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Threatened species and the spatial concentration of humans

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Abstract Public policies that encourage high-density human living arrangements have been predicated explicitly on the assumption that certain spatial distributions of a fixed-size human population are less environmentally damaging than others. We examine the empirical validity of this assumption across 127 countries by analyzing whether the concentration of human presence in each country is related statistically to the percentage of species that were on the IUCN Red List in 2004. Our findings indicate that concentration of the human population is associated with reduced imperilment among amphibians but increased imperilment among reptiles, and birds.

Keywords Gini coefficient · Imperiled species · Spatial concentration of humans

Introduction

It seems quite clear that the sheer number of humans (or any species) has a variety of ecological consequences (Cincotta and Engelman 2000; Kerr and Currie 1995; Thompson and Jones 1999). A successful species directly ''crowds out'' other species by appropriating habitat. As the population of a prey species increases, so, too, does the population of any predator and/or symbiotic species, albeit with a temporal lag. In turn, a boom in the numbers of a predator species leads to a reduction in the numbers of the prey species and population cycles among predator/prey species are well-documented.

However, while a link between the *spatial distribution* of humans (or human activity) and ecological outcomes has been conjectured, empirical support is lacking. For example, it has been suggested that intensively-managed timber, as a human activity, reduces the imperative to cut from ''natural'' forests, thus leaving greater

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area intact in undisturbed ecosystems (Bowyer 2001; South 1999; Sedjo and Botkin 1997). The implicit suggestion is that *in the aggregate* there are ecological advantages (in terms of biodiversity enhancement, reduced soil disturbance, reduced ecosystem fragmentation, and the like) to more intensive human processing of a relatively smaller number of hectares in planted trees than less intensive human processing of a relatively larger number of hectares of naturally generated trees, for a given timber harvest level.

Analogously, proponents of the SmartGrowth principle of Compact Building Design advocate policies that encourage higher densities of humans in cities as a means of reducing the putative ecological harms caused by urban sprawl. As indicated on the Environmental Protection Agency (EPA) website: (http://cfpub1.epa.gov/sgpdb/glossary.cfm?type=topic):

> ‘‘Compact Building design refers to the act of constructing buildings vertically rather than horizontally, and configuring them on a block or neighborhood scale that makes efficient use of land and resources, and is consistent with neighborhood character and scale. *Compact building design reduces the footprint of new construction*, thus preserving greenspace to absorb and filter rain water, reduce flooding and stormwater drainage needs, and lower the amount of pollution washing into our streams, rivers and lakes.’’ (emphasis added).

A strong assumption forms the foundation for this Compact Building Design policy perspective: not only does the sheer number of human beings matter, how you distribute the human population, generally speaking, matters also. In this regard, the analogy to intensively-managed forestry mentioned previously is virtually perfect, as indicated in this passage from the SmartGrowth.org website (www.smartgrowth.or/about/issues/issues.asp?iss=4):

> ‘‘As we build, we replace our natural landscape—forests, wetlands, grasslands with streets, parking lots, rooftops, and other impervious surfaces. The effect of this conversion is that stormwater, runoff which prior to development is filtered and captured by natural landscape, is trapped above impervious surfaces and runs off into streams, lakes, and estuaries, picking up pollutants along the way. Runoff can be reduced through clustering of development, thereby leaving larger open spaces and buffers. *Although compact development generates higher runoff and pollutant loads within a development, total runoff and pollutant loads are offset by reductions in surrounding undeveloped areas*.’’ (emphasis added)

The possibility that dispersion of the human population matters independently of the level of human population can be illustrated by example. Consider two countries, A and B, that are identical in every respect, including size of human population, land area, percent of human population living in urban areas, number and characteristics of ecological niches, species diversity, and so on. In country A, the urban population is confined completely within a single city of 100 square miles; in country B the urban population is distributed equally among 100 cities, each confined within a one square mile area. The critical question is whether the ecological impact of the otherwise identical human urban populations is the same across countries A and B.

