Remote Sensing of Environment 130 (2013) 219–232

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Generation of fine-scale population layers using multi-resolution satellite imagery and geospatial data ☆

Derek Azar [a], Ryan Engstrom [a,b], Jordan Graesser [a], Joshua Comenetz [a,*]

[a] U.S. Census Bureau, 4600 Silver Hill Road, Washington, DC 20233, United States
[b] Department of Geography, The George Washington University, 1922 F Street NW (Old Main), Washington, DC 20052, United States

ARTICLE INFO

Article history:
Received 2 March 2012
Received in revised form 19 November 2012
Accepted 23 November 2012
Available online 29 December 2012

Keywords:
Population distribution
Built-up area
Pakistan
Dasymetric
CART

ABSTRACT

A gridded population dataset was produced for Pakistan by developing an algorithm that distributed population either on the basis of per-pixel built-up area fraction or the per-pixel value of a weighted population likelihood layer. Per-pixel built-up area fraction was calculated using a classification and regression trees (CART) methodology integrating high- and medium-resolution satellite imagery. The likelihood layer was produced by weighting different geospatial layers according to their effect on the likelihood of population being found in the particular pixel. The geospatial layers integrated into the likelihood layer were: 1) proximity to remotely sensed built-up pixels, 2) density of settlement points in a fixed kernel, 3) slope, 4) elevation, and 5) heterogeneity of landcover types found within a search radius. The method for weighting these layers varied according to settlement patterns found in the provinces of Pakistan. Differences in zonal population estimates generated from the 100-meter gridded population layer resulting from this study, Oak Ridge National Laboratory's LandScan (2002), and CIESIN's Gridded Population of the World and Global Rural Urban Mapping Project (GPW and GRUMP) are examined. Population estimates for small areas produced using this paper's method were found to differ from census counts to a lesser degree than those produced using LandScan, GPW, or GRUMP. The root mean square error (RMSE) for small area population estimates for this method, LandScan, GPW, and GRUMP were 31,089, 48,001, 100,260, and 72,071, respectively.

Published by Elsevier Inc.

1. Introduction

Readily available and accurate data on spatial population distribution have multiple uses for humanitarian relief, disaster response planning, and development assistance. To assist in these areas, the U.S. Census Bureau, using remotely sensed imagery and population census data, created a highly detailed population distribution dataset for Pakistan. This work is part of the Census Bureau's ongoing Populations at Risk initiative, which follows a 2007 National Research Council (NRC) report that called for the Census Bureau to produce high-resolution, subnational estimates for those populations that are at risk of exposure to natural disasters and complex humanitarian emergencies.

Population data are a fundamental component of both policymaking and disaster response. In order to be useful, however, baseline data must be timely, detailed, and spatially enabled (Noji, 2005). These criteria can be met by reliable and recent population censuses and surveys. Many countries, however, including some prone to natural disasters and humanitarian emergencies, lack recent census and survey data. Additionally, the lack of a link between population data and digital geographic boundaries can further reduce the availability of information on populations at risk. In this case, data tables may exist for small areas at lower levels of administrative geography. However, without a link between digital maps and demographic data, users are limited to what can be gleaned from place names found within the census or survey. Researchers have recognized for over a decade that the technical difficulty linking human geography and data produced from remotely sensed sources is a barrier to the increased use of satellite data (Rindfuss & Stern, 1998). The absence of population data, either because the data are not collected or lack useful accompanying geographical data, is a formidable obstacle to policymaking and humanitarian response in parts of the developing world (NRC, 2007).

Satellite imagery can be collected over large areas at relatively low cost compared to the price of conducting a nationally representative population census or household survey. The idea of exploiting the synoptic coverage of satellite imagery to compensate for the uneven temporal and spatial resolution of census data is not new in the geographic literature. Areas of human activity appear to the naked eye readily in remotely sensed imagery. Surface characteristics of built-up areas make them recognizable by a human interpreter. For example, built-up areas tend to be bright in all visible bands and tend to be highly textured relative to most natural surfaces. Human observers

☆ This paper is released to inform interested parties of research and to encourage discussion. Any views expressed on statistical, methodological, or technical issues are those of the author(s) and not necessarily those of the U.S. Census Bureau.

* Corresponding author. Tel.: +1 301 763 1408; fax: +1 301 763 2516.
E-mail address: Joshua.Comenetz@census.gov (J. Comenetz).

0034-4257/$ – see front matter. Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.rse.2012.11.022

may use these textural cues in landscapes where building and natural materials are intermingled and when local materials are used for construction. Object-based classification of urban extents and settlement detection has focused on high-resolution imagery (Blaschke, 2010). There are examples of object-based classification used with medium-resolution satellite imagery to detect landscape features (e.g., forest patches, burned areas), but urban object-based remote sensing tends to focus on individual structures or linear features, rather than urban as a landcover.

Per-pixel classification of optical satellite imagery generally relies on the surface characteristics of texture and brightness in some way to classify an image. This methodology tends to have difficulty distinguishing between bright anthropogenic and natural surfaces, though texture-based indices can help ameliorate these difficulties and are used in this study (Guindon et al., 2004). However, human image interpreters can reduce error by using contextual clues that are not available in automated approaches. Consequently, the challenge for population geographers and remote sensing specialists is to 1) develop automated methods that can compensate for the missing experience and contextual awareness of the human interpreter when classifying built-up areas and 2) determine how best to relate built-up areas to population distribution.

