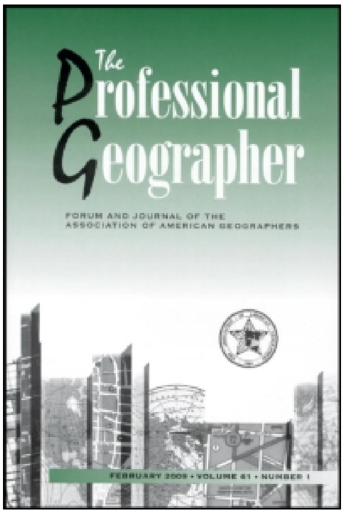

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Darkness on the Edge of Town: Mapping Urban and Peri-Urban Australia Using Nighttime Satellite Imagery

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This article explores the use of nighttime satellite imagery for mapping urban and peri-urban areas of Australia. A population-weighted measure of urban sprawl is used to characterize relative levels of sprawl for Australia's urban areas. In addition, the expansive areas of low light surrounding most major metropolitan areas are used to map the urban–bush interface of exurban land use. Our findings suggest that 82 percent of the Australian population lives in urban areas, 15 percent live in peri-urban or exurban areas, and 3 percent live in rural areas. This represents a significantly more concentrated human settlement pattern than presently exists in the United States. **Key Words: exurban population, nighttime satellite imagery, urban sprawl index.**

本文探讨了使用夜间卫星图像来测绘澳大利亚的城市和城市近郊。本研究使用了一种人口加权的城市扩张衡量方法来分析澳大利亚城市地区扩张的相对水平。此外，大城市地区周围那些低光的扩张出去的地区被用来测绘郊外土地利用的城乡结合部。我们的研究结果表明，百分之八十二的澳大利亚人口生活在城市地区，百分之十五居住在近郊区或远郊区，百分之三生活在农村地区。相比美国的目前情况，澳大利亚的人类居住模式明显更加集中。**关键词：城市远郊人口，夜间卫星图像，城市扩张指数。**

Este artículo explora el uso de imágenes de satélite de la noche para cartografiar áreas urbanas y peri-urbanas de Australia. Se usó una medida del desparramado urbano con peso poblacional para caracterizar los niveles relativos del desparramado en las áreas urbanas de Australia. Adicionalmente, las áreas expansivas de luz mortecina que rodean la mayoría de las principales áreas metropolitanas se usan para cartografiar la interfaz ciudad-monte, como una de las partes del uso exurbano de la tierra. Nuestros descubrimientos sugieren que el 82 por ciento de la población australiana vive en áreas urbanas, 15 por ciento vive en áreas peri-urbanas o exurbanas, y el 3 por ciento en áreas rurales. Esto representa un patrón de asentamiento humano significativamente más concentrado de lo que actualmente acontece en Estados Unidos. **Palabras clave: población exurbana, imágenes satelitales de la noche, índice de desparramado urbano.**

The Australian State of the Environment Report on Human Settlement patterns (Newton et al. 2001, 13) aptly notes:

> A nation's population and how it is geographically distributed are key influences on the environment, through the number of people and their patterns of consumption, the rate of growth and household formation, the attractiveness of environments with high amenity value, the relatively low density of settlements, and the scale economies and relative efficiencies of settlements of different sizes with respect to housing, services and infrastructure provision.

This statement reflects increased global interest in the growth and form of urban areas, particularly regarding the issues of environmental sustainability and urban sprawl. There is growing concern, especially in the United

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States, Australia, and other more developed states, that the proliferation and use of motor vehicles and highways has led to sprawling and unsustainable city forms that impose significant environmental, infrastructural, and public health costs (Newman and Kenworthy 1999; Burchell et al. 2002; Farr 2008). Although there have been conflicting perspectives in the costs of sprawl debate (Ewing 1997; Gordon and Richardson 2001), most of the literature has been supportive of compact cities and smart growth approaches (Wagner et al. 2005; Flint 2006; Soule 2006; Barnett et al. 2007).

Concomitant with the sprawl debate, researchers have been refining measurements of the areal extent and form of urban areas (Galster et al. 2001; Ewing, Pendall, and Chen 2002) including the application of newer methods such as remote sensing of land use/land cover change and nighttime light detection (Cova, Sutton, and Theobald 2004; Huang, Lu, and Sellers 2007). This research has provided additional data suggesting that urbanized areas, especially low-density exurban areas, are more extensive than previously thought. Most of this research has focused on the United States, but it is increasingly expanding to other regions of the world.

