Driving the human ecological footprint

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This comparative analysis shows that population size and affluence are the principal drivers of anthropogenic environmental stressors, while other widely postulated drivers (eg urbanization, economic structure, age distribution) have little effect. Similarly, increased education and life expectancy do not increase environmental stressors, suggesting that some aspects of human well-being can be improved with minimal environmental impact. Projecting to 2015, we suggest that increases in population and affluence will likely expand human impact on the environment by over one-third. Countering these driving forces would require increases in the efficiency of resource use of about 2% per year.

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Although there has been scientific consensus on the primary drivers of anthropogenic environmental degradation for well over a decade, little progress has been made in determining the precise relationship between drivers and impacts. This gap constitutes a significant barrier to identifying the policies that have the most potential for reducing human impact on the environment, projecting future impacts, and estimating the level of effort needed to reduce adverse effects on the environment. Here we assess the impacts of widely postulated drivers on anthropogenic environmental stressors.

Population and affluence have long been hypothesized to be primary drivers of environmental impact and there is growing evidence to support this hypothesis (Ehrlich and Holdren 1971; York *et al.* 2003). However, some arguments contradict this expectation with regard to affluence. A curvilinear relationship has been observed between affluence (usually measured as gross domestic product [GDP] per capita) and some types of environmental impact, particularly local ones such as air and water pollution, with environmental conditions improving at the highest levels of affluence (Cavlovic *et al.* 2000). Called the environmental Kuznets curve (EKC), this nonlinearity may be due to changes in economic structure, preferences, and patterns of consumption, or shifts in institutional arrangements, such as laws or taxes aimed at protecting the environment that accompany growing wealth. Economic growth may also have the opposite effect. For example, consumption generally increases with affluence, while average household size decreases, resulting in more households for a given population size (Liu *et al.* 2003; see also Web-only material, note 1). Recent analyses suggest that the number of households has more direct environmental impact than population size per se (Dietz and Rosa 1994; Cramer 1997, 1998; Liu *et al.* 2003). This trend toward increased household numbers associated with affluence is likely to increase environmental impact.

Three other aspects of population structure and economic activity have also been implicated in environmental impact. First, the young (typically defined as those under 15) consume less and are less engaged in production activities than the rest of the population, so a higher proportion of adults in a population may increase impact even as it enhances economic growth (Dietz and Rosa 1994; Bloom and Canning 2003). Second, increasing rates of urbanization around the globe may lead to either improved environmental efficiencies or to obstacles to the provision of ecosystem services (Ehrhardt-Martinez 1998). Urbanization, especially when based on rural-to-urban migration, is likely to produce changes in lifestyle and consumption patterns. Third, it is often hypothesized that a shift in the economy away from extractive industries and manufacturing and towards services (eg banking, health care, information processing) might reduce environmental impact. For some nations this simply means a displacement of material production to another country, but it has also been suggested that a shift toward services leads to "dematerialization" of the economy (Ausubel 1996) – a decreased reliance on energy and raw materials and thus an economy with reduced environmental impact. In addition, a nation's biogeographical features may condition its environmental effects directly, by historical use of ecosystem services, and indirectly, via climate, which drives energy use and housing types. For example, we would expect a country at high latitudes and thus with colder climates to use more energy for heating. Similarly, countries with a long history of readily available animal protein will consume more meat and thus have a more substantial environmental impact as a result. In previous analyses, we found that both latitude and land area influence a nation's environmental threats, presumably due to their effects on energy demand and usage efficiency, and we therefore include these as control variables (York *et al.* 2003). Elsewhere, we have discussed the theories of anthropogenic environmental change and noted that they are at an early stage of development

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Figure 1. *The ecological footprint is a measure of how consumption may affect the environment by taking account of food and fiber production, energy use, and human use of land for living space and other purposes.*

(Dietz *et al.* in press). As a result, these hypotheses regarding population, affluence, age structure of the population, urbanization, the service economy, and biogeography must be treated as preliminary. Even so, we believe that testing them will be useful in furthering the discussion of anthropogenic environmental change.

