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TAKING ADVANTAGE OF THE IMPROVED AVAILABILITY OF CENSUS DATA: A FIRST LOOK AT THE GRIDDED POPULATION OF THE WORLD, VERSION 4 (GPWv4)

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1. INTRODUCTION

The Gridded Population of the World (GPW) data set displays the global distribution (counts and densities) of the human population on a continuous surface. Since the release of the first version of this global population grid in 1995, the essential data inputs to GPW have been population census tables and cartography as these provide complete and exclusive geographic coverage of a country's population at a given point in time.

The GPW series, now in its fourth version (GPWv4), is a beneficial and valued asset for the research community. The third version of GPW has been extensively used in human and environmental problem-solving, including but not limited to vulnerability mapping (*e.g.*, Döll, 2009; Abson *et al.*, 2012), disaster impacts (*e.g.*, Badal *et al*., 2005; Guha-Sapir *et al*., 2011), and health dimensions of environmental change (*e.g.*, Ermert *et al*,. 2013; Caminade *et al.*, 2014).[1] GPWv4 has been updated using census data from the 2010 round of censuses and will be publicly available at http://sedac.ciesin.columbia.edu/ (Figure 1). The data presented here refer to the alpha version of the dataset.

This paper describes the methodology of GPW and the key highlights of GPWv4. It also discusses the challenges and opportunities associated with working with global census data and cartography.

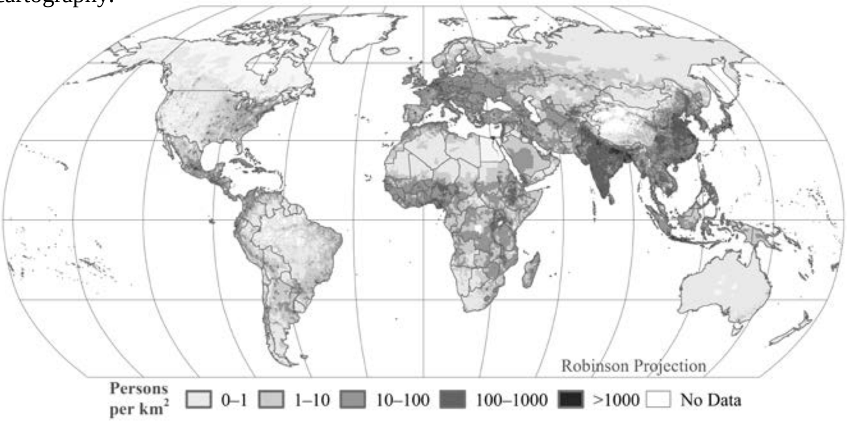

FIGURE 1
2010 POPULATION DENSITY ESTIMATES FROM GPWv4.
SOURCE: CIESIN, FORTHCOMING

2. METHOD

[1] For a complete list of GPWv3 citations, please see http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/citations.

2.1 OVERVIEW OF METHOD

The development of GPWv4 builds upon previous versions of the data set (Tobler *et al*., 1997; Deichmann *et al*., 2001; Balk *et al*., 2006). The two basic inputs to GPW are non-spatial population data (*i.e.*, tabular counts of population listed by administrative area) and spatially-explicit administrative boundary data. These were collected from hundreds of organizations, including national statistics offices (NSOs) and mapping or planning agencies. For GPWv4, population input data were collected at the highest resolution available from the results of the 2010 round of censuses, scheduled to occur between 2005 and 2014. Census data collected included cross-tabulated counts of total population by age (single- or five-year age groups), sex, and urban/rural status. Where census results were unavailable or not yet released, official population estimates from the NSO were used. These population counts or official estimates were then matched to digital geographic boundaries, ideally from census cartography. Matching was based on the common identifying codes or the unit names used in the census.

A global framework of international boundaries was used to ensure consistent alignment between countries. The Global Administrative Areas version 2 (GADMv2; www.gadm.org) data set was selected as the framework as it is publicly available and frequently used in the research community. The international boundaries of census geography data sets were adjusted to the GADMv2 framework, although in cases where the resolution of the census geography far exceeded the GADMv2 boundaries, the former were kept (*e.g.*, New Zealand, the United Kingdom, and the United States).

