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Hypsographic demography: The distribution of human population by altitude

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ABSTRACT **The global distribution of the human population by elevation is quantified here. As of 1994, an estimated 1.88×10^9 people, or 33.5% of the world's population, lived within 100 vertical meters of sea level, but only 15.6% of all inhabited land lies below 100 m elevation. The median person lived at an elevation of 194 m above sea level. Numbers of people decreased faster than exponentially with increasing elevation. The integrated population density (IPD, the number of people divided by the land area) within 100 vertical meters of sea level was significantly larger than that of any other range of elevations and represented far more people. A significant percentage of the low-elevation population lived at moderate population densities rather than at the highest densities of central large cities. Assessments of coastal hazards that focus only on large cities may substantially underestimate the number of people who could be affected.**

Altitude affects geophysical hazards for humans (1–3). The location of 11 of the world's 15 cities with more than 10 million people (4) (Tokyo, New York, Bombay, Shanghai, Los Angeles, Calcutta, Buenos Aires, Seoul, Lagos, Osaka, and Rio de Janeiro) suggests that much of the population lives at low elevations near coastlines. These people and those in low-lying drainage basins could be directly affected by sea-level rise, storm surges, climatic changes in precipitation, and flooding. Local and regional studies of coastal hazards (5–11) provide detailed analyses in many high-risk areas but do not provide a systematic global view of the spatial distribution of human population in relation to continental hypsography (that is, the distribution of land area by elevation). Global analysis enhances the value of local studies by developing a global picture to which they can be compared.

Altitude also affects biological hazards for humans, including infectious diseases such as malaria (12), filariasis (12), Lyme disease (13), encephalitis (13), visceral leishmaniasis (14), and toxoplasmosis (15). Altitude affects human reproductive physiology and birthweight (16), exposure to cosmic radiation (17), other physiological functions (18, 19), and agricultural production (20, 21). In Western medicine, altitude was recognized as a significant factor in human health by the 1730s and 1740s (22, 23).

The balance of benefits and hazards for human populations located at different altitudes depends on physical, biological, economic, and historical factors. For example, altitude correlates positively with income in census tracts of New England cities (24). Understanding the distribution of human population with respect to altitude is a first step toward understanding the balance of benefits and hazards.

We integrated global data on the geographical distribution of the human population with digital elevation models of the continents. The resulting moderate-resolution digital map gives the estimated human population in 1994 and the elevation with respect to sea level. This global data fusion has a number of applications. We focus here on the joint distribution of population and elevation.

DATA AND METHODS

The human population distribution (25) was based on censuses from 217 countries partitioned into a total of 19,032 secondary administrative subdivisions (corresponding to counties in the United States). The census years ranged from 1979 to 1994. Tobler *et al.* (25) estimated the 1994 populations of these 19,032 polygons by projecting from the census years to 1994. All subdivisions in each country were assumed to change exponentially at the same rate. The total 1994 population estimated in this way was 5,617,519,139 people. The uncertainty of this estimate probably exceeds 2%, based on the uncertainty of censuses in developed countries. For comparison, exponential interpolation between world population estimates for 1990 and 1996 (26, 27) gave 5.60×10^9 people. The 19,032 polygons totaled 132,306,314 km^2, 25.9% of the world's surface area (approximately 5.096×10^8 km^2) and 99.5% of ice-free land (approximately 1.33×10^8 km^2, ref. 28). The average population density of occupied land in these data is 42.45 people/km^2.