There are good reasons to believe that the impacts would not be identical. Depending critically on the precise location of both cities and ecologically sensitive species, it seems likely that the impervious surface of the single urban area in A would destroy a smaller number of species located in unique, geographically small, ecological niches than the equivalent area of impervious surface distributed in smaller parcels in B, that happen to coincide with a larger number of those unique, geographically small, ecological niches. Yet, in fact, such location issues may be of empirically trivial importance given that both countries require identical amounts of food, water, and other resources to sustain their respective populations of humans. These life-sustaining resources are drawn from the entire country, not just the specific location in which the population is physically housed. Thus, in the absence of specialization and trade, use of fertilizers and pesticides to boost agricultural harvests will be identical in the two countries, with identical impacts on their respective species' ecological imperilment.

There can be no doubt that, at an on-the-ground level of analysis, specific location decisions are critical to species imperilment. Concrete poured at specific location X may destroy the last remaining population of a rare flower but have a negligible ecological impact if poured at specific location Y. But questions about the site-specific impact of humans on species imperilment are fundamentally different than questions about whether, *in the aggregate*, the number of ecologically imperiled species is influenced by the size-distribution of a fixed population of humans. Exactly where that existing population is physically located may indeed have ecological implications; however, these site-specific implications are quite separable, in theory, from the ecological implications of different size-distributions of the human population.

A significant intellectual foundation for the belief that the structural configuration of a fixed-size population has ecological implications was provided by Liu et al. (2003) and Keilman (2003). They argue that the intensity of resource use, and thus the aggregate environmental impact, is greater when a fixed population of human beings is distributed in smaller households than in larger households. There may be spatial implications of alternative household dynamics, but this need not necessarily be the case. Two or more households can occupy the same space as a single household—e.g., a residential house that is re-made into separate apartments. Consequently, analysis of different household dynamics is not the same as analysis of different spatial distributions of a fixed population of humans.

Employing a cross-sectional analysis of the 49 continental states in the U.S., Brown and Laband (2006) investigated whether the structural organization of humans has an empirically significant *aggregate* impact, defined in terms of the ecological imperilment of plant and animal species. They constructed Gini coefficient measures of inequality in the concentration of human population in each state, using 4 indicators: (1) population, (2) the number of households, (3) night-time light distribution, and (4) distribution of roads. They failed to find evidence of a relationship between the distribution of human activity and the distribution of the number of ecologically threatened species (using NatureServe listings of species in each state that are at-risk of extinction). In this paper, we extend the Brown and Laband line of empirical inquiry by analyzing the relationship between the concentration of human populations and species imperilment in 161 countries.

Methods and data

The number of ecologically threatened species in a given country is modeled as depending on existing species richness (the number of different species), the level of endemism (number of species found only within that area and nowhere else), and the level and spatial distribution of human activity. A general functional form is:

$$\begin{aligned}\#\ \text{Threatened Species} = f\ (&\text{Total}\ \#\ \text{Species},\ \#\ \text{Endemic Species},\\ &\text{Level of Human Activity},\\ &\text{Concentration of Human Activity}).\end{aligned} \quad (1)$$

To avoid a dominant (explanatory) variable problem with total # species, we convert # threatened species and # endemic species to percentage form by dividing each by the total # species, yielding:

$$\begin{aligned}\text{Percent Threatened Species} = f\ (&\text{Percent Endemics, Level of Human Activity},\\ &\text{Concentration of Human Activity}).\end{aligned} \quad (2)$$

The percentage of threatened species in a country is expected to increase as the percentage of endemic species increases (Brown and Laband 2006; McPherson and Nieswiadomy 2005). For a given rate of naturally-occurring extinctions at a specific point in time, the number of ecologically threatened species in a given geographic area will be greater in areas characterized by relatively large numbers of species than in areas that do not support much biodiversity. Further, by virtue of having wider ranges of moisture, temperature, and geophysical attributes, some countries have greater numbers of unique ecological niches than others, which support plant and animal species found nowhere else. By definition, these endemic species are more likely than species with wider ranges of habitat to be characterized by low populations.

The percentage of threatened species is also expected to increase as the level of human presence/activity increases (McKinney 2001, 2002). We kill/harvest/consume other species directly to meet human consumptive needs. Sheer population pressures held constant, the type and extent of human activities clearly affect plant and animal populations indirectly through alteration of habitat (Kerr and Currie 1995). The nature/extent of these activities reflects man's economic well-being and the exact relationship between man's economic well-being and the impact on species imperilment is an empirical matter.

