials for damage from mangrove destruction. Due to lack of data availability over time, coastal population density is not used in the temporal transfer (Eq. SB.3) but rather P is taken as the income group's total population per unit mangrove area. We assume that all losses were incurred for the year in which the mangrove area was converted and, on account of slow regeneration (24), all subsequent years in the time period, 1980-2000.

Assignment of External Costs

To estimate the losses in local mangrove services due to shrimp culture alone, we apply Valiela's estimate that shrimp culture has led to ~38% of all mangrove conversion worldwide (22). We then estimate C_{ab} as described in **B**. To obtain the e terms from data from UN Comtrade and FAO FIGIS databases and ref. (25), we assume trade and consumption patterns for farmed shrimp are similar to those for shrimp in general.

D. Agricultural Intensification and Expansion

Estimation of External Costs

To analyze local external costs associated with agriculture, we use the approach taken for deforestation (**B**). Here A_{at} in Eq. SB.1 represents the area under agricultural cultivation in year t for all countries in income group a. We use data from FAOSTAT on agricultural land area, which includes arable land, permanent crops and permanent pasture. We adapt marginal cost estimates for the local external costs of agriculture as reported in the multi-country studies refs. (26-30) (main article Table 2). To keep the external costs local, we modified estimates in (26-29) to exclude climate change impacts from greenhouse gas emissions in order to avoid double-counting with the climate analysis, and we also excluded damages from bovine spongiform encephalopathy (BSE), a country-specific impact. To adapt valuations made for study countries to apply to income groups, we use the following:

(SD.1) $$MC_{at^*} = MC_{ct^*}\left(I_{at^*}/I_{ct^*}\right)\left(F_{at^*}/F_{ct^*}\right)$$

where I_{ct^*} is a population-weighted average GDP PPP per capita for the study countries, I_{at^*} is the average value for the income group as a whole, and F is fertilizer input per unit agricultural area calculated from data in FAOSTAT. We use F as a proxy for the level of intensity and thus the level of damages due to varying agricultural practices within the income group.

For benefits transfer in time, we adjust all marginal cost estimates using ratios for the income group for the year t and the year of the reference study t^* of: 1) population-weighted average GDP PPP per capita (I) and 2) average fertilizer use per unit agricultural area (F):

(SD.2) $$MC_{at} = MC_{at^*}\left(I_{at}/I_{at^*}\right)\left(F_{at}/F_{at^*}\right)$$

again using fertilizer input per unit agricultural area to represent the level of intensification and the increasing damages due to agricultural practices over 1961-2000. For each income group we compile averages of fertilizer use (nitrogenous, phosphate and potash fertilizer) over 1961-2000 from FAOSTAT.

Assignment of External Costs

We assign the local damages to ecosystem services as external costs to the consumption of agricultural products among the income groups using the approach already described in **B**.

E. Climate Change

Estimation of External Costs

To estimate the NPV of the projected external costs of climate change from greenhouse gases (GHG) emitted over 1961-2000, we draw from five well-known studies (Pearce *et al.* (31), Nordhaus and Boyer (32), Mendelsohn *et al.* (33), Stern *et al.* (34), Tol (35, 36)) that encompass a significant portion of the variation in the literature. The studies used integrated assessment models that link climate change and economic scenarios to predict impacts by geographical region as a percentage of that region's GDP. Three of the studies (31-33) presented estimates for a single future year given a particular increase in atmospheric carbon dioxide (CO_2) concentration or temperature; the *Stern Review* (34) provided estimates over 2050-2200 for two climate scenarios; and the model by Tol (35, 36) estimated damages over 1950-2200 for one scenario. (SI Table 9 contains world climate impact percentages we adapted.) We describe below how we apply the different projection data from the five studies to calculate NPV climate impacts over 2000-2100:

1) Pearce (31), Nordhaus and Boyer (32), and Mendelsohn *et al.* (33). We convert the future-year estimates from refs. (31-33) into annual external costs using as a benchmark the IPCC IS92a scenario, an optimistic intermediate scenario for global CO_2 emissions, population growth and economic development that has been used widely as a reference emissions path in impact studies (37, 38). To apply estimates of world damages as percentages k of world GDP for a future year t^*, we set t^* appropriately based on temperature rise (2.5˚C for refs. (31, 32)) or CO_2 concentration (ref. (33)) according to IS92a projections (39, 40). For the year of 2.5˚C increase, we assign average damages of 1.75% of world GDP as estimated by Pearce *et al.* and 1.5% world GDP as estimated by Nordhaus and Boyer; for 2100, we assign 0.065% GDP world benefits ("PCM" model) and 0.025% GDP world damages from Mendelsohn *et al.* (SI Table 9). We use actual GDP PPP for years 2000-2005 (World Bank WDI Database) and make projections for 2006-2100 based on the annual GDP growth rate projected by the IS92a scenario. We use a relationship derived from 1995 data in (41) to convert IS92a's projections of market exchange rate (MER) income to PPP-adjusted income ($y = -0.2805x + 2.8154$, where y = ln(per capita income, PPP/MER) and x = ln(per capita income, MER)).

Next, to estimate the NPV of global annual damages D in year t from these three studies, we employ an equation from (42) used also in (43), which we split into two equations:

(SE.1) a) $D_t = k_t Y_t f_t (1+r)^{2005-t}$ b) $k_t = k_{t^*} (T_t / T_{t^*})^{\gamma} (1+\varphi)^{t^*-t}$

with additional terms in Eq. SE.1a for discounting (discount rate r) and to account for impacts from 1961-2000 emissions only. In the above equations, Y_t represents the world GDP PPP in year t, T_t and T_{t^*} are the increases in temperature (˚C) forecasted by the IS92a scenario for years t and t^*, γ relates temperature rise to damage, and φ is a parameter that links the level of damage to the speed of change. We use $\gamma = 1.3$ and $\varphi = 0.006$ from (42). The portion of the NPV global impacts in year t that may be attributed to GHG emissions over 1961-2000 only is represented by f_t. Here we use a model described in (45) (ECOFYS, available at http://unfccc/int/resource/brazil/results2.html) and global data on the emissions of three main GHG gases (CO_2, CH_4, and N_2O) from all sectors including fossil fuel burning and land-use change (ref. (46) and WRI's Climate Analysis Indicators Tool (CAIT), http://cait.wri.org) to estimate the future radiative forcing due to emissions over

1961-2000 only, and also for emissions predicted by the IS92a scenario. Then, for every future year in which we assess world climate impacts, we multiply the impacts by f_t, the proportion of radiative forcing predicted for that year and scenario that could be attributed to 1961-2000 emissions.

We translate the resulting global impacts D_t to fit our income group framework by applying the regional or income-based impact percentages given in the reference studies. To do so, we apply the regional or income-based impact percentages to year 2000 country GDP PPP values, reconstitute the three income groups to estimate the distribution of global impacts, and finally adjust this distribution based on our estimate of the changed shares of GDP PPP among the groups in the mid-period year 2050 according to the regional IS92a projections.