The average polygon area is about 6,950 km^2 and the average number of people per polygon is about 295,000. Assuming a uniform (or flat) distribution of population within each polygon, Tobler *et al.* (25) used these data as the basis for a mass-conserving spatial redistribution to produce unsmoothed gridded population estimates [http://www.ciesin.org/datasets/gpw/globldem.doc.html] of 2,003,971 quadrangles 5′ on each side with a population density greater than one person per 147 km^2 (0.007 people/km^2). The errors introduced by the assumption of a uniform population density within each polygon are distributed unequally over space, depending on the local spatial resolution and quality of census data. (We did not use the smoothed population estimates of Tobler *et al.*) Some low lands in the Canadian arctic were not included in these quadrangles. The total number of people in the unsmoothed gridded model was 5,622,166,374, larger than the total population calculated from the original 19,032 points by 0.083%. This discrepancy is believed to result from the gridding procedure (W. Tobler and U. Deichmann, personal communications) but is significantly smaller than the expected error in the original population estimates. The occupied quadrangles totaled 129,674,365 km^2, 25.4% of the world's surface area and 97.5% of ice-free land.

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Abbreviations: HAD, Human Altitude Density bivariate histogram; IPD, integrated population density; LAD, Land Area Density bivariate histogram; N, north; S, south.

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Continental hypsography was derived from global, 30 arc sec (30″) gridded elevations provided by the EROS (Earth Resources Observation Systems) Data Center, Sioux Falls, South Dakota [http://edcwww.cr.usgs.gov/landdaac/landdaac.html]. The 30″ elevation model was derived from Defense Mapping Agency digital terrain elevation data Level 1 (3″) gridded topography as well as from data from several other international mapping agencies (including those of Japan, Mexico, and New Zealand). The gridded topography covered North and South America, Africa, Europe, Asia, Australia, Oceania, Greenland, and Antarctica (29, 30).

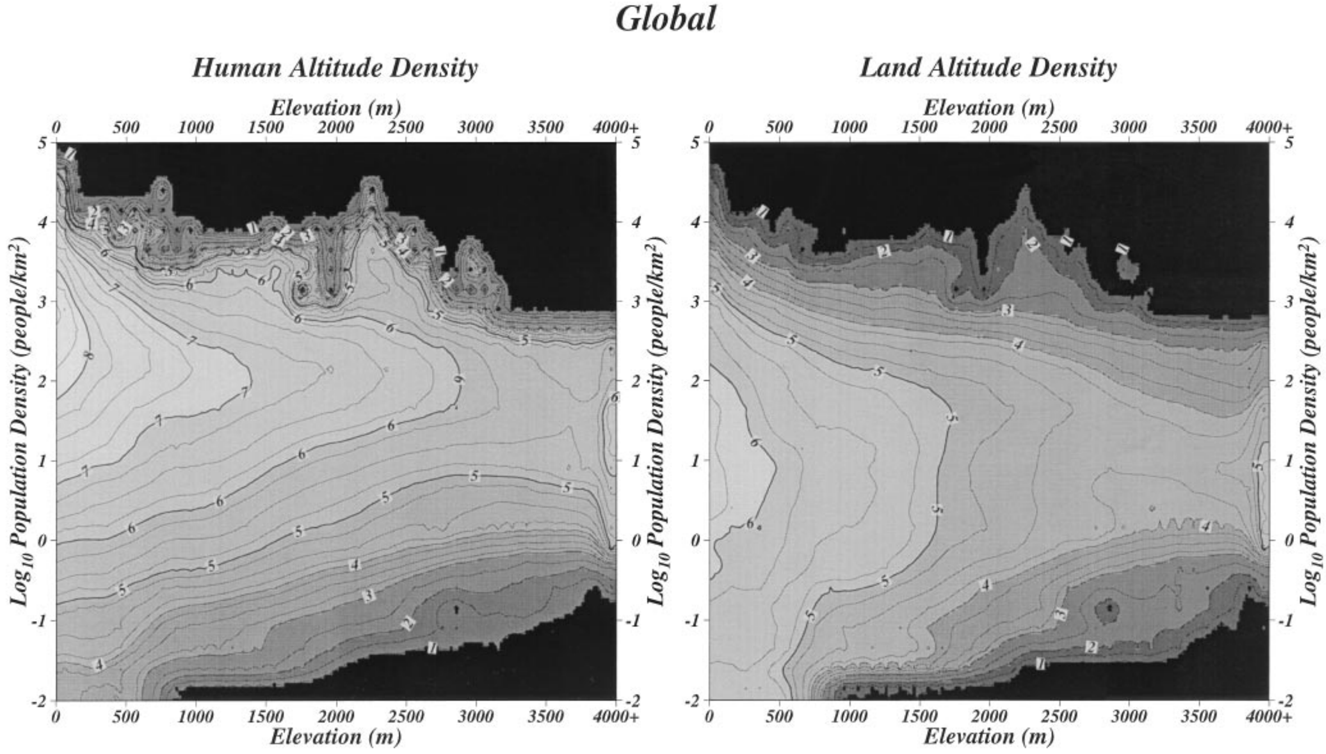
We coregistered the demographic and hypsographic data by calculating the median of the 30″ elevations within each 5′ quadrangle (9.3 km square at the equator, 9.3 km by 6.6 km at latitude 45°) for which a population estimate was available. We also estimated population density for each quadrangle but did not account for differences in the fractional land area of quadrangles on coastlines; in these areas, population densities are minimum estimates.