The theoretical link between the economic well-being of humans and environmental degradation runs as follows: desperately poor people are willing to accept increased environmental degradation as a necessary by-product of generating an improved material standard of living. As individuals' standard of living improves, they are able increasingly to turn their attention away from exploiting the natural environment for food, shelter, and other necessities of life, and toward appreciation of the wonders of nature. That is, other species become valuable to humans not only because they can be used to improve man's well-being (in terms of providing food, shelter, medicines, etc.), but because their *existence* becomes important to us. In terms of empirical application, this implies an inverted U-shaped relationship between measures of economic well-being, such as per capita income, and measures of environmental degradation—the so-called Environmental Kuznets Curve (EKC).

Employing cross-sectional analysis and typically focusing on specific pollutants, a number of researchers have found empirical evidence that is consistent with the

EKC (Cropper and Griffiths 1994; Grossman and Krueger 1995; Hettige et al. 1992; Hilton and Levinson 1998; List and Gallet 1999; Seldon and Song 1994). However, these findings and the interpretations drawn from them have been criticized on the grounds that perhaps the reason that richer countries experience diminishing levels of environmental degradation is that they 'export' their environmental harm to other, poorer countries (Stern et al. 1996; de Bruyn et al. 1998; Arrow et al. 1995; Rothman 1998; Suri and Chapman 1998). A recent study looking at imperilment of birds and mammals across 113 countries in 2000 found evidence of an inverted U-shaped EKC (McPherson and Nieswiadomy 2005).

As the previous quotations make clear, advocates of the principle of Compact Building Design argue that *in the aggregate* the environment is harmed less by a concentrated human population than a dispersed human population. Thus, the predicted relationship between the percent of threatened species and the concentration of human activity is negative—i.e., the percentage of threatened species decreases with increasing concentration of human presence/activity, and vice-versa.

Our regression model also included two additional explanatory variables thought to be related to species imperilment: the extent of protected area within each country and whether or not the country is an island. Protected areas exist, in part, to safeguard threatened species by sharply curtailing the activities and depredations of man. But the empirical relationship between the extent of a country's area that is set aside in protected zones and the percent of species that are ecologically threatened is ambiguous—do protected areas lead to reduced numbers of endangered species or do protected areas exist precisely because so many species are imperiled?

It is well-known that, in terms of species imperilment, island nations differ significantly from mainland nations (Czech et al. 2000). Endemism is higher on islands and because escape is virtually impossible, island-specific flora and fauna are particularly sensitive to the introduction of invasive species, such as *Rattus rattus*.

Country-specific data on species by taxa (total species, threatened/imperiled species, and endemic species) for 2004 and the percent of protected area in each country were taken from the World Resources Institute EarthTrends Environmental Portal (http://earthtrends.wri.org/searchable_db) and from the World Conservation Union (IUCN). The IUCN publishes a Red List that identifies species facing a relatively high risk of global extinction (i.e. those listed as Critically Endangered, Endangered or Vulnerable). Human population data was obtained from the United Nations Population Division (http://www.un.org/esa/population). Data on per capita gross domestic product (GDP) at purchasing power parity were taken from the International Monetary Fund's World Economic Outlook database (http://www.imf.org/external/pubs/ft/weo/2004/01/data/index.htm). We used a Gini Coefficient measure of concentration of the human population in each country (Klein 2002), with index values ranging from 0 (a uniformly dispersed population) to 1 (all population congregated at a single location). The index was computed by superimposing a world political map on a LandScan 2002 map (http://www.ornl.gov/gist/landscan/index.html) to create a gridded population distribution map for each country, based on census count distributions to cells determined by proximity to roads, land cover, slope, and night time lights, then aggregating across cells within a country (Environmental System Research Institute 2002; Damgaared and Weiner 2000; Dixon et al. 1987).

We estimated the following reduced form model for taxa-level data on mammals, birds, reptiles, amphibians, and vascular plants:

$$\begin{aligned}\text{PTS} &= \beta_0 + \beta_1\ \text{PES} + \beta_2\ \text{POPDEN} + \beta_3\ \text{GCPOP} + \beta_4\ \text{PCGDP} \\ &\quad + \beta_5\ \text{PCGDP}^2 + \beta_6\ \text{PPA} + \beta_7\ \text{ISLAND} + \varepsilon,\end{aligned} \tag{3}$$

where for each country, PTS = % of species at risk of extinction, PES = % endemic species, POPDEN = population density (thousand person per sq. kilometer), GCPOP = Gini Coefficient Index for population concentration, PCGDP = per capita gross domestic product at purchasing power parity (constant US $), PPA = % protected area, ISLAND = a dummy variable (1 = island, 0 = mainland), and ε = the error term. We estimated our model using the SAS Robust Regression weighted least squares technique.