2) Stern *et al.* (34). We take a similar approach to apply the range of world impact percentages over 2050-2100 given in the *Stern Review* (34). We use the lower (5th percentile) and upper (95th percentile) predictions of market, non-market and catastrophic impacts k_t from the "high-climate" scenario so that our analysis covers the range of literature predictions (0.73-7.8% world GDP in 2100; SI Table 9). To extrapolate the global impact percentage k_{2050} over 2000-2049, we use Eq. SE.1b and the IPCC SRES A2 temperature profile (http://www.grida.no/climate/ipcc/emission/090.htm) used as the "baseline" path by Stern *et al.* (Although the A2 scenario predicts more warming than IS92a (A2: ~4°C rise for 2100, IS92a: ~2.9°C), A2 is also considered an intermediate path.) Then, using Eq. SE.1a we calculate the NPV global impacts over 2000-2100, with world GDP PPP (Y_t) and f_t estimated as described in 1), now using the A2 scenario.

Next, we divide these global impacts among the three income groups using disaggregated regional output obtained from Stern *et al.* This data contains projections of market, non-market, and catastrophic impacts as a percentage of regional GDP for the 8 regions in Stern *et al.*'s baseline (A2) climate scenario. The mean global impact predictions from this scenario are similar to those from the high-climate scenario, and the regional distribution of impacts is expected to be similar between the two scenarios as well. With this data, we estimate how NPV world GDP impacts may be divided among the income groups for years over 2000-2100. However, since our NPV global estimates described in the previous paragraph are PPP-adjusted, we must scale these GDP impact shares according to the future GDP PPP distributions among the income groups for these years. We estimate the latter from A2 regional GDP projections, with parity adjustment as described above in 1) (41). Finally, we multiply the yearly GDP PPP impact shares to the world impacts (Eq. SE.1a) to determine the high-, middle-, and low-income PPP impacts.

For the sake of comparison, we also perform the above calculations with an end date of 2150.

3) Tol (35, 36). Tol's model predicts climate benefits of 0.75% world GDP in 2000, and damages of 0.58% world GDP in 2100 (SI Table 9). The model provides annual market and non-market impacts for 16 regions. To convert Tol's results for our income group framework, we separate each of the regions into countries c and reaggregate the impacts into the three income groups. For each income group a, we calculate the NPV impacts as follows:

$$D_{at} = \sum_{c} k_{ct} f_t Y_{ct} (1+r)^{2005-t} \quad \text{(SE.2)}$$

For year t, k_{ct} is the impact percentage of GDP predicted for country's source region, Y_{ct} is the country's GDP PPP that we estimate as described above using actual data over 1961-2005 and projections made using the source region's IS92e GDP growth rates from Tol's model and ref. (41), and f_t is the fraction of IS92e global impacts attributable to 1961-2000 emissions only. (For comparison, the IS92e scenario gives a similar warming path as the A2 scenario.) Again, we also calculate the impacts with an end date of 2150.

Assignment of External Costs

We allocate the climate impacts based on each income group's share of GHG emissions over 1961-2000 using cumulative emissions weighted by global warming potential (GWP) (38), an approach that counts all emissions in the period equally regardless of the year in which they were emitted.

F. Stratospheric Ozone Layer Depletion

Estimation of External Costs

To estimate the NPV over 1985-2100 of a subset of human health impacts due to stratospheric ozone layer depletion, we use a global model commissioned by Environment Canada (EC) (47). Based on a model by the U.S. Environmental Protection Agency (EPA) (48), the EC model considers four adverse health effects: melanoma skin cancer, two types of non-melanoma skin cancer, and cataracts. The model takes into account changes to surface UV-B based on actual emissions of the halogen source gases before 1993 and predicted emissions as mandated by the Montreal Protocol and amendments up to 1995 (47).

As an age-structured population model, the EC model covers the time span of 1985-2100 and divides the globe into 11 latitude bands. The population within each band is subdivided into developed and developing categories, where the latter refers to countries for which delayed phase-out schedules were set in Article 5(1) of the Montreal Protocol (Ozone Secretariat ODS Report Centre, http://ozone.unep.org/Data_Access/). Relevant characteristics of the population are included, such as skin color and gender percentage. Cumulative dose-response functions are used to calculate the increased incidence of skin cancers and cataracts from higher UV-B exposure, and mortalities from skin cancers are calculated from incidence rates using fixed percentage values. 20% of cataracts are assumed to be UV-B induced (47).

From the EC model source data, we extract the health effects scenario attributable to ozone layer depletion given implementation of the Montreal Protocol. We calculate skin cancer mortalities using the lower bounds of the ranges in (47): 0.1% for non-melanoma and 10% for melanoma cases, with the latter supported by recent U.S. data (1995-2001) on the relative survival rates 5 and 10 yr after melanoma diagnosis of 92% and 89% (49). We assume a period of 5 yr between skin cancer diagnosis and mortality (49). For cataract incidence, we calculate lower and upper bounds using the combinations of dose-response coefficients used for bounds in (49). We separate model results into 22 categories (developed and developing populations in 11 latitude bands) and aggregate into the three income groups using the Article 5(1) list of countries (ODS Report Centre database) and each country's approximate geographic center (The World Factbook database, http://www.cia.gov/cia/publications/factbook/index.html).

As in the climate analysis (**E**), we aim to value the costs of emissions undertaken over 1961-2000 only. We focus on chlorofluorocarbons (CFCs), which accounted for ~83% of the world's consumption of ozone-depleting substances (ODS) weighted by ozone-depleting potential (ODP) in 1986 (ODS Report Centre database). Since the EC model considers health impacts from chlorofluorocarbon (CFC) emissions ending in ~2011, we use an exponential model (Eqs. SF.1-2) (50) to estimate CFC concentration profiles between 1985-2100 due to emissions over 1961-2000 and 1961-2011 separately:

(SF.1) $$c(t) = c_{SS}\left(1 - e^{-t/\tau}\right) + c_0 e^{-t/\tau}$$

where c_{SS} and c_0 are the steady state and initial concentrations, respectively:

(SF.2) a) $c_{SS} = \left(P\tau N_a / M_i N_m\right)$ b) $c_0 = \left(m_0 N_a / M_i N_m\right)$.

Here, τ is the atmospheric lifetime, P the CFC emissions rate, N_a is Avogadro's number, M_i the molecular weight of the CFC, and N_m the number of air molecules in the atmosphere, 1.1×10^{44} (50). We use parameters for CFC-11 in all calculations: τ = 50 yr, and M_i = 136 g/mol (50). We use country data on the CFC consumption in mass ODP over 1986-2000, and global estimates of CFC-11 production over 1960-1970 and 1970-1990 (50, 51). We assume that all CFCs produced or consumed in a certain year are emitted into the atmosphere in that year.

For all years in which we assess ozone health impacts from (47), we multiply the impacts by the fraction of CFC concentration predicted for that year attributable to 1961-2000 emissions. SI Table 10 shows the resulting distribution of health cases over 1985-2100 by income group.