We summarized the relationship between Earth's human population and its occupied land area by means of two empirical bivariate frequency distributions (two-dimensional histograms), one for absolute population (numbers of persons) and one for occupied land area, as functions of population density and elevation (Fig. 1). Because population density varied over at least seven orders of magnitude, we worked with $\log_{10}$(population density) in our figures, though not in our tables. The empirical bivariate density function of global human population as a function of population density and elevation (Fig. 1 *Left*), which we call the Human Altitude Density (HAD), describes how many people live at each possible combination of population density and elevation. The empirical bivariate density function of occupied land area as a function of population density and elevation (Fig. 1 *Right*), which we call the Land Altitude Density (LAD), describes how much occupied land Earth has at each combination of population density and elevation. Figs. 1–3 give detail on elevations between sea level and 4,000 m above sea level, and on population densities between 0.01 and 100,000 people/km^2. Values outside these ranges (e.g., for quadrangles below sea level or above 4,000 m elevation or with >100,000 people/km^2) are accumulated in the peripheral bins of the histograms and are included in summary statistics in Table 1.

We also analyzed the joint distributions of population, land area, and IPD (total population divided by total land area) in each of four latitudinal zones and three elevational zones, using the ungridded 19,032 polygons. The four latitudinal zones are as follows: southern (S) temperate (72°S ≤ latitude < 23.45°S), S tropical (23.45°S ≤ latitude < 0°), northern (N) tropical (0° ≤ latitude ≤ 23.45°N), and N temperate (23.45°N < latitude ≤ 72°N). This range of latitudes excludes five polygons in Greenland with total area of 60,380 km^2 and total population of 10,255. The three elevational zones are as follows: low (elevation ≤500 m), medium (500 m < elevation ≤ 1,500 m), and high (elevation >1,500 m). We chose these zones because we observed that IPDs are lower in the range 500–1,500 m elevation than at either higher or lower elevations (Fig. 3).

RESULTS

Global human population is heavily localized at low elevations (Fig. 1 *Left*). Both the highest and lowest population densities in these data occur at elevations <100 m. Most humans live at


Global

Human Altitude Density

Land Altitude Density

FIG. 1. (*Left*) Joint distribution of human population by elevation and population density, or Human Altitude Density (HAD), as a contour map. Contour lines show $\log_{10}$(people). Example: the contour curve on the left that is labeled 8 passes through combinations of elevation and population density where about 10^8 people live. Horizontal bin size is linear in elevation with a linear increment of 100 m, and vertical bin size is linear in $\log_{10}$(people/km^2), with each bin covering a constant factor of $10^{0.25}$ (= 1.78) in population density. Thus 4 vertical bins span a 10-fold increase in population density. (*Right*) Joint distribution of land area by elevation and population density, or Land Altitude Density (LAD), as a contour map. Contour lines show $\log_{10}$(land area (in km^2)). For example, there are about 10^6 km^2 of occupied land at each combination of elevation and population density through which the contour curve on the left that is labeled 6 passes. In both distributions, the values falling outside the bounds of the histogram are accumulated in the peripheral bins.