With the exception of some EKC predictions, these hypotheses have not been extensively tested. Instead, our understanding rests largely on local case studies of limited generalizability and on quantitative analyses that focus on only one aspect of environmental impact, such as deforestation or local levels of toxic emissions. Moreover, the existing scientific literature not only ignores tradeoffs among impacts (eg fossil fuel use versus nuclear power), but also overlooks the distinction between production and consumption impacts. Owing to the expansion of world trade, the impacts of consumption can be seen at a considerable distance from the place of production. A key advantage of the environmental stress measure we use, the ecological footprint (described below), is that it attributes stresses to the country where consumption occurs and thus reflects individual and collective decision making about consumption. Here, we estimate at the nation–state level the relative importance of each of the hypothesized drivers of environmental impact. We then use our results to project future levels of stressors. We also examine the relationship between environmental stress and two measures of well-being – life expectancy and education – with the goal of determining the extent to which well-being could increase without concomitant increases in environmental threats.

Model

To systematically test hypotheses, we use the STIRPAT model (stochastic impacts by regression on population, affluence, and technology), a conversion of the often-used formula for analyzing environmental impacts called IPAT (also called the Kaya identity) into stochastic form (Dietz and Rosa 1994; Chertow 2001; York *et al.* 2002). IPAT postulates that impacts = population x affluence x technology, or $I = PAT$. While useful as an accounting equation, the IPAT identity cannot be used to test hypotheses. STIRPAT is a non-linear regression equation where its coefficients represent the hypotheses to be tested:

$$I = aP^{b}A^{c}e$$

Here b and c are the elasticity of population and affluence, e is an error term representing all variables not included in the model, and a is a constant that scales the model. In the original IPAT formulation, T served much the same role as e does in STIRPAT in the sense that, while designated "technology", it captured, by default, the effects of all factors not included in the model because it was calculated by solving $T = I/(P*A)$. STIRPAT easily accommodates alternative formulations, such as partitioning population into number of households and average household size, or the inclusion of additional variables, such as age structure, urbanization, economic structure, and well-being.

Finding an adequate measure of anthropogenic stressors is an ongoing challenge (Parris and Kates 2003; Dietz *et al.* in press). First, it is important to differentiate stressors from environmental change – measuring the latter involves the difficult task of taking into account the response of ecosystems to the former. Second, because there are tradeoffs across kinds of stresses (eg hydroelectric power versus fossil fuels) it is useful to find measures that aggregate across specific stressors. Our measure of anthropogenic stressors is the ecological footprint (EF). The footprint aggregates across different forms of stress by converting them all to the hypothetical number of hectares of land and sea area at global average levels of productivity that would be needed to renew current levels of resource consumption (Wackernagel *et al.* 1999, 2002). Specifically, the EF is calculated by taking basic forms of consumption – crops, meat, seafood, wood, fiber, energy, and living space – and converting them, at world average productivity, into six types of biologically productive land and sea space: cropland, forest land, grazing land, water area for seafood production, land for infrastructure, and land needed to absorb CO_2 emissions from energy production. Note that the logic is to convert all consumption into a common metric by using global average productivity. In the form we use it, the footprint is not intended to compare a nation's consumption with its resource base, which would require the use of national levels of productivity rather than global averages. It is one of the most comprehensive and most widely adopted overall measures of threats to environmental sustainability. Among its strengths are the capture of tradeoffs, for example, between fossil fuels and nuclear power (accomplished by assigning the same land area to fossil fuel production as to proximate nuclear production, since no measure exists to account for nuclear energy's long-term risks) or between consumption of fish (water area footprint) and consumption of meat (grazing land and cropland footprint). EF's major limitation is that it does not account for local impacts such as biodiversity loss or pollution emissions (except for CO_2). However, cross-national data on local impacts are so meager that none are available at present for such fine-grained analysis. The EF for a nation is calculated using national statistics on consumption and economic activity. Data on the EF are from the World Wide Fund for Nature circa 2001, the most recent year for which consistent data on a large proportion of all nations has been published (Loh and Wackernagel 2004).

Measures of human well-being are from the United Nations (UN 2003) as are population and urbanization projections (UNPD 2003, 2004). All other measures are from the World Bank for 2001 (World Bank 2004). The dataset was restricted to countries with populations over one million, so that the large number of very small countries would not dominate the analysis. All variables have been transformed by taking base 10 logs, save for the two variables representing latitude, which are binary. Models were estimated using ordinary least squares regression. (Details of our statistical procedures can be found in the Web-only material, note 2.)