Since countries conduct their censuses at different time periods, annual growth rates were used to adjust census counts to the target year of 2010 to allow for global comparison. Exponential growth rates were calculated for each administrative unit by matching the total population from the input data to those from a previous census enumeration. In cases where matching at the highest resolution was not possible between the two points in time, censuses were matched and growth rates were calculated at a coarser resolution (*e.g.*, state), and applied to each unit (*e.g.*, municipality) within that state. This occurred for a number of reasons: substantial reorganization of administrative units took place between the two enumeration periods; previous census data were not released to the same resolution as the current census data; or only coarser geographies were comparable since high-resolution enumeration areas were newly created for each census. The 2010 population estimates were extrapolated to 2000, 2005, 2015, and 2020 using the calculated growth rates. National-level estimates for 2000, 2005, 2010, 2015, and 2020 were further adjusted to the estimates of the United Nation's *World Population Prospects*, which often correct for over- or under-reporting in the nationally-reported figures (United Nations, 2011).

To create the gridded population data set, the population estimates were distributed to a 30 arc-second (~1km) grid using an areal-weighting method. This method will be discussed further in the following section. For grid cells that intersect sub-national or national boundaries, population is allocated based on the proportion of the area of the each unit located in the grid cell. A water mask was applied to the data to prevent lakes and ice-covered areas from distorting the actual population density. Population grids for each of the target years and for each of the census variables, unadjusted and adjusted to the UN estimates, are available at the country, regional, and global level. GPWv4 is easily updatable for future versions, allowing for the seamless integration of higher resolution data and newly-released results as they become available.

2.2 AREAL-WEIGHTING METHOD

Information collected through census enumeration is very often linked to areal units that vary in size and shape between and within nations. In order to produce a globally-comparable surface, it is necessary to disaggregate these areal units into grid cells of standard resolution. The disaggregation of statistical information associated with vector areal units into rasterized grid cells can be accomplished by a number of methods, but can be broadly characterized into two categories: those that include ancillary data to allocate the population within a unit, and those that do not. The areal-weighting method, also known as uniform distribution or proportional allocation, does not use any other geographic data in order to spatially disaggregate the census population. This method allocates population into grid cells through the simple assumption that the population of a grid cell is an exclusive function of the land area within that pixel. There are a number of more highly-modeled methods, including dasymetric modeling and smart interpolation (Hay *et al.*, 2005), that incorporate additional geographic data. These data are used to produce weight matrices for determining how to apportion population by pixel. Several global data products use ancillary data in their spatial modeling, incorporating remotely sensed data on land cover, urban extent, accessibility, or all of the above in order to delineate population surfaces (Bhaduri *et al.*, 2002; Balk *et al.*, 2006; Tatem *et al.*, 2007). GPWv4, however, uses the areal-weighting approach.

The main benefit of disaggregating demographic variables by areal-weighting is the maintenance of the fidelity of the input data. Census information modeled with this approach may be freely and easily incorporated into global analyses that make use of ancillary data sets that might be endogenous to more highly-modeled surfaces. The main drawback of using areal-weighting as the disaggregation method is the variability of the precision of pixel-level estimates. The precision and accuracy of a given pixel is a direct function of the size of the input areal unit. In countries where the input units are quite large, the precision of individual pixels within that unit is degraded. There are clear implications of this for the data user. In order to produce the best estimates, the data user must be aware of the size of the input areal units and select a study area that is larger than any given single unit. To guide users, GPWv4 includes an ancillary global grid that characterizes the size and local variation of the input units. The second implication is that higher resolution input areal units increase the accuracy of pixel-level estimates in the areal-weighted data product (Tatem *et al.*, 2007).

3. HIGHLIGHTS OF GPWv4

3.1 SUBSTANTIAL INCREASE TO SPATIAL RESOLUTION OF INPUT UNITS

Given that the accuracy of a given pixel depends highly upon the size of the input units, considerable effort was taken with GPWv4 to acquire the highest available spatial resolution of census data and to improve upon previous versions. GPWv3, released in 2004, was based on the 2000 round of censuses and included over 375,000 input units. Substantial improvements have been made to the fourth version, which includes nearly 12,500,000 input units (Table 1). Improvements to the United States input data drives this large increase between versions; GPWv3 used census tract data (approximately 60,000 units) for the United States, while GPWv4 incorporates census block data (over 10,500,000 units). However, considerable advancements have also been made globally. Excluding the United States, GPWv4 includes nearly 1,900,000 units for the rest of the world, a more than five-fold increase over GPWv3.