Table 1. Summary statistics for the distributions of humans and of land area

	Distribution of humans		Distribution of land area	
	m	People/km^2	m	People/km^2
Maximum	5,516	79,407	5,516	79,407
Upper quartile	523	648	846	24.5
Median	194	262	408	4.3
Lower quartile	59	90	161	0.8
Minimum	−79	0.007	−79	0.007
Mean	435	967	673	42
SD	630	3,385	826	198
Correlation between elevation and population density	−0.061		−0.062	

Distributions are by elevation (m) and by population density (people/km^2), based on 19,032 administrative subdivisions with elevations interpolated from the EROS digital elevation model. Example: 75% of people lived at or below 523 m elevation and at or below a population density of 648 people/km^2; 75% of occupied land area occurred at or below 846 m elevation and at or below a population density of 24.5 people/km^2.

densities between 1 and 10,000 people/km^2 with a persistent modal density of 100–200 people/km^2 at elevations >300 m. As elevation decreases below 300 m, the modal population density increases rapidly to >500 people/km^2 below 100 m above sea level. The distribution of $\log_{10}$(people/km^2) is asymmetric at all elevations, with modal densities consistently displaced toward high values. While there is a gradual increase in the minimum population density (for a given elevation) with increasing elevation, the maximum population density decreases very rapidly with increasing elevation in the lowest 300 m and fluctuates widely at higher elevations. The prominent spur of high population density (>1,000 people/km^2 around 2,300 m elevation) reflects the heavily populated Mexican plateau. The population at elevations >4,000 m represents primarily Andean and Tibetan populations.

The global distribution of land (Fig. 1 *Right*) qualitatively resembles that of people. However, most land area is occupied at a modal population density around 10 people/km^2 at all elevations, even though most people live at a modal density of ≈100 people/km^2 at almost all elevations. The median person lives at a population density of 262 people/km^2, although the median km^2 of populated land is occupied at a population density of 4.3 people/km^2. Because density is inversely proportional to area for a given population, the center of mass of the HAD occurs at a higher population density than that of the LAD. More people than land experience high population density in crowded regions. Similarly, the median km^2 of populated land occurs at 408 m elevation, well above the 194 m elevation of the median person. The center of mass of the LAD occurs at a higher elevation than that of the HAD because the higher elevations are, on the whole, thinly populated, and more land than people experiences low population density.

Marginal distributions of both population and occupied land area as functions of elevation and population density can be