Results

Table 1 shows the regression estimates for a STIRPAT model (model a) that analyzes the effects of the hypothe-

Table 1. STIRPAT models of anthropogenic environmental threats

Independent variable	*Full model (model a)*	*Full model with well-being indices (model b)*	*Reduced model for projections (model c)*
Population	0.934***	0.930***	0.931***
Gross domestic product per capita – linear term	–0.863*	–0.901*	–0.661*
Gross domestic product per capita – quadratic term	0.178***	0.183***	0.161***
Percent GDP not in service sector	–0.017	–0.020	na
Percent population urban	0.069	0.060	na
Percent population aged over 15	0.422	0.400	na
Land area	0.062**	0.065**	0.052*
Temperate	0.071*	0.069*	0.085**
Arctic	0.189**	0.188**	0.181**
Education index	na	–0.050	na
Life expectancy index	na	0.082	na
Intercept	1.098	1.189	0.562
Adjusted R^2	0.971	0.971	0.966
n	128	128	135

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; na = not applicable

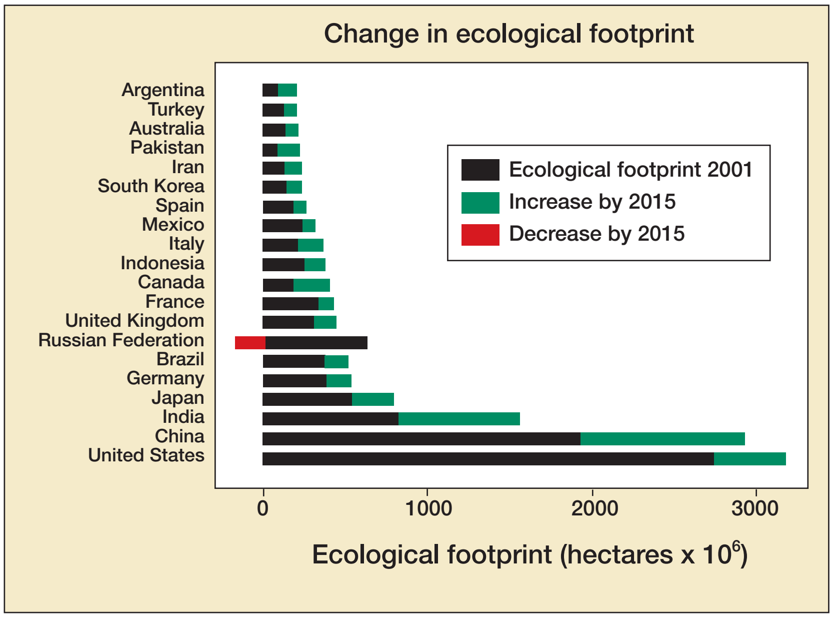

Figure 2. *Projected change in ecological footprint for the 20 nations with the largest footprints by 2015.*

sized drivers – total population, affluence (measured as GDP per capita), proportion of the economy not in the service sector, proportion of the population living in urban areas, proportion of the population aged 15 or over, land area per capita, and binary variables to differentiate countries in the tropics, temperate, and arctic/sub-arctic latitudes – on our comprehensive measure, the EF. Population has an elasticity of slightly less than 1 ($F_{1,118}$ = 6.20, P = 0.01), meaning that a 1% change in population induces a nearly equal percentage change in impacts. GDP per capita shows a curvilinear relationship with impacts, where, within the range of observations, higher levels of affluence produce larger footprints than would be expected from a strictly proportional relationship. The minimum would be at approximately $260 GDP per capita, well below the least affluent country in our sample. This finding directly contradicts the EKC hypothesis, but is consistent with other recent cross-national analyses (Stern 2004). The proportion of GDP in the service sector, the proportion of the population that is urban, and the proportion of the population in the high consumption and production age groups have no net effect on environmental impact. The amount of land per capita tends to increase impact, and countries in the temperate and arctic latitudes tend to have greater impact than those in the tropics. The effect of land area may suggest that patterns of more wasteful resource use have emerged in large nations, while the effect of latitude suggests that cold climate increases footprint, probably due to increased energy consumption.