Without an accepted method to value global health effects in monetary terms, we take two approaches. First, we report health damages in disability-adjusted life years (DALYs), a metric that combines years lost from premature mortality (YLL) and those lost from disability (YLD) (52-54):

(SF.3) $$\text{DALY} = \text{YLL} + \text{YLD}.$$

For a particular health effect, YLL is calculated as the number of deaths multiplied by the standard life expectancy at the age of death. For melanoma and other skin cancers, we estimate a case-weighted global average age of death as 53.4 yr from the EC model for melanoma (comparable to the estimate of 54.2 yr from the World Health Organization's (WHO) Original Global Burden of Disease 2002 Estimates (WHO GBD 2002, http://www.who.int/healthinfo/bodgbd2002original/-en/index.html). We follow guidelines in ref. (53) for setting the standard life expectancy at the age of death based on data in life tables from the WHO Statistical Information System (WHOSIS, http://www.who.int/whosis/en/). We use the same ideal life expectancy for all world regions and do not weight life-years at different ages differently.

Similarly, YLD is computed as the number of cases times the disability weight for the health effect (0 for perfect health and 1 for near-death) and the average duration of the case until death or remission occurs (53, 54). The WHO GBD 2002 lists d_w = 0.045 for melanoma and other skin cancers, and ref. (54) lists d_w = 0.271 for impaired vision due to cataracts. We assume the average duration of the health effect is the standard life expectancy at the average age of onset, which for cataracts we take as 73 yr using U.S. data cited in (47). We assume the same d_w for a life-year lived with a given disability regardless of location, sex or age (53).

In a second approach, we estimate the monetary value of the global health damages using U.S. valuations from cost-of-illness and willingness-to-pay studies. Here we scale the U.S. values for each income group a using a ratio of parity-adjusted per capita gross national income I in the study-year t^*:

(SF.4) $$D_{a,t^*} = D_{US,t^*}\left(I_{a,t^*}/I_{US,t^*}\right).$$

We scale D_{a,t^*} for other years t as follows:

(SF.5) $$D_{a,t} = D_{a,t^*}\left(I_{a,t}/I_{a,t^*}\right)$$

where we use actual PPP-adjusted income for years 1985-2005 and project 2005 values over 2005-2100 using GDP predictions from the IPCC IS92a scenario (39) and the relationship between growth in GDP and GDP PPP from ref. (41) as described in section **E**. Main article Table 2 contains details on all valuations employed, which we update using the Medical Care component of the U.S. Consumer Price Index. Even though treatment may be ongoing, we only assess costs for the year in which the case is predicted to occur. To estimate the costs of mortalities, we calculate both the value of statistical lives (VSL) lost, the monetary value accorded to risk of mortality, and the value of life-years lost (VLY) (Table 2).

Assignment of External Costs

We allocate the global health damages borne by the income groups according to each group's CFC consumption (mass ODP) over 1961-2000 (ODS Report Centre database).

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II. Discussion of Methods

Our choice of discount rate r has a strong impact on the values we estimate, as expected. Our choice of ε, the elasticity of the marginal utility of income that we use to equity-weight the costs, also has a pronounced effect, shifting the distribution of costs among the income groups. For all topics we consider, we provide sensitivity analyses to these factors (SI Table 3, r = 0-3%; SI Table 4, $\varepsilon = 1$).

A. Overfishing

Due to the availability of global data on fisheries catches and the relative scarcity of such data on stock biomass, we base our assessment of foregone catch on the former rather than the latter. Fisheries catches, which increased globally from 1950 to the late 1980s (1), hide the damage caused by overfishing as the global fisheries fleet has doubled in size since 1970 and productivity gains from technological changes have also increased markedly (2). In fact, the biomass of large predatory fish in the world's oceans has been decimated since the onset of industrialized fishing (3), and the mean trophic level of coastal fisheries catch, an indicator of the health of the ecosystems, has declined consistently worldwide since the early 1970s (1, 4). Our estimates of foregone catch are likely conservative as our list of overfished species is incomplete for several reasons. Using catch data from the Sea Around Us Project (SAUP), we only consider fish for which data are available at the species level; over 1961-2000 these catches account for 67% by mass of all fisheries catches reported. Secondly, we analyze species in fishing areas only if both catch and price data are available from SAUP. Third, to minimize the attribution of natural fluctuations in fish populations to overfishing, we consider as overfished only those species whose catch fell to ≤30% of maximum catch over 1961-2000 for at least 10 years in a row or 15 years in total. This approach reduces foregone catch from short-lived stocks such as anchoveta (*Engraulis ringens*) that naturally exhibit wide variations in abundance due to climatic factors (1). Furthermore, we do not consider non-commercial fish that have declined or become endangered as a result of by-catch (30% of global catch); illegal, unreported, or unregulated catches (5, 6); or stocks that experienced substantial declines before 1961. Finally, the overexploitation of fish stocks and their resulting inability to recover fully (7) could cause continued damages which we do not account for here.

Another source of uncertainty arises from our simple approach to choosing MSY levels for the stocks we designated overfished. An alternative would be to use single-species assessments of MSY for all of the species on our list. However, such assessments have been ignored in the management of many stocks, and even when used, they have often failed dramatically by underestimating the severity of decline and the effects of fishing during the decline, and also by assuming compensatory responses in recruitment that have failed (1). Also, changes in fishing technology have had great impact on catch per unit fishing effort, making MSY assessments based on fishing effort outdated (1, 4). For these reasons and given the scope of our study, for our lower estimate we apply simple MSY criteria using species lifespan and age to maturity as metrics for intrinsic production rate. Another uncertainty arises in the treatment of very long-lived fish, whose low fecundity and late maturation may not permit sustainable fishing at all (4, 5). We take a conservative approach and do not count any foregone catch for these species for our lower estimate, applying MSY levels from data from the NOAA's Northeast Fisheries Science Center (NEFSC) for only *Sebastes spp.* in our upper estimate.

Several drivers of overfishing have been identified, including subsidies, high fish prices due to scarcity, and high levels of demand from changing preferences, globalization, and population growth (4). Here, we distribute the foregone catch as an external cost to the consumption of fishery products, and we determine who would have benefited from the foregone catch by analyzing in which countries' waters the fish were caught. While we calculate the foregone catch by year, we apply one set of country fishing statistics averaged over the whole period. In addition, we use one set of trade statistics averaged over 1990, 1995 and 2000 for all fish and fishery products. This approach adds inaccuracy as geographical fishing patterns have shifted over the forty-year period, and earlier overfishing may have contributed disproportionately to later stock decline. Also, trade statistics for all fish and fishery products probably differ from those for the depleted stocks alone. Here, we allocate the catch from the high seas equally per capita among the world's population since this is equitable and simple. In addition, our approach for converting total foregone catch revenue to net revenue is quite approximate. Ratios of net profits to total earnings vary widely for fishing vessels around the world (8), and we do not weight the average ratio we use by the share of total catch landed by each type of fishing vessel.

B. Deforestation

Due to the paucity of consistent valuations, we apply three tropical forest valuations to all low- and middle-income countries, and one temperate forest valuation to all high-income countries. This approximation surely introduces large uncertainties since the local services provided by forests are dependent on many location- and scale-specific factors including soil type, terrain, species types and densities, local human population density and cultural values, accessibility to markets, and demand and supply of related goods and services (9). Second, valuations of forest services in the literature vary greatly. For non-timber forest products (NTFPs) alone, values spanning (2003 US$) 9-1407 $ha^{-1}yr^{-1}$ have been reported (9-11); the highest value we employ is (2005 US$) 282 $ha^{-1}yr^{-1}$. Another reason our estimates are conservative is that we estimate only selected local external costs from deforestation; important non-marketed local services not considered in the valuations we use include nutrient cycling and waste treatment. On the other hand, we assume that losses in ecosystem services are incurred annually for a given area as long as the area remains deforested. In reality, measures may be undertaken to mitigate the loss of certain services, such as storm protection.