This article explores the patterns of human settlement in Australia by utilizing existing census data from the Australian Bureau of Statistics (ABS) and nighttime satellite imagery provided by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS). This approach to mapping the urban and peri-urban areas of Australia is relatively simple and systematic in that it is uniform throughout the continent of Australia. The nighttime satellite imagery provided by the DMSP OLS is collected on a global basis at a uniform spatial resolution ($\sim$1 km^2) and the processing used to derive stable "city lights" data products is performed in a consistent manner across the globe (Elvidge et al. 1999). The ABS conducts a census of the population every five years and this census is of high quality with respect to both spatial and temporal resolution (in 2006 the Australian Census cost about A$15 per person).

The focus of this research is the juxtaposition and analysis of a physical measurement (the DMSP OLS-derived city lights data) with a spatially referenced demographic survey (the ABS census of Australia). We believe that the nighttime imagery provides an informative alternative view of the spatial distribution of the population of urban and peri-urban areas. This is primarily due to the fact that the administrative boundaries of the ABS census experience reduced spatial resolution as population density decays with distance from urban centers. Consequently the mapping of urban and peri-urban areas with the nighttime imagery provides a different and perhaps better picture of the spatial distribution of population. We recognize that there are limitations to this effort that are inherent to both the theoretical and practical questions associated with defining urban and peri-urban. Moreover, there are problems associated with the spatial and spectral resolution of the DMSP OLS sensor and signal saturation in urban centers resulting from the high gain setting of the sensor during standard operations (Elvidge et al. 2007). Nonetheless, the broad geographic scope and the uniformity of method across such a large spatial extent provide an interesting perspective on some of the issues associated with population distribution as it pertains to urban and peri-urban form. Nighttime satellite imagery measures emitted light, predominantly from anthropogenic sources, that identifies human presence in a manner very distinct from most other satellite imagery that sees reflected sunlight during the day.

A key premise of this work is the idea that the physical measurement of nocturnal light emissions measured at a uniform spatial resolution ($\sim$1 km^2) informs us about the nature or intensity of human settlements in ways that cannot necessarily be discerned from the dramatically variable size of the collection district boundaries of the ABS census. Data products derived from DMSP OLS imagery have been used to map urban extent (Imhoff et al. 1997), estimate intraurban ambient population density (Sutton, Elvidge, and Obremski 2003), map economic activity (Sutton and Costanza 2002; Ebener et al. 2005), and estimate CO_2 emissions (Doll, Muller, and Elvidge 2000). Previous investigations with these data products have characterized urban sprawl and exurban development in the United States (Sutton 2003; Sutton, Cova, and Elvidge 2006). This work is similar to these previous works in that an aggregate measure of per capita land consumption is calculated for the urban areas of Australia via the use of the nighttime imagery. This aggregate measure is used as an urban sprawl index.

The following questions are explored in this article:

1. How big are exurban areas in Australia?
2. What are the relative sizes in terms of areal extent and population of these exurban areas?
3. How many people live in exurban areas?
4. How do the size, density, and extent of these urban and exurban areas compare with comparable areas in the United States?

Urban Decentralization Processes

The study of urban form has long roots in geography, including classical models of U.S. urban spatial structure (Burgess 1924; Hoyt 1939; Harris and Ullman 1945), as well as more contemporary models that reflect the massive decentralization of population and employment away from central urban cores (Hartshorn and Muller 1989; Vance 1990; Harris 1997). Together with the Edge City concept popularized by Garreau (1991), these models all share common features, such as the following:

1. The relative decline of the central business district in comparison to the rise of outlying business districts and the dispersal of employment opportunities throughout the larger metropolitan area.
2. The role of radial highways and circumferential beltways in facilitating outward growth.
3. The desire of many residents to live in single-family dwellings on relatively large lots in outlying suburban or exurban areas that are still readily accessible to employment, retail, social, recreational, and other daily activities.

The urban processes that have created this massive expansion of the "outer city" have been most highly pronounced and farthest advanced in the United States, but other developed and some developing countries have also been experiencing "American-style sprawl" (Nivola 1999; Murakami et al. 2005). These processes have most certainly affected urban development patterns in Australia, where the dominant urban centers (Sydney, Melbourne, Brisbane, Perth, and Adelaide) have been growing steadily in total population and outward in area over the last fifty years (Stimson and Baum 2003). Australia's urban development and transportation policies have stimulated this outward growth by emphasizing automobility, road and highway transport, and reduced funding for transit, which has drawn sharp criticism from those in the sustainable urbanism and transport community (Gleeson, Curtis, and Low 2003; Laird and Newman 2003; Mees 2003; Low 2005). The result has been increasing numbers of Australians opting for low-density peri-urban living environments.