Liu *et al.* (2003) found that the number of households is a key predictor of resource use and biodiversity loss. To test the robustness of their conclusion, that number of households is a more direct driver of impact than population per se, we estimated a model that disaggregated population into the log of average household size and the log of number of households. Liu *et al.* provided data on household size and number of households for the year 2000, from which we extrapolated to the number of households in 2001 by dividing mean household size for 2000 into the 2001 population. Both household variables were significant and positive. However, this reduced the sample size by 27 because of data limitations. Furthermore, the perfect co-linearity of the log of these two variables with the log of population precludes formal testing of the superiority of one model specification over the other. Both the adjusted R^2 and the Bayesian information criterion suggest that the model using population per se was the better choice for projections, so we proceed on that basis.

Model b adds UN indices for educational achievement and life expectancy to model a to investigate the relationship between environmental impact and human well-being, rather than simply the relationship between affluence and impact. These two measures, when combined with GDP per capita, constitute the widely used human development index. The results show that neither measure, educational achievement nor life expectancy, is related to environmental impact, controlling for the other variables in the model. This important, albeit counterintuitive, finding suggests that while increasing affluence does drive impacts, it is possible to improve other aspects of human well-being without adverse environmental effects.

Based on the resultant parsimonious model c (population, GDP per capita, land area, and latitude) we developed projections of the EF for 2015 using UN medium population projections and an assumption of moderate economic growth. These results illustrate potential changes in impact if current trends continue. In developing GDP projections, the annualized growth rate for each country over the past 10 years was constrained to the upper and lower quartiles, to prevent unusual growth patterns from dominating the analysis. The resulting projections range from a 0.5% per year decline in GDP per capita to a 2.4% per year increase. EF projections use the bias correction for logarithmic models suggested by Wooldridge (2000).

The projection produces a global footprint estimate of about 18.1 billion hectares in 2015, 34% larger than the current (2001) footprint of 13.5 billion hectares (Loh and Wackernagel 2004). Ecological footprints are often compared to the 11.4 billion productive hectares on Earth. This places the current human footprint at 1.2 "planets." Our projections indicate that, by 2015, human demands will increase to 1.6 planets. This is an annual growth rate