Several activities have led to deforestation and the loss of forest services upon land conversion depends not only on the forest characteristics and the original services provided, but also on the particular state of the converted forest. Thus, the valuations we use for tropical forest conversions are conservative, as the starting points were not virgin forests but forests that were deemed sustainably logged. Regarding our adjustment of the marginal costs through time, the application of adjustment factors other than those we use may result in more accurate and possibly higher values for early years in our time period. Torras applied an estimate of total economic value per unit area of tropical forest for a given year to other years by scaling with remaining forest stock (10). In addition to uncertainties on the valuation side, there are also inaccuracies in the data on deforested and afforested land area due to the methodologies used for collection (12). Furthermore, the data on changes in forest area do not take into account forest quality, which for temperate and boreal forests in Europe, for example, is known to have deteriorated from 1986-1995 (12).

We assume that all local external damages were borne within an income group's member countries, although in many cases damages such as erosion and the loss of fisheries protection extend beyond national borders, with bordering countries belonging to different income groups. While there are several direct and indirect drivers of deforestation, we assign the local damages as external costs to the consumption of both agricultural and wood and wood-related products, weighted equally. We find that distributing the damages according to either agricultural or wood products alone does not change the distribution markedly (SI Table 11).

In our treatment of export and production statistics, we make several simplifying assumptions. First, we assume that the mass of agricultural products generated per unit area of converted forest is constant for different types of products, and that the cultivation of all types of crops is equally damaging. We make a similar assumption for the extraction of wood and wood products. Thus in our study, the production by an income group of a certain mass of goods for export to other income groups caused the same level of local environmental externalities as does production of the same mass for within-group consumption. Exports may in fact be more damaging. Second, we use fractions of monetary value rather than mass for bilateral export terms, assuming that the monetary value generated is proportional to forest area lost and to damages incurred.

C. Mangrove Loss

In our estimate of the local external costs of mangrove loss we make several simplifying assumptions. Much of our discussion of the deforestation analysis (**B**) is pertinent here as well, and our estimate here is likely conservative for many of the same reasons. First, we apply one valuation study to all instances of mangrove loss among the three income groups. The values we use for lost local services (2005 US $2,409-2,780 $ha^{-1}yr^{-1}$) are low compared to those reported in (13) for all mangrove services ($2,000-9,000 $ha^{-1}yr^{-1}$), especially considering that most mangrove services may be local (14). Also, the occurrence of high property values in high-income countries suggests that the value of storm protection we apply to this group, which has experienced 11% of the mangrove losses we account for, is conservative (15). Important services we do not consider include biodiversity maintenance, erosion control, nutrient cycling, and water purification (16). Additional impacts from intensive shrimp farming we do not consider include eutrophication, pollution, shrimp disease outbreaks, loss of genetic diversity in wild populations, and the decline in natural stocks of both offshore shrimp used for juvenile supply and fish used for shrimp food, as well as socioeconomic impacts such as loss of food security and livelihood, income and land redistribution, and conflict (13, 16, 17). For example, Naylor *et al.* estimate a loss of 100 kg of wild fish for every hectare of mangrove lost (17). Furthermore, we do not consider any damages past the year 2000 from losses between 1980-2000.

We should also note that for transferring damages, we use coastal population density to transfer the valuation for the study country to the income groups, and total population (coastal and non-coastal) divided by mangrove area for scaling into the past. We use both of these indicators as proxies for the level of human interaction with mangrove ecosystems. While this approach is approximate, it probably captures the general trend; the percentage of the world's population living within 100 km of the coastline grew by 10% over 1990-1995, compared to an increase of 6% for total population divided mangrove area for the same period. We recognize, however, that this approach is apt to underestimate storm protection losses in high-income countries where property is highly valued and coastal population density is relatively low.

There is much uncertainty in the estimates of mangrove area loss that we employ. For example, annual rates of mangrove loss that we estimate for Thailand over 1980-2000 from (19) and 1961-1993 (18) differ by a factor of four. We give preference to values from Valiela *et al.* (18) where available as this study is well-cited (20), and also because the extrapolation of losses to 2000 used in (19) may be less reliable. In addition, only completely deforested areas are included in the area estimates so that mangroves significantly degraded by shrimp culture but not completely converted are not included (18). Compared to rates of mangrove loss, restoration and natural regrowth occur only very slowly (18), and thus our scenario, which assumes annual storm damages after deforestation, is reasonable and similar to that used in (20).

There are a variety of direct and indirect drivers of mangrove loss including mariculture, forestry, agriculture, urbanization, and war (18). Shrimp culture is the single greatest threat worldwide, and citing ref. (18) we attribute 38% of all local external costs to this driver. This is likely an underestimate overall due to the underreporting of shrimp farm area, but an overestimate in some regions such as Africa where drivers of mangrove conversion are not well quantified (18). In our analysis of trade statistics we have assumed that trade patterns for farm-raised shrimp match those for all shrimp. We use data for single years to estimate bilateral export terms, although trade patterns may have been quite different for the earlier years in the time period we consider. Also, while there are several low- and middle-income countries with mangroves, only a few high-income countries contain these habitats, and for these countries shrimp production data from FAO FIGIS are incomplete. We base our estimate of the high-income group's export-to-production fraction on values for the United States only, recognizing that more complete data may change this value. Still, the bulk of shrimp production occurs in developing countries (2), so the overall effect would be small.

D. Agricultural Intensification and Expansion

Our application of a single FAO valuation study to all low- and middle-income countries (21) introduces the biggest source of uncertainty in our estimate of the local external costs of agriculture worldwide. In reality, the climate, topography, particular type of cultivation and means of management practiced in a certain area together determine the impacts of agriculture to the local ecosystem services in a region (23). Certainly, the FAO study we cite is very approximate; the study considers four countries with mainly humid climate, three with mainly dry climate, and India, three-quarters humid or sub-humid and a quarter arid or semi-arid (21). Yet, despite progress in this direction (22) the regional impacts of agriculture are not well known at this time, partly because many of the ecosystem services affected are non-marketed, and also because the external costs impact several economic sectors and are dispersed over geographical distances and time (23, 24).

