Global and country-level estimates of human population at high altitude

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Estimates of the global population of humans living at high altitude vary widely, and such data at the country level are unavailable. Herein, we use a geographic information system (GIS)-based approach to quantify human population at 500-m elevation intervals for each country. Based on georeferenced data for population (LandScan Global 2019) and elevation (Global Multiresolution Terrain Elevation Data), 500.3 million humans live at ≥1,500 m, 81.6 million at ≥2,500 m, and 14.4 million at ≥3,500 m. Ethiopia has the largest absolute population at ≥1,500 m and ≥2,500 m, while China has the greatest at ≥3,500 m. Lesotho has the greatest percentage of its population above 1,500 m, while Bolivia has the greatest at ≥2,500 m and ≥3,500 m. High altitude presents a myriad of environmental stresses that provoke physiological responses and adaptation, and consequently impact disease prevalence and severity. While the majority of high-altitude physiology research is based upon lowlanders from western, educated, industrialized, rich, and democratic countries ascending to high altitude, the global population distribution of high-altitude residents encourages an increased emphasis on understanding high-altitude physiology, adaptation, epidemiology, and public health in the ~500 million permanent high-altitude residents.

Results

Over 500 million humans live at ≥1,500 m (6.58% of the total population), 219 million at ≥2,000 m (2.88% of the total population), 81.6 million at ≥2,500 m (1.07% of the total population), 25.2 million at ≥3,000 m (0.33% of the total population), 14.4 million at ≥3,500 m (0.19% of the total population), 6.4 million at ≥4,000 m (0.084% of the total population), 2 million at ≥4,500 m (0.027% of the total population), and 0.31 million at ≥5,000 m (0.004% of the total population). Table 1 presents the standard and model atmosphere-calculated barometric pressure, partial pressure of inspired oxygen, and global populations at 500-m elevation intervals.

Discussion

We used georeferenced population and elevation data to estimate the global and country-level population of humans at high altitude. We estimate that 81.6 million humans live at ≥2,500 m, and that these humans are primarily from non-Western countries. This figure is considerably less than non-GIS-based estimates (8) and expands upon GIS-based estimates (2, 9, 10) by providing country-level estimates at 500-m elevation intervals. We present population for 500-m intervals to provide flexible interpretation of “high altitude,” as the threshold for high altitude to elicit a physiological response varies between individuals and populations. Research is encouraged in countries with considerable high-altitude populations, to understand how the environmental stress (physiological and social) of high altitude impacts physiology, adaptation, health, and disease.

Where Do Humans Live at High Altitude? Humans reside at high altitude in each continent; notably, the majority of humans at high altitude live in non-Western countries. As with medical research generally (11), high-altitude research has focused on the lowlander of European descent ascending to high altitude (12). Select permanent high-altitude populations have been studied, with considerable differences in physiological measures reported (1); however, the populations studied represent just a fraction of humans at high altitude. Among the studied populations, differences in candidate genetic variants that may be adaptive and
their phenotypic associations have been identified (1, 10). The distribution of where humans live at high altitude, presented herein, and their duration of high-altitude residence affords a broad natural experiment to better define the relationships between genotype and phenotype and provide insight into the evolutionary and mechanistic bases of physiological adaptation to high altitude. Further, an