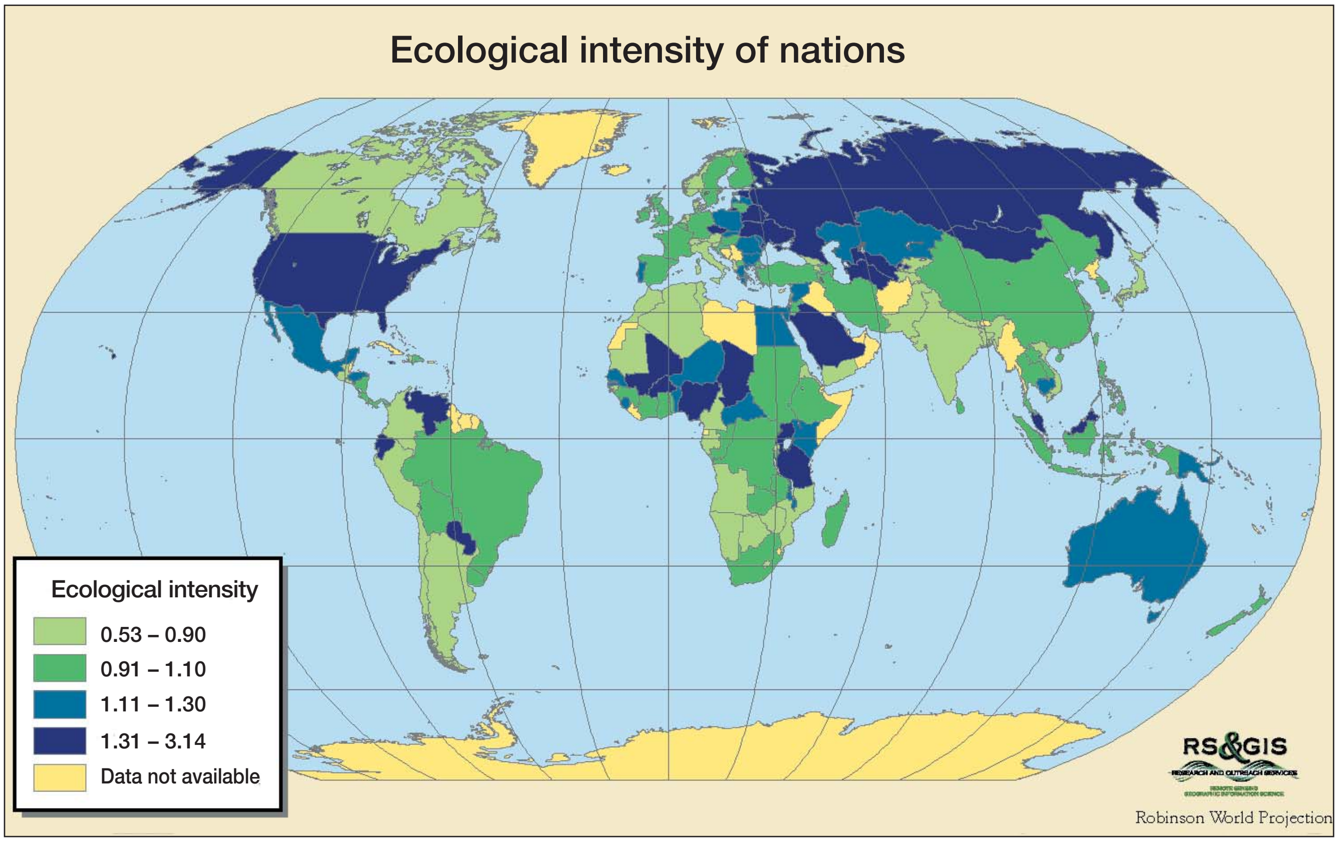

Figure 3. *Ecological intensity is a measure of how much impact a nation has, net of other drivers. It is an impact multiplier, with a value of 1 indicating that a nation is at global average intensity, a number less than one indicating below average intensity, and a number greater than one indicating greater than average intensity.*

in the global footprint of 2.12% per year. If, as frequently suggested, technological progress can redress environmental problems (Ausubel 1996), the requisite technological improvement needs to exceed 2% per year. Energy efficiencies of national economies have improved by as much as 5% per year in some cases, so this goal may be technologically feasible, although difficult in the face of economic and institutional obstacles (IPCC 2000). We also do not know whether the production efficiencies of non-energy resources can be improved so rapidly.

Figure 2 displays the 20 nations that we project to have the largest EFs in 2015. Not surprisingly, the greatest absolute increase in the EF will occur in China and India, where population growth continues, while economic growth is also increasing rapidly. The projected increases for China and India are 984 million and 738 million hectares, respectively, or 37% of the total global increase in footprint projected. The evolving environmental policies in these nations will undoubtedly be critical in the move towards global sustainability. On the other hand, the impact of the US alone, while projected to increase less rapidly than that of China or India, constitutes 17.5% of the global environmental impact in 2015, as opposed to just over 20% at present. Given its declining population and a 7% projected decline in per capita affluence, the footprint of the Russian Federation is expected to decline by nearly one quarter.

The model also can be used to estimate the current ecological intensity of nations, where ecological intensity is defined as the country-specific multiplier that determines how large the footprint of a nation is, taking account of population size, affluence, and other driving forces. Figure 3 shows the ecological intensity of the countries of the world used in our analysis, based on model c in Table 1. (See the Web-only material, note 3 for details.) For example, the ecological intensity of the US is 1.4, which means that the US has an overall ecological footprint that is 1.4 times as large as would be expected based on its population size, level of affluence, land area, and latitude alone.

Discussion

These results warn against complacency about global environmental impacts. Contrary to the expectations of the EKC, increased affluence apparently exacerbates rather than ameliorates impacts, and, when combined with population growth, will substantially increase the human footprint on the planet. The increases in environmental efficiency needed to compensate for these increasing impacts are within the range of some past energy efficiency improvements, but cannot be expected to occur without focused international effort.

Two optimistic observations can be made from our analysis. First, the largest increments in EFs are expected from two nations, China and India. Since these huge economies will develop much of their infrastructure in the early 21st century, they are positioned to invest in more efficient technologies. China would need to improve its technological efficiency at a rate of about 2.9% per year and India by 2.2% per year to offset the projected growth of their respective EFs. Second, it appears to be possible to decouple improvements in human well-being from increases in environmental impact so that, for example, the Millennium Development Goals of the UN might be achieved without increased environmental impact if appropriate strategies are used.

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