In general, the five studies that we cite (21, 24-26) valued impacts to different subsets of services using different methodologies, and thus the order of magnitude of the impacts to the three income groups is more informative than direct comparison between the groups. Although our approach is rudimentary, the impact estimates we used appear conservative. The FAO (21), Pretty *et al.* (24, 25) and Tegtmeier and Duffy (26) studies accounted for only a subset of agriculture's local external costs. Substantial impacts from acute and chronic pesticide poisoning are not considered in (21, 24, 25), and estimates in (26) appear partial and conservative (27). In our analysis, the study by Tegtmeier and Duffy (26) provides the lower and upper bound valuations for the high-income group, with the valuations derived from the Pretty *et al.* studies falling within this range. While ref. (26) included some willingness to pay measures, the studies by Pretty *et al.* considered only ecosystem service losses that contributed to financial costs due to treatment, prevention, administration, or monitoring. Such costs tend to underestimate people's willingness to pay to create positive externalities (24). Also, the costs of restoring the environment and human health to pristine states were not considered. The FAO study, in turn, did not value reductions to water quality by pesticides, fertilizers, or microorganisms, nor did it value the loss of wild biodiversity. The FAO and Pretty *et al.* studies did not quantify the impacts to water availability, and none of the studies quantified the loss of agricultural genetic diversity (*i.e.*, domesticated breeds) or considered the time lags of the ecosystem impacts.

Comparison with other studies indicates the valuations we cite are conservative. In refs. (21, 24-26), damages to soil for the US and UK were estimated to range between \$2.4-79 $ha^{-1}yr^{-1}$ (2005 US\$). Although preventive costs are not directly comparable with damage costs, we note that the U.S. Dairy Association Farm Service Agency's Conservation Reserve Program paid an average of \$108 $ha^{-1}yr^{-1}$ to U.S. land owners for planting "long-term, resource conserving covers" for a range of ecosystem benefits including mitigation of soil erosion (28). For salinization and waterlogging, the FAO study calculated (1989 US) \$2 billion in losses for the eight South Asian countries considered, in comparison to Postel's estimate of productivity loss worldwide of \$11 billion (29), and both estimates represent 1% of annual agricultural production. We also estimate the parity-adjusted percentage of net present value of local ecosystem losses over 1961-2000 as approximately 1% of world GDP PPP and 13% of world agricultural GDP PPP, which we calculate using statistics for agriculture as a percentage of GDP from (WRI EarthTrends database) along with GDP PPP figures.

Another source of uncertainty arises from our use of fertilizer application per hectare of agricultural land as a proxy for both the level of intensification and the damage potential of changing agricultural practices over 1961-2000. The use of nitrogen and phosphorus fertilizers, which has increased dramatically worldwide in the past fifty years, is directly linked to the loss of ecosystem services through water pollution, biodiversity losses, and emissions of the greenhouse gas nitrous oxide (23). While commercial fertilizers are used heavily in the most productive of the world's major cropping systems, the main ecological impact of subsistence cropping is soil fertility decline rather than excessive application of chemical fertilizers (23). Thus our choice of fertilizer use per area may not accurately represent intensity changes in subsistence systems, nor can it capture the different impacts of various farming practices or the ecological benefits of technological advances. According to FAOSTAT data on nitrogenous, phosphate and potash fertilizers, we estimate that world fertilizer use per agricultural area increased by a factor of 2.7 from 1965 to 2000; other metrics of intensification that we could use, such as labor per cropland area or irrigated share of cropland, less than doubled over the same time period (23). Errors arising from our treatment of trade statistics are discussed in section **B** (Deforestation).

E. Climate Change

Undoubtedly, forecasting the NPV impacts of climate change over the next century is subject to great uncertainties. Outcomes are highly sensitive to the scenarios chosen and the types of impacts considered. Here we use three IPCC scenarios that cover a range of emissions, climate, and regional economic growth projections. In the year 2100, the three scenarios we apply (IS92a, IS92e, and A2) predict temperature increases of 1.2-3.8 °C (30).

In our analysis, we derive our upper bound climate impacts from the *Stern Review*'s upper bound predictions, which take into account market and non-market impacts as well as the important risk of climate catastrophe (31). Although the upper bound projections of climate impacts by Stern *et al.* are on the high end of literature predictions to date (32), we include these estimates because unlike most other studies, the Stern analysis attempted to account for the recent evidence of feedbacks in the climate system and the resulting potential for abrupt and large-scale impacts (31). Indeed, since the first IPCC assessment the scientific understanding of climate instability has undergone a massive change, with the discovery that large climate transitions have occurred in the past over just a period of years to decades (33). For all we know now, however, the recent predictions by Stern *et al.* may be conservative, as socially contingent impacts such as human migration, conflict, and large changes in capital investments were not fully considered in the analysis and broader risks are possible (31). In any case, a great deal of criticism of the analysis by Stern *et al.* surrounds the low discount rate of 1.4% used (32). Here, we use a higher rate of 2% (giving a discount factor halfway between that for rates of 1.4% and 6%, the standard discount rate) and we present results for rates up to 3% (SI Table 3). We acknowledge the importance of other criticisms that question the potential double-counting of risk and the assumption of static climate vulnerability over more than 200 years (32). We decrease the effect of the latter criticism by calculating NPV impacts to 2100 only, even though the atmospheric lifetime of GHG emissions in 2000 extends past 2100 (CO_2: 5-200 yr, N_2O: 114 yr). If we choose 2150 as the end date instead, both the upper and lower bounds of NPV climate impacts increase ((9.7)-41 trillion (2005 international $)), with "ecological debt" to the low-income group increasing to $7.3 trillion.

We point out that the impact projections by Stern *et al.* have been endorsed by many leading economists and as such, justifiably provide an upper bound for our meta-analysis. In a similar vein, for our lower bound we apply estimates from an optimistic model (34) that produces marginal costs at the lower end of literature estimates (32). In addition, we use conservative assumptions in applying the impact projections from Pearce (35) and Nordhaus and Boyer (36). Had we applied these predictions in the projected year of CO_2 concentration doubling rather than that of 2.5°C increase (both conditions are valid according to refs. (35, 36)) with the intermediate-to-pessimistic IS92e scenario instead of the more optimistic IS92a path, climate impacts from Pearce would exceed those we calculate from Stern *et al.* by 79%. Furthermore, in recent work Nordhaus (37) predicted a doubling of CO_2 and a 3°C temperature rise would cause world losses up to 2.95% of GDP, nearly twice the value we use from ref. (36).

While three of the five studies we apply suggest large net damages (31, 35, 36), one study gives damages or benefits to different income groups depending on the impact prediction applied (38), and the remaining study suggests net benefits over the time period we consider (34). The global impacts we estimate from Pearce *et al.* (35) and Nordhaus and Boyer (36) are restricted to net damages because they are each based on single, world damage percentage for a future year; impacts estimated from Stern *et al.* are also net damages because we apply damage percentages for every year in the time period. Income-group impacts from Mendelsohn *et al.* (38) are similarly restricted to net damages or benefits depending on the scenario applied. By contrast, Tol's model of yearly impacts predicts net present damages or benefits depending on the discount rate r and time horizon τ used. Considering all projected warming and not just that attributable to emissions over 1961-2000, for r

= 2% the model gives a NPV of (2005 international) $27 trillion in NPV global *damages* over 2000-2200. (In non-parity adjusted US$, we estimate 30 trillion in NPV benefits over 2000-2100, and 57 trillion in damages over 2000-2200). To quantify the impacts due to emissions over 1961-2000 only, we multiply the annual impacts by a factor f that decreases into the future and thus, has an effect similar to raising the discount rate. Therefore, our calculation of the NPV impacts as a global benefit using Tol's model (r = 2%) is not surprising given the near-term benefits described in (39) from the model for OECD countries, China, and the Middle East.