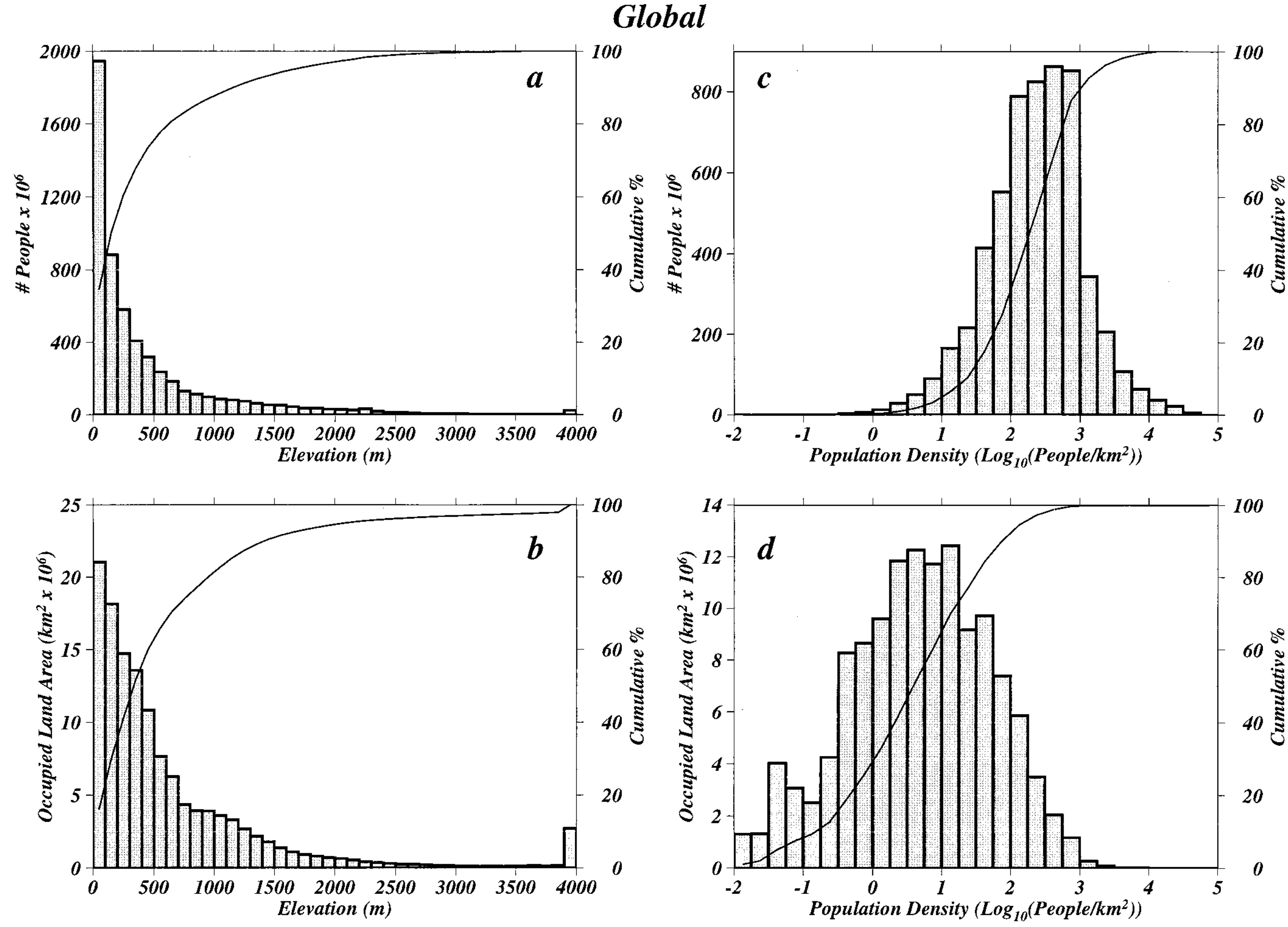


FIG. 2. Marginal frequency histograms (filled bars, left ordinates) and cumulative distributions (solid curves, right ordinates) of number of people by elevation (*a*); occupied land area by elevation (*b*); number of people by population density (*c*); and occupied land area by population density (*d*). Derived from Fig. 1.

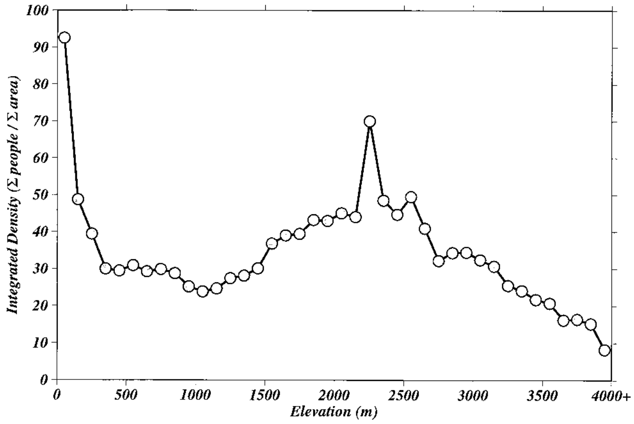


FIG. 3. IPD (summed people divided by summed km^2) by elevation.

derived from the HAD and LAD (Fig. 2). Approximately 55% of the world's population lives at densities of 100−1,000 people/km^2 (Fig. 2*c*). The number of people diminishes gradually as population density decreases below 100 people/km^2 and drops rapidly as population density increases above 1,000 people/km^2.