1.1. Review of population distribution methodologies

Research into the use of satellite and related geospatial data to infer population distribution began during the 1960s. The longest thread of study in this area has focused on landcover categories in well-established urban areas in the United States and other developed countries (Lo, 1989, 2003; Tobler, 1969). Estimates of impervious area based on satellite data may also be used to indicate the extent of human settlement, without specific reference to per-pixel population density (Small, 2005; Small & Nicholls, 2003) or as an indication of human encroachment on natural systems (Goetz & Jantz, 2006). For studies where population density is modeled, the goal is to relate observable characteristics in satellite imagery to population distribution as recorded in censuses in an attempt to produce a higher-resolution population estimate. Wu et al. (2008) provide a useful typology for organizing population disaggregation research. In general, previous research has attempted to either 1) disaggregate census data collected at an administrative level, by tracts, or other census geography to some smaller unit, or 2) to infer population counts using a per-pixel, continuous approach based on a set of related variables. Both approaches are driven by a mathematical relationship established between population count or density and a set of spatial variables. This relationship may be simple, especially in the case of dasymetric mapping, or more complex, such as a statistical estimate produced using multiple variable regressions (Hay et al., 2005; Liu et al., 2006).

Dasymetric mapping employs a series of spatial partitions to introduce a higher resolution level into a dataset than the level at which the data were originally captured. Geospatial layers with resolutions that exceed a population dataset's are used to parse that dataset into areas smaller than the base mapping unit (Eicher & Brewer, 2001). The goal is to use the higher resolution data to produce weights to disaggregate the population data, thus creating a higher resolution population dataset. Landcover data derived either from remote sensing or collected from other sources are an often-used layer for disaggregation (Holt et al., 2004; Liu & Clarke, 2002; Mennis, 2003). Nighttime light emission can also be used in combination with landcover data (Briggs et al., 2007), but glow filtering into neighboring pixels has been shown to substantially reduce accuracy with this approach (Small & Nicholls, 2003). Dasymetric mapping approaches also make use of remotely sensed variables similar to those used when attempting to conduct continuous, per-pixel analysis (Wu & Murray, 2007; Wu et al., 2008). The variables tend to be used differently, however, with zonal averages common in dasymetric mapping and per-pixel values used as input in continuous mapping approaches. Oak Ridge National Laboratory's LandScan global gridded population layer—for which the Census Bureau has provided the demographic base—is also produced using a weighted, dasymetric approach (Dobson et al., 2000).

Continuous approaches attempt to associate directly spectral or spatial characteristics of pixels or groups of pixels with population density (Harvey, 2002; Li & Weng, 2005; Liu & Clarke, 2002; Liu et al., 2006) or with derived proxies for population density (Chen, 2002). Continuous approaches include those where a model is developed that allows for a per-pixel population estimate based on continuously variable input surfaces. Such models allow for the production of population estimates for extremely small areas—on the order of a neighborhood block. The success of per-pixel models has primarily been driven by ancillary data, such as zoning and cadastral data that are rarely available in data-scarce countries, and they have never been implemented at the national level. Martin et al. (2002) noted that both continuous and dasymetric approaches to population mapping using census data and ancillary geospatial layers produce results that may be even more useful than the census data as collected.

Research on population estimation using remote sensing sited in data-rich countries allows for the inclusion of high-resolution, reliable census data. Lu et al. (2006) achieved a high degree of accuracy relating population density and built-up area fraction using block-level census data for the United States and an ETM+ derived built-up area layer, masked using zoning information.

The Gridded Population of the World (GPW) and Gridded Rural–urban Mapping Project (GRUMP) use related methodologies based on administrative areas, with the GRUMP approach explicitly accounting for urban population centers. The most recent version (version 3) of GPW disaggregated the 375,000 administrative polygons into an unsmoothed, gridded population product. Grid cells that overlap more than one administrative unit are allocated using proportional areal weighting. GRUMP is methodologically similar but incorporates urban footprints and associated population data as additional units for population disaggregation (Balk et al., 2006). This contrasts with the LandScan method where the total population of administrative areas may be altered. The United Nations Environment Programme produces a similar product, the Global Resource Information Database (GRID) population layer. The layer is designed to be integrated with other biophysical layers to allow for a quantification of exposure and risk. It distributes population using administrative boundaries and a model of accessibility to settlements based on the transportation network (Nelson, 2004).

Hay et al. (2005) questioned the ability of various methodologies to produce meaningful information below the level of input census data and stated that ancillary data are insignificant compared to the influence of input administrative data on accuracy. The verification method in this paper uses census counts from low-level administrative units in response specifically to Hay et al. (2005) in order to demonstrate that methods that include ancillary data can add meaningful information below the input administrative level. Methods with more ancillary data tend to provide smoother surfaces and thus are cartographically appealing. However, cartographic appeal does not necessarily translate into meaningful information at a finer scale. Higher-resolution gridded population layers only add meaningful information when they demonstrably correlate with population distribution at the finer scale.

Tatem et al. (2007) and Linard et al. (2012) demonstrate that a dasymetric mapping approach using landcover data can produce more detailed population maps even in data-scarce regions such as parts of Africa. Their work provides an important example of population mapping outside North America and Europe. While the research is useful because of the lack of data generally available in Africa, artifacts due to the use of landcover data are evident. For example, the gradation of population density moving from a settlement core, to periphery, and then to hinterland, may be non-existent, with a blob-like