There are pronounced differences between the five studies in the distribution of the climate damages among income groups. Early work predicted that nearly every region of the world would bear climate damages, with some studies suggesting that developing nations would be somewhat more at risk, and others proposing the damages would be generally proportional to income (40, 41). More recent work has suggested that warmer regions and island states will likely suffer more severe impacts than the cooler regions. A debate continues as to the impacts in cooler regions; some researchers have described near-term benefits from warming (34, 38) whereas others have questioned these results. In addition to the differences in the literature, our conversion of regional results from the five reference studies into the three income-group framework is necessarily rough, and introduces distribution errors. From the Tol and Stern *et al.* models, we employ output on the changing regional impacts over time for 16 and 8 regions, respectively. In contrast, the studies by Pearce *et al.*, Nordhaus and Boyer, and Mendelsohn *et al.* listed regional impact percentages (12, 9, and 4 groups, respectively) for a single year only.

A number of uncertainties underlie the wide range predicted for climate impacts. On the physical side, the relationship between GHG emissions and temperature rise in the future is uncertain, as are the adaptive capacities of natural and human systems. There is also a whole set of economic, social, and political uncertainties regarding future emissions, the future world economy, and the distribution of income among regions. While output from Stern *et al.* and Tol contain GDP projections for geographical regions, in our application of the other studies we estimate the future division of world impacts among the income groups. To do so, we need projections of how GDP in the mid-period year 2050 may be distributed among the current high-, middle-, and low-income groups. These we derive in an approximate fashion from GDP projections for 8 IS92 world regions. In addition, to estimate future climate impacts from emissions over 1961-2000, we apply a proportional approach to radiative forcing similar to that described in (42); accounting for nonlinearities would weight early and late emissions in the period differently.

Here we allocate the net impacts from climate change as externalities to each income group's share of GHG emissions over 1961-2000. The emissions resulted from a variety of activities (*e.g.*, fossil fuel combustion, cement production, and agricultural practices like land conversion, livestock production, rice cultivation, and the application of nitrogen fertilizer). Currently agriculture alone may contribute one-fifth of current global warming potential (GWP), so although we divide the externalities by emissions, an allocation based on the consumption of the resulting products would be different. We use cumulative GWP-weighted emissions to allocate "responsibility" among the three income groups. Höhne & Blok have shown that other metrics such as cumulative radiative forcing or temperature increase, which are more directly related to the impacts, would produce similar results (42). Indeed, our choice of time period (1961-2000) has a larger effect on the allocation than the particular indicator we use. We also note that the two emissions datasets we employ are temporally incomplete, and involve both interpolation and extrapolation. Statistics on industrial activity and land-use change are inaccurate and sometimes non-existent, especially for developing nations and for decades before 1990. For different gases, regions, and time periods, the two datasets differ from each other by up to 30%.

As expected when considering long-term future impacts, our choice of the discount rate has a dramatic effect on the NPV climate impacts, even changing the sign of the impacts as discussed (SI Table 3). Our choice of equity weights also has a significant impact (SI Table 4). We use weights based on year 2000 GDP PPP values, although each income group's relative share of world GDP will likely change in the future and countries may shift among income categories as well.

F. Stratospheric Ozone Layer Depletion

The estimates of the NPV health damages that we present are based on the most comprehensive analysis of these impacts to date (UNEP Ozone Secretariat, http://www.ozone.unep.org/). Still, they are likely conservative for several reasons. As considered in the Environment Canada (EC) model (43), the Montreal Protocol and its amendments before 1997 account for the large part of the resulting reduction in stratospheric chlorine (according to the UNEP Ozone Secretariat), and so levels of ozone depletion considered here are not overestimates. Rather, recent research has shown depletion to be greater than predicted, partly due to reservoirs of ozone-depleting substances in industrialized nations (44).

Uncertainties in the health model arise from the levels of UV-B exposure used, the demographic data used, and the choice of incidence and mortality rates as well as dose-response coefficients (43). Other assumptions also introduce uncertainty such as the choice of time between diagnosis and mortality for skin cancers and the fraction of cataract incidence attributable to increased UV-B exposure. In addition, our conversion from the population categories described in the model to income groups is imprecise. Whereas we use the approximate geographic midpoint of countries for the assignment to latitude band groups, several countries span more than one latitude band and population centroids for countries such as Australia and Russia are further south than the midpoints we use (according to Gridded Populations of the World, http://sedac.ciesin.columbia.edu/-gpw/index.jsp). In most cases, we believe that increased precision would not change the distribution of damages significantly within the greater context of uncertainty.

In the use of DALYs, we made several assumptions. For example, we estimated and applied a global average age of mortality from all skin cancers; in reality, deaths occur at earlier and later ages in low- and high-income countries, respectively (ref. (45) and the WHO Original Global Burden of Disease 2002 Estimates, http://www.who.int./healthinfo/bodgbd2002original/en/index.html). On the other hand, we apply a maximum life expectancy measure for all income groups, as recommended in ref. (46). Also, although functions for weighting life-years at different ages are available (46), we use uniform age weights. We also use uniform disability weights regardless of age, location, or gender, as described in ref. (46). Furthermore, we apply a disability weight for "melanoma and other skin cancers" to all cases of melanoma and non-melanoma cancers, and we assume that patients experience this level of disability for all years in their lives following the development of these cancers.

Regarding the monetary valuations we apply, certain costs are incomplete (47, 48). For various health risks it has been shown that comprehensive measures for costs to society using willingness-to-pay methods range between 1.3 - 2.4 times that of the cost-of-illness estimates applied here for skin cancers (47). This factor and also, that we assess only one year of health damages for each case, may offset cost reductions from advances in detection and treatment of these cancers and the resulting reductions in mortality rates. On the other hand, the cataract costs we apply are comprehensive but may be outdated as treatment costs for cataracts have declined substantially since 1987. We do not, however, consider the costs or the DALYs due to cataract-induced blindness or premature death, potentially quite large for developing nations (43, 49). Certainly in poorer countries, health treatment for skin cancers and cataracts may not exist or may be prohibitively expensive for the average citizen. Due to the lack of developing country valuations, we assume that our parity-adjusted income-based scaling of U.S. willingness-to-pay and cost-of-illness measures to other countries is representative of the overall social welfare losses from the health impacts suffered.

For skin cancer fatalities, the value-of-a-statistical-life (VSL) estimates we use range from $930,000 to $5 million (2005 US$) for low- and high-income citizens, with the latter in the mid-range reported in the literature for the U.S. population (34, 50). Since skin cancer incidence increases with age, the VSL lost in skin cancer deaths may be lower than those for average adult mortalities. Although we use the whole VSL value as was done in ref. (47), we also calculate the value of life years lost (VLY) to account for this issue.

Our allocation of the health impacts borne by income group according to ODS consumption is subject to many of the same issues we discussed in the allocation of climate impacts (**E**). Here, among all ODS we consider only CFCs, using CFC country data over 1986-2000 that is incomplete due to unreported, illegal use. Also over 1961-1985, we use only CFC-11 data and apply our estimate of the 1986 income-group division of CFC use. These inaccuracies are coupled with our assumption of complete conversion of CFC consumed or produced in a year to emissions. Still the overall pattern in distributed impacts between low- and middle- or high-income countries is likely to be representative. Moreover, we note that we do not estimate any projected damages of ozone-layer depletion to agriculture, fishing, or materials as was done in ref. (43), or of ODS use to climate change.