Approximately 1.88 × 10^9 people, or 33.5% of world population, live within 100 vertical meters of sea level (Fig. 2*a*). Only 15.6% of all occupied land lies below 100 m elevation. Occupied land below 100 m elevation contains a disproportionate percentage of the world's population compared with other elevations. Kopec (3) estimated that 17% of all land (not limited to occupied land) lies below 100 m elevation. On the basis of very rough estimates, he suggested that "somewhere around" 19.2% of people might live below 100 m elevation. Our population estimate may be regarded as an improvement.

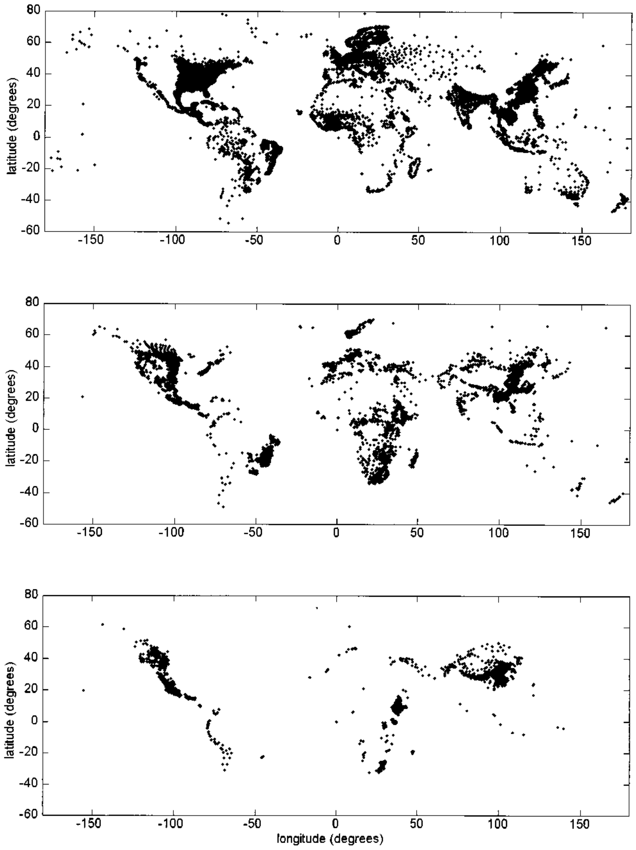


FIG. 4. Location of land at elevations ≤500 m (*Top*), >500 m and ≤1,500 m (*Middle*), and >1,500 m (*Bottom*), shown by the centroids of the 19,032 polygons in each elevational zone.

Globally, as elevation drops from 800 m toward sea level, the number of inhabitants increases faster than linearly (Fig. 2*a*), while the occupied (and total) continental land area (Fig. 2*b*) increases almost linearly. Consequently, average population density gradually increases with decreasing elevation below 800 m, with an abrupt increase in average density below 100 m.

The number of people at each elevation (taken from Fig. 2*a*) divided by the occupied land area at each elevation (taken from Fig. 2*b*) gives the IPD at each elevation (Fig. 3). The IPD of land below 100 m elevation is significantly larger than that of any other elevation range and represents far more people. The broad bulge centered around 2,300 m elevation arises primarily from the Mexican plateau and the south-central Asian highlands. The IPD at elevations around 2,300 m exceeds that at 200–300 m and approaches that below 100 m. However, the number of people who live at 2,000–2,500 m is small (1.3 × 10^8) compared with the number of people living below 500 m elevation (4.4 × 10^9).