These improvements in the number of input units are distributed globally. Overall, 98 countries were gridded at a higher administrative level than in GPWv3. Administrative levels are typically described numerically, increasing from administrative level 0 (country), administrative level 1 (*e.g.*, province, state), administrative level 2 (*e.g.*, county, municipality) and so forth. Thus, a higher administrative level implies more units of a smaller size, although level names and the number and size of units vary within and among countries. While the most frequent administrative level remains at level two, 87 countries are now gridded at level 3 or higher, compared to only 47 countries in GPWv3 (Table 2; Figure 2). Regions where considerable improvements were made in many countries include Europe, the Middle East, and Africa, as well as small island states in Oceania and the Caribbean. Large variation in administrative level occurs in Africa, where data ranges from suboptimal (*e.g.*, in Libya, Eritrea, and the Republic of Congo) to the highest possible resolution (*e.g.*, South Africa and Kenya). Suboptimal data was also used for many countries in the Middle East and Central Asia. In total, 33 countries saw an increase of between 100-999 units between versions 3 and 4, while a further 26 countries increased by over 1,000 units.

TABLE 1
SUMMARY INFORMATION OF INPUT UNITS BY CONTINENT

Continent	**Administrative Level (mode)**	**Total Number of Units**	**Average Effective Resolution (km)**	**Average Persons per Unit ('000)**
Africa	2	122,853	57	104
Asia	2	130,137	45	219
Europe	3	635,169	17	16
North America	1	11,185,700	12	20
Oceania	1	96,911	12	9
South America	2	326,813	40	27
Global	**2**	**12,497,583**	**33**	**81**

TABLE 2
IMPROVEMENTS IN EFFECTIVE RESOLUTION FROM GPWv3 TO GPWv4

Level Used	**GPWv3**		**GPWv4**	
	Frequency	**Average Resolution (km)**	**Frequency**	**Average Resolution (km)**
0	24	22	9	32
1	64	56	50	48
2	95	55	95	36
3	41	27	65	24
4	5	19	11	8
5	1	9	9	5
6	0	--	2	2
Overall	**230**	**46**	**241***	**33**

* Due to recent territorial changes, there are 11 more countries or territories being gridded in GPWv4 than in GPWv3.

With this large increase in the number of input units, the average size of the administrative units in GPWv4 has decreased. The country-specific average resolution can be thought of as the "cell size", if all units of a country were square and of equal size. Smaller numbers indicate higher or finer resolution. It is calculated as follows:

$$\text{Mean resolution in km} = \sqrt{(country\ area)/(number\ of\ units)}$$

The average resolution of all countries changed from 46 km in GPWv3 to 33 km in GPWv4 (Table 2), indicating a higher overall resolution in the new version. By continent, Africa has the coarsest average resolution of 57 km, stemming from the large size and suboptimal data of many African countries. Oceania and North America, continents with many small island states, have the finest average resolution at 12 km (Table 1). The average resolution at each administrative level typically became finer between versions 3 and 4, with level 0 being the exception (Table 2). Many of the countries that are gridded at level 0 are small nations. In GPWv4, we have been able to improve the resolution of a number of these small countries (*e.g.,* San Marino, Åland Islands, Luxembourg, and Maldives); however, some of the countries and territories that remain at level 0 (*e.g.,* Svalbard and Jan Mayen Islands) have very large surface areas. As such, the average resolution is now coarser for the remaining countries gridded at level 0. Nonetheless, the overall effect of increasing the number of input units in GPWv4 is to improve the average resolution and to increase the accuracy of this areal-weighted data product.