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III. Tables

SI Table 4. Distributed costs C_{ab} with ε, the elasticity of the marginal utility of income, set to 1 for equity weighting.

			Income group *a* (2005 international \$ × 10^9)			
	Direct or indirect driver considered here	Income group *b*	Low	Middle	High	World
Climate change	Emissions of greenhouse gases carbon dioxide, methane, and nitrous oxide	Low	(210) - 3,100	(2,200) - 1,900	(53) - 180	(2,500) - 5,200
		Middle	(710) - 11,000	(7,300) - 6,300	(180) - 620	(8,400) - 17,000
		High	(670) - 9,900	(6,800) - 5,900	(170) - 580	(7,900) - 16,000
		World	(1,600) - 24,000	(16,000) - 14,000	(400) - 1,400	**(18,000) - 39,000**
Agricultural intensification and expansion	Consumption of agricultural goods	Low	9,000	44	1.4 - 4.7	9,000
		Middle	57	24,000	15 - 50	24,000
		High	130	950	250 - 860	1,300 - 1,900
		World	9,100	25,000	270 - 920	**34,000 - 35,000**
Stratospheric ozone-layer depletion	Emissions of chlorofluorocarbons	Low	2.5 - 5.6	8.6 - 16	4.3 - 6.8	15 - 28
		Middle	44 - 98	150 - 280	76 - 120	270 - 500
		High	110 - 240	380 - 700	190 - 300	680 - 1,200
		World	160 - 350	540 - 1,000	270 - 430	**970 - 1,800**
Deforestation	Consumption of agricultural goods and wood and wood-related goods, weighted equally	Low	1,300 - 6,700	0.44 - 7.9	-	1,300 - 6,700
		Middle	25 - 130	300 - 5,300	-	330 - 5,400
		High	31 - 160	20 - 360	(4.9)	47 - 520
		World	1,400 - 6,900	320 - 5,700	(4.9)	**1,700 - 13,000**
Overfishing	Consumption of fish and fisheries products	Low	0.11 - 0.26	0.047 - 0.15	0.0025 - 0.012	0.16 - 0.42
		Middle	2.2 - 6.8	110 - 350	0.24 - 1.2	110 - 350
		High	5.3 - 9.7	19 - 59	1.2 - 6.0	26 - 75
		World	7.6 - 17	120 - 400	1.5 - 7.1	**130 - 430**
Mangrove loss	Consumption of farmed shrimp	Low	170	0.30	0.00062	170
		Middle	6.5	150	0.063	150
		High	150	120	2.7	260
		World	320	260	2.7	**590**
	Totals	Low	10,000 - 19,000	(2,100) - 1,900	(48) - 220	8,000 - 21,000
		Middle	(580) - 10,000	17,000 - 36,000	(87) - 880	16,000 - 47,000
		High	(250) - 9,600	(5,300) - 8,000	280 - 1,800	(5,600) - 19,000
		World	9,400 - 38,000	9,800 - 46,000	140 - 2,900	19,000 - 87,000

SI Table 5. For the overfishing analysis, lower bound guidelines based on species' lifespans t_{max}, for maximum sustainable yield (MSY) as a percentage of maximum catch C_{max} over 1961-2000.

t_{max} (yr)	Lower bound MSY (%)
$t_{max} \leq 5$	30
$5 < t_{max} \leq 10$	20
$10 < t_{max} \leq 15$	10
$15 < t_{max} \leq 30$	5
$t_{max} > 30$	0

SI Table 6. For the overfishing analysis, the list of species with normalized catch ≤ 0.3 for at least 10 yr in succession or 15 yr total over 1961-2000, and lower and upper assignments of MSY as a percentage of maximum catch C_{max} in that time period. A dash indicates we did not find data for the species. Upper values listed in italics are derived from data from the NOAA's Northeast Fisheries Science Center (NEFSC, http://www.nefsc.noaa.gov/sos/).

Species	t_{max}	t_m	Lower MSY %	Upper MSY %
Anarhichas lupus	26.2	5.5	5	10
Boreogadus saida	7	2-5	20	40
Brevoortia tyrannus	8.4	2.1	20	40
Chaenocephalus aceratus	16.9	3.8	5	10
Chaenodraco wilsoni	9.8	2.4	20	40
Champsocephalus gunnari	13	4	10	20
Clupea harengus	25	2-5	30	*66*
Clupea pallasii	19	1.4	30	60
Clupeonella cultriventris	11.7	3.3	20	40
Coryphaenoides rupestris	54	9-11	0	0
Decapterus maruadsi	3	0.8	30	60
Dentex angolensis	7	-	20	40
Electrona carlsbergi	5.1	1.6	20	40
Engraulis capensis	4	1	30	60
Engraulis mordax	7	1-4	20	40
Engraulis ringens	3	1	30	60
Euphausia superba	6-7	2-3	30	60
Euthynnus alletteratus	8	2	20	40
Gadus morhua	15.2	3.1	10	*49*
Glyptocephalus cynoglossus	25	-	5	*39*
Gobionotothen gibberifrons	41	9.7	0	0
Hippoglossoides platessoides	30	2-11	5	*25*

Hippoglossus hippoglossus	50	-	0	0
Hippoglossus stenolepis	57.9	11.1	0	0
Illex illecebrosus	1	-	30	60
Jasus lalandii[A]	10	-	20	40
Lepidonotothen squamifrons	19	7-9	5	10
Limanda aspera	19	4.5	5	10
Makaira mazara	28	4	5	10
Mallotus villosus	5	3	30	60
Melanogrammus aeglefinus	20	2-5	5	*25*
Merlangius merlangus	20	2-4	5	10
Merluccius bilinearis	12	2-3	10	20
Merluccius gayi peruanus	13	-	10	20
Merluccius hubbsi[B]	-	6	10	20
Merluccius merluccius	20	2-8	5	10
Micromesistius australis	30	2-5	5	10
Micromesistius poutassou	20	1-5	5	10
Nemadactylus bergi	-	2	20	40
Notothenia rossii	16	-	5	10
Oncorhynchus gorbuscha	3	2	30	60
Oncorhynchus keta	6	2-5	20	40
Oncorhynchus nerka	7	2-4	20	40
Osmerus eperlanus	10	2-4	20	40
Ostrea lutaria[C]	6	-	20	40
Paralithodes camtschaticus	20-30	-	5	10
Parastromateus niger	10.6	2.4	10	20
Patagonotothen brevicauda	8.8	2.4	20	40
Perna viridis	2-3	-	30	60
Pleuragramma antarcticum	20	3-4	5	10
Pollachius virens	16.9	3.6	5	*33*
Pomatomus saltator	9	2	20	40
Pseudochaenichthys georgianus	12	4	10	20
Reinhardtius hippoglossoides	30	7-12	5	10
Sarda chiliensis chiliensis	-	2	30	60
Sarda sarda	5	1	30	60
Sardina pilchardus	5.8	1.6	20	40
Sardinops sagax	6.6	1.7	30	60
Scomber japonicus	18	2-3	5	10
Scomber scombrus	17	2-3	5	*67*
Sebastes alutus	100	-	0	*23*
Sebastes marinus	60	10-12	0	*23*