Results

Sample statistics for our data are reported in Table 1. Actual GC values ranged from 0.5898 to 0.9986. Singapore (0.5898), Togo (0.6515), and Rwanda (0.6529) have the most dispersed human populations; with large tracts of largely uninhabited land, Mongolia (0.9986), Australia (0.9981), and Canada (0.9975) have the most concentrated human populations.[1]

With the exception of reptiles, our regression results (Table 2) indicate consistently that the percent of endemic species (PES) in a country is a strong, positive predictor of species' ecological imperilment at the taxa level. Endemic species are defined by unique ecological niches that they exploit. For the most part, these species are characterized by relatively small populations. Since ecological imperilment for a species is defined, in part, by a low population, a relatively large percentage of endemic species almost certainly will mean a relatively large percentage of ecologically imperiled species. The absolute level of human presence/activity in a country, defined in terms of population density, is a significant, positive predictor of ecological fragility among mammals and birds. We find evidence of an Environmental Kuznets Curve relationship between a country's economic well-being, defined in terms of per capita GDP, and species imperilment for birds and mammals, but not for reptiles, amphibians, and vascular plants. This is consistent with the findings of McPherson and Nieswiadomy (2005).

Of critical importance to our analysis, we find a statistically significant relationship between species' ecological imperilment and our Gini coefficient measure of human spatial concentration among birds, reptiles, and amphibians. However, the observed relationship (positive) and the predicted relationship (negative) are completely at odds in 2 of the 3 cases. The explicit foundation for the SmartGrowth principle of Compact Building Design is that as a larger proportion of a fixed-size human population is concentrated in fewer locations, there are fewer ecological harms visited by that human population on the environment, in the aggregate. While this presumed relationship does indeed appear to characterize amphibians, we find

[1] It may seem odd that the island nation of Singapore, where everyone lives in the city, has the most dispersed human population. However, remember that our measure is based on the distribution of population counts across equal-size area-cells. Singapore's human population as a whole may be located in a single city, but across cells in the city that population is distributed more evenly than is the human population in countries with greater land area, where certain parts are very thinly populated while others are densely populated by humans.

Table 1 Descriptive statistics for percent threatened species and covariates

Variable		Vascular plants	Mammals	Reptiles	Amphibians	Birds
pfs	Mean	1.120	9.817	4.718	12.560	3.373
	SD	2.458	6.117	5.677	18.937	2.722
	Min.	0.000	0.000	0.000	0.000	0.000
	Max.	18.000	40.000	36.364	97.872	21.083
pes	Mean	13.434	4.516	10.870	16.533	3.462
	SD	18.880	9.342	16.726	24.275	7.654
	Min.	0.000	0.000	0.000	0.000	0.000
	Max.	89.998	61.818	90.741	91.667	45.476
popd	Mean	178.218	156.777	156.777	158.575	156.777
	SD	671.629	567.318	567.318	574.351	567.318
	Min.	1.679	1.679	1.679	1.679	1.679
	Max.	6959.677	6959.677	6959.677	6959.677	6959.677
gcpop	Mean	0.870	0.877	0.877	0.876	0.877
	SD	0.097	0.096	0.096	0.095	0.096
	Min.	0.590	0.590	0.590	0.590	0.590
	Max.	0.999	0.999	0.999	0.999	0.999
pcgdp	Mean	9996.586	10088.633	10088.633	9811.659	10088.633
	SD	10103.762	10515.950	10515.950	10360.910	10515.950
	Min.	591.945	591.945	591.945	591.945	591.945
	Max.	39535.159	61596.874	61596.874	61596.874	61596.874
ppa	Mean	8.065	7.329	7.329	7.335	7.329
	SD	7.895	7.219	7.219	7.141	7.219
	Min.	0.000	0.000	0.000	0.000	0.000
	Max.	34.200	34.200	34.200	34.200	34.200
Island	Mean	0.245	0.199	0.199	0.191	0.199
	SD	0.432	0.400	0.400	0.394	0.400
	Min.	0.000	0.000	0.000	0.000	0.000
	Max.	1.000	1.000	1.000	1.000	1.000
N		110	161	161	157	161

that the observed relationship between species' ecological imperilment and concentration of human activity is *positive*, not negative, among birds and reptiles. This means that concentrating the human population in cities is associated with more, not fewer, ecologically imperiled species across these two taxa, a finding completely at odds with the expressed claims on various SmartGrowth websites. We find no statistically significant relationship between geographic concentration of the human population and ecological imperilment among mammals and vascular plants.