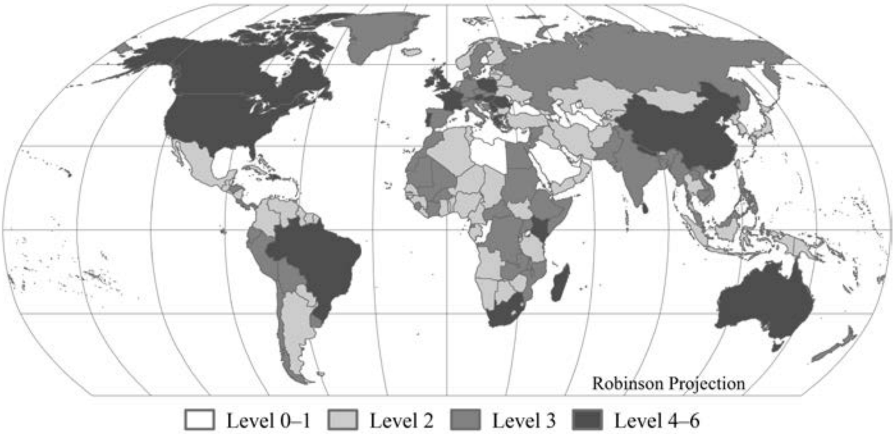

FIGURE 2
ADMINISTRATIVE LEVEL USED IN GPWv4 BY COUNTRY

The substantial increase in input units has come about for two primary reasons. First, GPWv4 is gridded with an output resolution of 30 arc-seconds (~1km), a grid resolution that is now standard among global gridded population datasets (Bhaduri *et al*., 2002). Previous versions of GPW, gridded to a resolution of 2.5 arc-minutes (~ 4km), were too coarse to take advantage of the high-resolution data from countries, such as the United States. The finer grid resolution of the current version allows us to fully utilize all available high-resolution census data. Second, in the decade since GPWv3 was released, there have been considerable advances in the availability of online and open source census data (United Nations, 2013). Census bureaus have benefitted from improvements in technology to allow them to more easily distribute their results to the public using electronic and online formats. The increase in freely accessible tabular and boundary data has allowed us to greatly improve the accuracy of GPWv4.

3.2 ADDITION OF NEW CENSUS VARIABLES

There has been a large demand from the research community to include demographic information in global population grids in order to extend their usefulness for social applications (*e.g.*, Gallego, 2010; Tatum *et al.*, 2012). Since social vulnerability varies across population groups (*e.g.*, Adamo and de Sherbinin 2011), understanding the spatial distribution of the population structure is essential.

Age and sex structure are fundamental characteristics to include in gridded population data. Demographic processes differ by age and sex, which is clear in the heterogeneity of fertility, mortality, and migration rates by age and sex (Lutz *et al.*, 1998). The numerical balance between sexes affects social and economic relationships, such as marriage and family formation, while age distribution is important for understanding demographic factors, including the proportion of children, elderly, working-age, or reproductive age in a population (Poston, 2005). The degree of vulnerability to climate change (Bell *et al.*, 2008), natural hazards (Mazurana *et al*., 2011), and infectious diseases (Tatem *et al*., 2012) is also strongly influenced by the distribution of a population’s age and sex structure. Identifying susceptible populations, therefore, requires information on the spatial distribution of these demographic variables.

With over half of global population currently living in urban areas, and a projected 2.6 billion more urban residents expected by 2050 (United Nations, 2012), urban/rural population distribution is another important census variable to include in gridded population data. Rapid urbanization is one of the global processes that is reshaping population distribution and transforming the geography of place-based vulnerability and risk (Adamo, 2010).

In order to broaden the applicability of GPW, version 4 is expanding to include three census variables: 1) age, as single- or five-year age groups, 2) sex, and 3) urban/rural status. Where possible, the variables will be cross-tabulated, resulting in a consistent global gridded population data set with detailed estimates of age, sex, and urban/rural distribution within each country.

Figure 3 illustrates a single-age GPWv4 grid, showing the distribution of infants (age 0) in Costa Rica. This grid can be used as an input to calculate infant mortality rates, which is an indicator used to measure the health and well-being of a population. Additionally, a recent analysis used cross-tabulated GPWv4 grids of urban and rural female adolescent population in Bhutan, in conjunction with intercity roads and adolescent fertility rates, to provide increased insight into adolescent pregnancy (CIESIN, 2013). Reducing adolescent birth rates worldwide is part of the Millennium Development Goals, the internationally agreed development targets for 2015. These detailed breakdowns of population distribution provided by GPWv4 will be a vital tool for investigations in an extensive range of issues of relevance to sustainable development, including urbanization, migration, hazard vulnerability, disaster preparedness, and health.