Stephanolepis cirrhifer	8.8	2.4	20	40
Tetrapturus audax	9	2-3	20	40
Theragra chalcogramma	22.1	4.9	5	10
Thunnus alalunga	10	4-6	20	40
Thunnus albacares	8	2-5	20	40
Thunnus maccoyii	20	8-9	5	10
Thunnus thynnus	15	3-5	10	20
Thyrsites atun	10	2-4	20	40
Todarodes pacificus	1	0	30	60
Trachurus declivis	25	2-4	5	10
Trachurus japonicus	6	-	20	40
Trachurus mediterraneus	12	-	10	20
Trachurus trachurus	11	2-3	10	20
Trachurus trecae	11	2.6	10	20
Trematomus eulepidotus	12.9	3.2	10	20

[A] For most species in the genus *Jasus* the maximum lifespan is unknown, but laboratory-raised *J. lalandii* have lived up to ten years (*5*).
[B] Low resilience, minimum population doubling time 4.5 - 14 yr (*2*).
[C] Medium resilience, minimum population doubling time 1.4 - 4.4 yr (*2*).

SI Table 7. For the overfishing analysis, formulas used to calculate the distribution C_{ab} of the foregone catch "borne" by each of the three income groups *b* as external costs of consumption by each group *a*.

		Bearers of foregone catch		
		Low	Middle	High
Consumers of fish and fishery products	Low	$F_{LL}\left(1-e_{L\to M}-e_{L\to H}\right)$	$\sum_{a=L,M,H} F_{aM}\, e_{a\to L}$	$\sum_{a=L,M,H} F_{aH}\, e_{a\to L}$
	Middle	$\sum_{a=L,M,H} F_{aL}\, e_{a\to M}$	$F_{MM}\left(1-e_{M\to L}-e_{M\to H}\right)$	$\sum_{a=L,M,H} F_{aH}\, e_{a\to M}$
	High	$\sum_{a=L,M,H} F_{aL}\, e_{a\to H}$	$\sum_{a=L,M,H} F_{aM}\, e_{a\to H}$	$F_{HH}\left(1-e_{H\to L}-e_{H\to M}\right)$

SI Table 8. Formulas used in the deforestation, mangrove loss, and agricultural analyses to calculate the distribution C_{ab} of the local damages borne by each of the three income groups *b* as external costs of consumption by each group *a*.

		Bearers of external costs from loss of local forest services		
		Low	Middle	High
Consumers of wood or agricultural products	Low	$D_L(1-e_{L\to M}-e_{L\to H})$	$D_M(e_{M\to L})$	$D_H(e_{H\to L})$
	Middle	$D_L(e_{L\to M})$	$D_M(1-e_{M\to L}-e_{M\to H})$	$D_H(e_{H\to M})$
	High	$D_L(e_{L\to H})$	$D_M(e_{M\to H})$	$D_H(1-e_{H\to L}-e_{H\to M})$

SI Table 9. For the climate change analysis, the distribution of the PPP-adjusted, NPV (2005 international $ billions) climate impacts over 2000-2100 due to emissions over 1961-2000 only. The source studies and the impact percentages from the sources, as well as the IPCC scenario we use are noted. A discount rate of 2% is used in all cases. Numbers in parentheses indicate net benefits.

		Bearers of projected climate impacts attributable to 1961-2000 GHG emissions			
Pearce *et al.* average of 1.75% world GDP for year of 2.5˚C increase; IS92a scenario					
	Income group	Low	Middle	High	World
Emitters of GHG gases, 1961-2000	Low	300	370	110	780
	Middle	1,000	1,200	380	2,600
	High	950	1,200	350	2,500
	World	2,300	2,800	840	5,900
Nordhaus and Boyer 1.5% world GDP for year of 2.5˚C increase; IS92a scenario					
Emitters of GHG gases, 1961-2000	Low	330	67	270	670
	Middle	1,100	230	910	2,200
	High	1,000	210	860	2,100
	World	2,500	510	2,000	5,000

Mendelsohn *et al.* "PCM" model (0.065)%, "CCSR" model 0.025% world GDP for 2100; IS92a scenario					
Emitters of GHG gases, 1961-2000	Low	1.0 | 1.9	(17) | 7.5	(17) | 3.8	(33) | 13
	Middle	3.5 | 6.5	(57) | 25	(57) | 13	(110) | 45
	High	3.3 | 6.1	(54) | 23	(54) | 12	(110) | 42
	World	7.8 | 15	(130) | 56	(130) | 29	(250) | 100

Tol (0.75)% world GDP in 2000; 0.58% world GDP in 2100; IS92e scenario					
Emitters of GHG gases, 1961-2000	Low	(50)	(1,300)	(180)	(1,600)
	Middle	(170)	(4,500)	(620)	(5,200)
	High	(160)	(4,200)	(580)	(4,900)
	World	(380)	(10,000)	(1,400)	(12,000)
Stern *et al.* 0.73-7.8% world GDP in 2100; A2 scenario					
Emitters of GHG gases, 1961-2000	Low	120 | 740	180 | 1,100	120 | 640	420 | 2,500
	Middle	390 | 2,500	620 | 3,800	410 | 2,100	1,400 | 8,500
	High	370 | 2,300	580 | 3,600	390 | 2,000	1,300 | 7,900
	World	880 | 5,500	1,400 | 8,600	920 | 4,800	3,200 | 19,000

SI Table 10. Global health damages over 1985-2100 from ozone-layer depletion due to emissions of ozone-depleting substances over 1961-2000 (discount rate r = 2%). Values are derived from the Environment Canada model (SI Methods ref. (47)). Lower and upper bounds are separated by | where calculated.

Health impact	cases (1,000s)
Melanoma cases	300
Non-melanoma cases	
Basal cell	2,600
Squamous cell	1,200
Cataract cases	24,000 | 49,000
Melanoma and non-melanoma deaths	69

SI Table 11. Sensitivity analysis to allocation of the external costs of deforestation C_{ab} according to the consumption of agricultural goods only, agricultural goods and wood-based goods equally weighted, and wood-based goods only (2005 US$ billions, discount rate 2%). C_H represents the external benefits to high-income nations from afforestation, which we do not distribute based on consumption but include in the sum of the world's externalities, C_W.

	Allocation of external costs by consumption of:		
	agricultural goods	50% agricultural goods, 50% wood and wood-related goods	wood and wood-related goods
C_{LL}	72 | 370	71 | 360	70 | 360
C_{LM}	0.13 | 2.3	0.101 | 1.8	0.074 | 1.3
C_{ML}	0.59 | 3.0	1.4 | 7.0	2.2 | 11
C_{MM}	70 | 1,200	68 | 1,200	66 | 1,200
C_{HL}	1.1 | 5.6	1.7 | 8.7	2.3 | 12
C_{HM}	2.7 | 48	4.6 | 82	6.5 | 120
C_H	(17)	(17)	(17)
$\boldsymbol{C_W}$	**130 | 1,700**	**130 | 1,700**	**130 | 1,700**