We now summarize the distribution by latitude of land and people at different elevations (Fig. 4). The N high tropics are most densely settled (76 people/km^2), followed closely by the N temperate low zone (70 people/km^2) and the N tropical low zone (64 people/km^2) (Table 2). At every elevation, the S temperate zone is the least densely settled. At medium and high elevations, the N tropics are more densely settled than the latitudinal zone on either side, and are much more densely settled in the highest zone.

The middle elevations at 500–1,500 m are less densely settled than lower and higher elevations, when all latitudes are combined as well as in the N and S tropics considered separately. But in the N temperate zone, population density declines with increasing elevation, whereas in the S temperate zone, population density increases with increasing elevation.

DISCUSSION

This study suggests that most of the world's population at low elevations lives at moderate population densities rather than at the high densities characteristic of central large cities. However, the unsmoothed gridded population model assumes a uniform distribution within each secondary administrative subdivision. If a subdivision has high population density in some places and low population density in others, the extremes will average out. The unsmoothed gridded model therefore provides minimum estimates of maximal local population density within each administrative subdivision, and our conclusion is subject to revision when population data with finer spatial resolution are available.

If our conclusion is correct, then estimates of the impact of low-elevation hazards should consider that a significant number of low-elevation residents may not live in central cities. The land in the lowest 100 m is primarily coastal plain but also includes some low-elevation drainage basins that extend significant distances inland. These results reflect a tendency to settle low-lying peneplains that facilitate agriculture, transportation, and trade in many regions.

The high population density in the N high tropics could reflect a long-time avoidance of vector-borne diseases such as malaria that are mainly transmitted at lower elevations, or it could reflect more recent rapid population growth in these relatively poor regions. In some tropical areas, elevated volcanic terrain provides both climatic advantages and fertile soils and supports dense agrarian populations (e.g., in Mexico, Central America, Indonesia, Philippines, Ethiopia, Kenya, and Tanzania). More generally, active tectonics may generate landscapes favorable for humans by creating potentially fertile sedimentary basins surrounded by mountain barriers (31).

Table 2. Population, land area, and population density in each combination of latitudinal and elevational zones, and marginal distributions

	S temperate	S tropical	N tropical	N temperate	All latitudes
Population, 10^9					
$\leq$500 m elevation	0.0853	0.2943	1.0684	2.6921	4.1400
>500 m, $\leq$1500 m	0.0463	0.1591	0.2728	0.6098	1.0881
>1500 m	0.0123	0.0627	0.1364	0.1780	0.3894
All elevations	0.1439	0.5161	1.4777	3.4799	5.6175
Area, km^2					
$\leq$500 m elevation	6,966,040	14,025,518	16,463,223	38,256,874	75,711,655
>500 m, $\leq$1500 m	3,500,417	8,283,784	7,463,315	24,709,168	43,956,684
>1500 m	605,930	1,819,037	1,792,296	8,360,332	12,577,595
All elevations	11,072,387	24,128,339	25,718,834	71,326,374	132,245,934
Density, people/km^2					
$\leq$500 m elevation	12.2451	20.9832	64.8962	70.3691	54.6811
>500 m, $\leq$1500 m	13.2270	19.2062	36.5521	24.6791	24.7539
>1500 m	20.2994	34.4688	76.1035	21.2910	30.9598
All elevations	12.9963	21.3898	57.4559	48.7884	42.4777

Example: 1.07×10^9 people live on 16.5×10^6 km^2 of land at elevations $\leq$500 m in N tropical latitudes, with an average population density of 65 people/km^2.

Historical time series of global population maps would make it possible to distinguish early from modern origins of dense populations in the high-altitude tropics.