We also observe that, excepting the reptiles, there appears to be no relationship between species imperilment and the percentage of land set aside as protected areas. There is a mildly significant, negative relationship between the percent of protected area in a country and species imperilment among reptiles.

Finally, our results are mixed with respect to the ecological imperilment of species found on islands. As expected, we find that island-based mammal species are more imperiled than continent-based mammals. However, island-based bird species are less imperiled than continent-based bird species and we find no evidence of a statistically significant impact of island on the other 2 taxa groups. We do not have a ready explanation of this latter finding, which contradicts the record of extinctions—higher

Table 2 Regression results for % threatened species in each country

Explanatory variable		Vascular plants	Mammals	Reptiles	Amphibians	Birds
Constant	B	0.5102	2.0177	–2.6812	17.1319***	–1.3401
	SE	(0.4254)	(2.9996)	(2.4392)	(5.6015)	(1.0401)
pes	β	0.0099***	0.2700***	0.0233	0.4699***	0.5103***
	SE	(0.0024)	(0.0363)	(0.0186)	(0.0306)	(0.0283)
popd	β	0.0539	9.6174***	0.2817	–1.4955	2.0258***
	SE	(0.2788)	(2.4594)	(0.4730)	(1.0500)	(0.6700)
Gcpop	β	–0.1204	5.4385	6.9997**	–17.3127***	3.3676***
	SE	(0.5023)	(3.5434)	(2.8659)	(6.5904)	(1.2181)
Pcgdp	β	–0.0286*	0.1630	0.0230	0.1511	0.1144***
	SE	(0.0146)	(0.1144)	(0.0630)	(0.1442)	(0.0393)
$pcgdp^2$	β	0.0006	–0.0060*	–0.0012	–0.0051	–0.0029**
	SE	(0.0004)	(0.0034)	(0.0015)	(0.0033)	(0.0011)
ppa	β	0.0019	–0.0344	–0.0656*	0.0344	–0.0226
	SE	(0.0048)	(0.0430)	(0.0361)	(0.0859)	(0.0147)
island	β	0.0545	1.9409*	1.1754	0.5263	–1.4570***
	SE	(0.1076)	(1.0046)	(0.8506)	(1.8167)	(0.3573)
N		110	161	161	157	161
R^2		0.2679	0.3488	0.2384	0.5360	0.5764

***, **, * denotes significance at the 0.01, 0.05, and 0.10 level, respectively

for island-based birds than continent-based birds. Of course, this differential record of extinction may imply that the island-based bird species still living (thus included in our sample) likely are not imperiled.

Discussion

While it is possible that deliberate clustering of humans in high-density urban areas is preferable, from an ecological standpoint, to a more dispersed human population, the only anecdotal evidence we have suggests just the opposite—the last century of dramatically increased urbanization almost everywhere in the world is associated with significant global environmental degradation. But this also has occurred during a period of rapid population growth, so separating association from causation is problematic. People who live in cities need to be fed, which implies a significant agricultural effort that likely distresses natural systems. The materials that are used to build and maintain the cities require significant extractive industries and power generation. These activities also are associated with environmental degradation. So it is not at all clear whether accidental or deliberate configuration of the human population into densely populated urban areas actually will provide significant environmental benefits.

Our empirical findings cast doubt on the presumption that environmental impacts are minimized when human presence/activity is spatially concentrated. While it may be that localized observations on specific pollutant loadings seem consistent with this presumption, at a more encompassing scale and measure, reflected in species imperilment, we find mixed evidence. Although concentration in the human population may, at a broad scale, reduce ecological stresses on amphibians, they appear to have no effect on mammals or vascular plants and may actually increase ecological stresses on birds and reptiles.

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