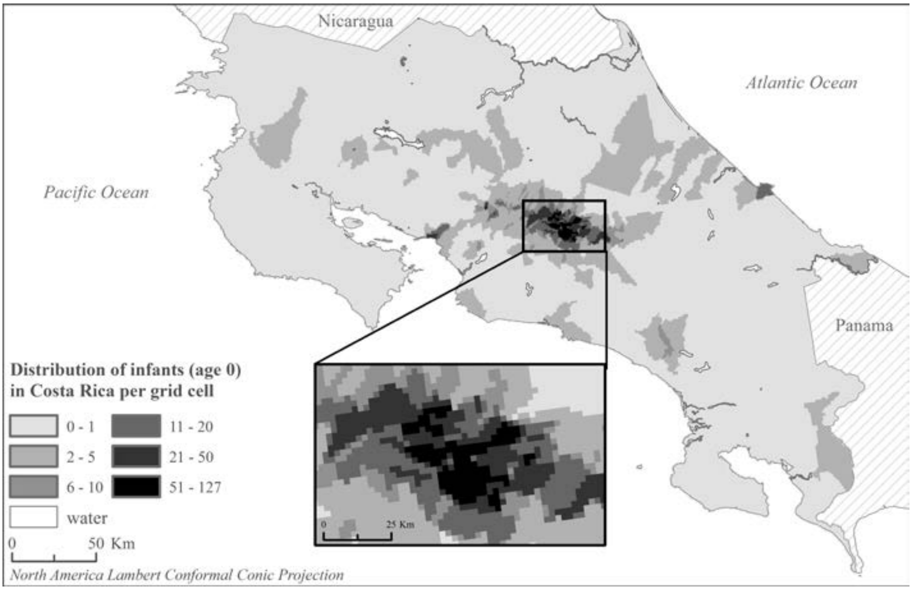

FIGURE 3
DISTRIBUTION OF INFANTS (AGE 0) IN COSTA RICA, 2010 ESTIMATE

Due to national differences in what characterizes urban and rural areas, there is no consistent global definition of urban or rural population. Countries, therefore, either establish their own definition in accordance with their needs or use regional definitions when including urban/rural status in their population censuses (United Nations, 2008). Definitions of urban areas are typically created using one or more criteria, including but not limited to: population count, population density, distance between buildings, distance from urban centers, non-agricultural economic activity, and sufficient critical facilities. Additionally, some countries, particularly small island nations, do not include urban/rural status as part of their census. As a result, definitions of urban population vary greatly among nations; for the purposes of GPWv4, the country-specific urban definition is used.

The three variables added in GPWv4 are all considered to be basic and essential tabulations for population and housing censuses (United Nations, 2008); however, acquisition of these variables from the 2010 round of censuses at the sub-national level varied by country. Sex was the most commonly available census demographic and was typically available at the same resolution as total population. Due to issues of confidentiality, age-sex cross-tabulations were sometimes only available at a coarser resolution, particularly for countries with small populations. Urban/rural status, especially in conjunction with the other variables, was the most challenging variable to acquire. However, technological advancements by NSOs and other data providers, such as interactive online databases, have greatly improved the ability for users to access detailed census data in the format they require. One such interactive database is Redatam+SP (http://www.eclac.cl/redatam/), which has expanded to include recent and historical census data for over 30 countries from four continents. The increased use of these databases by NSOs and the general improvement in census data availability greatly assisted in incorporating additional census variables into gridded population data.

4. CHALLENGES IN ACQUIRING AND WORKING WITH CENSUS DATA

4.1 CHALLENGES IN ACQUIRING DATA

Recent improvements in technology have resulted in increased use of the Internet for census data dissemination in the 2010 round of censuses as compared to previous years. The GPWv4 developers and other users of global population data have greatly benefited from these advances in dissemination. However, despite this progress, acquiring census data from many countries remains a challenge. According to a 2011/2012 survey of 121 countries that had completed their 2010 round census, paper publications were the primary method of data dissemination for 52 percent of respondents, followed by static Web pages (28 percent), and interactive online databases (14 percent; United Nations, 2013), indicating there is still room for ongoing improvements with online dissemination. When census data is only available through paper or PDF reports, high-resolution tabular data are often not included, requiring direct contact with census bureaus to attempt to locate data not available online. This also occurred with published tables on static Web pages. Thus for some countries, high-resolution data remained challenging and time-consuming to locate online and in some cases was not possible, limiting the accuracy of those countries' grids. GPWv4 has been structured to allow for easy updating should higher resolution data become accessible in the future.

There is also an asymmetry between the availability of tabular census data and census geography. Digital census cartography at the same resolution as available census data is of most use for gridding population data. However, tabular data is often more readily available and easily found online than digital census boundaries. Some countries, particularly small or developing ones, may not have or are still developing skills with geographic information systems (GIS). Sixty-four percent of 117 responding countries reported using GIS in their 2010 round census operations, based on a United Nations Statistics Division survey (United Nations, 2013). Those countries that do not use GIS may provide static maps, which require digitization and are typically at coarse administrative levels, or may not provide any census cartography. Additionally, while some NSOs disseminate their own cartographic data, the two types of data are often produced and disseminated by separate statistical and mapping agencies.