A simple null model of population distribution would suppose hypothetically that people's latitude and people's elevation are determined independently. For example, since the fraction 0.7370 (= 4.1400/5.6175) of all people live at $\leq$500 m elevation, and the fraction 0.2631 (= 1.4777/5.6175) of all people live in the N tropics, the fraction of all people expected to live in the N low tropics would be $0.7370 \times 0.2631 = 0.1939$, and the expected number of people living the N low tropics would be $0.1939 \times 5.6175 \times 10^9 = 1.0892 \times 10^9$. In fact (Table 2), 1.0684×10^9 people live in the N low tropics. In this case, the discrepancy between the null model and the observation is minimal. On the other hand, for the N temperate low zone, the expected number of people would be 2.5646×10^9 if latitude and elevation were independent, but the observed number is 2.6921×10^9. In this case, the observed discrepancy (1.275×10^8 people) is substantial. More people live at N temperate low elevations, and fewer at N temperate medium and high elevations, than expected from this null model. In the tropics, the deficits, relative to expectation, are largely reversed.

Using the same null model applied to land area rather than numbers of people shows (not surprisingly) that the land area at different elevations is not distributed independently of latitude. The N temperate zone has less land at low elevation, and more land at medium and high elevations, than expected from the global marginal distributions of land by latitude and elevation. The geological features that account for these discrepancies from the null model are the large continental plateaux at temperate latitudes: the sutures between Asia and the Indian and Arabian plates (e.g., the Tibetan plateau, Caucasus, Hindu Kush, Zagros Mountains), the N and S American Cordillera, and the S African plateau. The N tropics have the reverse discrepancies. These discrepancies are associated with the enormous low Amazon basin and IndoAustralian Archipelago.

The combination of more people and less land (relative to expectations from these simple null models) contributes to a high population density, compared with the world average, in the N high tropics and in the N low temperate zone. The population and land area of the N high tropics are a relatively small fraction of the world totals, but the population of the N low temperate zone is 48% of the world total, so the discrepancies from the null model are important.

Future Work. Higher-resolution population data are now available for Asia [http://grid2.cr.usgs.gov/globalpop/asia/intro.html] and Africa [http://grid2.cr.usgs.gov/globalpop/africa/]. Future work should determine to what extent these more refined estimates would change our global estimates.

The joint distribution of population and elevation is a basic aspect of hypsographic demography. Other basic aspects include the joint distributions with elevation of mortality (e.g., expectation of life or infant mortality), fertility (net rate of reproduction or total fertility rate), and migration. Spatially referenced databases of these key demographic variables, and of most economic variables, are not yet available.

It would be useful to analyze proximity to coastlines (32), rural versus urban residence, climatic variables (rainfall, temperature, and humidity), soil types, social, political, and economic characteristics, and nonhuman biotic characteristics (33–36). Historical data would make it possible to examine whether population density was more highly correlated with variables conducive to agricultural production in the past than now, as a result of increasing global economic integration. Associations among geographic variables (such as being landlocked), rates of population growth, and rates of economic development in developing nations (37) provide hypotheses for further testing on a global scale with higher-resolution data.

Our systematic description of the human population in relation to elevation illustrates an approach that can be applied to spatially distributed natural hazards such as earthquakes, droughts, and floods. The approach also provides a quantitative basis for assessing the human impact of potential environmental changes such as sea-level rise, provided such analyses adequately incorporate the economic, cultural, political, and other environmental factors that vary from place to place (38, 39). Although a rich country might react defensively to sea-level rise by building seawalls, such a response would be suboptimal even from the rich country's perspective if the same sea-level rise induced tens or hundreds of millions of people to flee inundated lowlands in a poor country and to seek refuge in the rich country. In Japan, already an estimated 2 million people are reported to live below the tidal high-water mark, while small nations on low-lying Pacific islands face growing fears of inundation (40).

It remains to use the present snapshot of the spatial distribution of the human population as a basis for projections of the future. If time series of global population maps were available, it would be possible to test spatially explicit population projection models (41).

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