| Altitude, m | Standard atmosphere* | Model atmosphere† |
|------------|----------------------|-------------------|
|            | Barometric pressure 5 ºC (mmHg) | Barometric pressure 20 ºC (mmHg) | P(O2) 5 ºC (% of sea level) | P(O2) 20 ºC (% of sea level) | Barometric pressure (mmHg) | P(O2) (mmHg) | P(O2) (% of sea level) | Population (millions) | % Population |
|            | >715 | >717 | >140 | >140 | >94 | >94 | >718 | >140 | >94 | 5,821.54 | 76.555 |
| 500 to 999 | 140 to 140 | 88 to 94 | 88 to 94 | 679 to 718 | 132 to 140 | 89 to 94 | 839.582 | 11.041 |
| 1,000 to 1,499 | 122 to 131 | 123 to 132 | 82 to 88 | 641 to 679 | 124 to 132 | 83 to 89 | 442.937 | 5.825 |
| 1,500 to 1,999 | 114 to 122 | 116 to 123 | 76 to 82 | 605 to 641 | 117 to 124 | 78 to 83 | 281.185 | 3.698 |
| 2,000 to 2,499 | 563 to 599 | 106 to 114 | 108 to 115 | 71 to 76 | 72 to 77 | 137.585 | 1.809 |
| 2,500 to 2,999 | 529 to 563 | 101 to 108 | 66 to 71 | 68 to 72 | 537 to 570 | 103 to 117 | 56.352 | 0.741 |
| 3,000 to 3,499 | 497 to 529 | 92 to 99 | 94 to 101 | 61 to 66 | 63 to 68 | 505 to 537 | 96 to 109 | 10.786 | 0.142 |
| 3,500 to 3,999 | 467 to 497 | 85 to 92 | 88 to 94 | 57 to 61 | 59 to 63 | 475 to 505 | 90 to 106 | 8.015 | 0.105 |
| 4,000 to 4,499 | 437 to 467 | 79 to 85 | 82 to 88 | 53 to 57 | 55 to 59 | 447 to 475 | 84 to 106 | 4.385 | 0.058 |
| 4,500 to 4,999 | 410 to 437 | 73 to 79 | 76 to 82 | 49 to 53 | 51 to 55 | 420 to 447 | 78 to 106 | 1.711 | 0.023 |
| ≥5,000 ≤3,500 | 396 to 410 | ≤3,500 | ≤3,500 | ≤3,500 | ≤3,500 | ≤3,500 | ≤3,500 | ≤3,500 | ≤3,500 | 0.313 | 0.004 |

Barometric pressure is also impacted by latitude (higher at the equator) and season. P(O2) = (barometric pressure − 47 mmHg) × 0.2093.

*Barometric pressure = 760 × [1 − 0.0065 × elevation in meters/(273.15 + temperature)]^{5.255}.
†Barometric pressure = exp(6.63268 − 0.1112 × elevation in kilometers − 0.00149 × elevation in square kilometers).
expanded understanding of the potential physiological differences arising from life at high altitude will lead to improvements in the diagnosis and treatment of disease, ultimately improving the health and well-being of high-altitude populations.

**Limitations.** Mobile, nomadic, or pastoralist populations and those with lowest income and most at risk are underrepresented in census data (13). Therefore, we have likely underestimated the most vulnerable populations and may have disproportionately undercounted rural high-altitude populations. The LandScan Global datasets are not recommended to be used as a change or migration tool, as the LandScan database is constantly improving its input data (14). Further, the LandScan dataset provides only a population count and not demographics (e.g., age, sex, ethnicity, etc.). Nevertheless, LandScan is the community standard for global population distribution.

**Materials and Methods**

Population estimates were calculated using QGIS 3.4.0-Madeira software. Population data were acquired from Oak Ridge National Laboratory’s LandScan Global 2019 dataset (14). LandScan provides an ambient population count for cells with a spatial resolution of 30 arc-seconds (~1 km²). LandScan uses the best available census counts to estimate population and applies a spatial distribution model that includes land cover, roads, slope, urban areas, village locations, and high-resolution imagery analysis. The mean elevation data from the Global Multi-resolution Terrain Elevation Data (GMTED2010) were also acquired at a resolution of 30 arc-seconds (~1 km²) (15). Country borders were acquired from the Database of Global Administrative Areas (GADM, version 3.6; https://gadm.org/download_country_v3.html). Further details on the methodology are provided in SI Appendix.

**Data Availability.** All study data are included in the article and Dataset S1.

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