The aforementioned challenges with acquiring tabular census data and boundary data led to compromises in data processing for GPWv4. When census cartography was not available to match the resolution of the tabular census data, non-census boundaries were used where available; the resulting difficulties in working with such boundaries are described in the following section. When no other boundaries were available to match the census data, the country would be gridded at the coarser resolution of the available census boundaries. This occurred in over 25 countries, meaning we were unable to utilize the higher-resolution census data to the detriment of the grid's accuracy. In a small number of countries, non-census geography was available at a higher resolution than the census data. Again in these cases, coarser data of one format meant we could not take advantage of the resolution of the other. To maximize the useful integration of census data and boundaries, the United Nations Statistics Division suggests that "the objective of the census organization should be to release geographically referenced census data at the smallest level that does not compromise data privacy or statistical validity" (United Nations, 2009, 144).

4.2 CHALLENGES WITH INTEGRATING CENSUS AND BOUNDARY DATA

The process of integrating tabular census data with spatial boundaries can be straightforward when both data sets contain common identifying codes. However, for many countries, this was not the case, resulting in a time-consuming integration process. When non-census boundaries were used, census geocodes were often not included. The two data sets must, therefore, be matched using unit names, a lengthy exercise if boundaries and census refer to the same unit by different names or use different spelling. Additionally, the non-census boundaries are likely not from the same year as the census, and substantial administrative changes may have occurred in the intervening years. In some cases, it was the tabular census data that lacked an identifying code, making integration challenging even when digital census cartography was available. Therefore, in many instances, significant effort was needed to reconcile census areas with those present in the GIS data and to assign common identifiers.

Challenges in working with census data also stem from changes to the census over time. The nature of census geography is to change in relation to the spatial variation of population distributions over time. Although administrative boundaries are relatively more stable over time than enumeration areas, substantial changes to these legal jurisdictions commonly occur. The issue is magnified with increases in spatial resolution, with smaller sub-units generally being altered more frequently than the larger administrative boundaries in which they are contained. Geographic data on census enumeration areas are often difficult and sometimes impossible to obtain, especially for multiple census years. Administrative boundary data is widely available, but predominantly for a single point in time that is often not stated. Integration of census and geographic data, therefore, commonly includes changes and updates to the source input data.

The fact that these changes are occurring is not problematic in and of itself, but the lack of centralized documentation on changes over time can make working with data from multiple census periods very challenging. This integration of data from multiple census periods occurs in GPWv4 when calculating annual growth rates or integrating current census data with non-census geography that reflects an earlier period in time. Primary research of paper and digital sources is often necessary, and when descriptions of the new areas can be located, they are sometimes text based, which makes digitization challenging. A small number of countries have included maps or text to document such changes within their census documentation. In India, the Map Division of the Office of the Registrar General & Census Commissioner maintains an administrative atlas which tracks changes in census administrative areas from 1987–2011 (Office of the Registrar General & Census Commissioner, India, 2011). The types of changes it captures range from name changes, to the dissolution of territories, to the creation of new territories. Other examples include Brazil and Norway, whose censuses both provide lists of new municipalities and their relation with previous administrative units. These types of documents are valuable when integrating census data over multiple periods; however, change documentation of this quality was rarely available for censuses in other countries.

5. FINAL REMARKS

GPWv4 has taken advantage of the recent improvements in the availability of census population and geography data to greatly increase the accuracy of this data set. However, there remain many opportunities for improvement. GPWv4 and similar products are limited by the availability and quality of census data. Therefore, obtaining high-resolution census data and matching census geography remains a priority for improving global gridded population data sets. The following recommendations for NSOs in coordination with national mapping agencies would greatly facilitate the acquisition and integration of these data: 1) developing a digital data dissemination strategy for both tabular and boundary data; 2) providing census data in database format (*e.g.,* Excel); 3) including common identifying codes that are shared by tabular and boundary data; 4) documenting changes in administrative areas from one round to the next; 5) clearly documenting potential uncertainties and sources of error; and 6) explicitly stating terms of use and re-dissemination for data.

6. ACKNOWLEDGEMENTS

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