- Increasing numbers of people with the disposable income and work flexibility (temporal and locational) to exercise the choice of a peri-metropolitan setting.
- The potential in telecommunications to release people from the need for daily proximity to jobs and businesses.
- Improved road and commuter rail standards.
- Decentralization of jobs within metropolitan regions, which in turn permits commuting from more distant and peripheral areas.
- Factors such as a rise in the incidence of early retirement, resurgence in the popularity of holiday homes and weekend recreational trips, and a partial shift in preferences away from the coast in favor of inland locations.

The forces just described have driven peri-urban development in Australia but not to the extent that it has occurred in the United States. Exurban areas of Australia's five major cities are mapped and characterized based on the mapping of low-intensity measurements of nocturnal emissions of visible light around major urban areas. These results for Australia are contrasted with similar studies of urban areas in the United States.

Methods

Methods of Image Processing and Statistical Analysis

The primary data used in this analysis were a year 2000 city lights nighttime satellite image of Australia and a population density grid ($\sim$1 km^2) derived from the ABS 2001 census of the population. The accuracy of the gridding of

Figure 1 *Representation of primary data products used over southeastern portion of Australia.*

the ABS data was very high ($R^2 = 0.9999$ between aggregated and attribute values of population for the ABS census collection district polygons). In addition, we used a Landsat image covering much of south Australia, some ground observations geo-referenced with a Global Positioning System (GPS), a "populated place" data set from the ABS, and a polygon coverage of built-up areas from the ABS. The nighttime lights product is a mosaic of many orbits of the DMSP OLS in which clouds, gas flares, lightning, and other ephemeral and extraneous signals have been screened out, leaving only city lights (Elvidge et al. 1999). The ABS 2001 built-up areas data set and the Landsat imagery were used primarily for comparison and validation purposes only. The population density grid was used to ascertain the population of the various urban, exurban, and rural areas identified in the nighttime imagery.

The nighttime imagery of Australia is mostly dark (e.g., no light is emitted from most of Australian land). These dark areas are categorized as rural and constitute roughly 98 percent of Australia's areal extent. In fact, many of these areas are not even rural but are more adequately described as uninhabited wilderness. This is in agreement with the geography of Australia, as the largest part of Australia is desert or semi-arid lands with only the southeast and southwest corners of the continent having a temperate climate and the greatest concentration of population.

The lit areas have a range of light intensity that generally increases with increasing "urbanness" or population density. A threshold of light intensity is chosen and applied uniformly to all of Australia to delineate high-intensity emissions (urban areas) from low-intensity emissions (exurban or peri-urban areas). This results in a three-category map of Australia defining urban, peri-urban, and rural. This map is combined with the ABS population data to obtain population figures for all the urban and exurban areas delimited by the nighttime imagery. A representation of these data sets for southeastern Australia is provided in Figure 1.

The most difficult and problematic element of this effort consisted of selecting a light intensity threshold in the nighttime imagery that best distinguishes urban areas from peri-urban areas. The threshold that accomplished this to our highest level of satisfaction was a value of 10 (of the 6-bit 0–63.0 range of the DMSP OLS city lights data product). This threshold was chosen from the evaluation of ground photographs that were spatially referenced with GPS (see example in Figure 2), inspection of Landsat imagery, and the expert opinion of the Australian authors. Thus, our classification scheme for the image was 0 (dark) is rural, 1 to 10 (low levels of light) is peri-urban, and 11 to 63 (bright lights) is urban (Figure 1). It should be noted that this threshold for Australia is much lower than what it would be for the United States (e.g., lower levels of light define urban areas in Australia). This suggests that Americans are much brighter than Australians when observed nocturnally from space but perhaps not as bright as Australians in terms of efficiently using energy to provide nocturnal lighting. The coarse spatial resolution of the nighttime satellite imagery ($\sim$1 km^2) forces this thresholding to result in a less than ideal classification of Australia into rural, peri-urban, and urban categories; however, the urban boundary of the city of Adelaide derived from this threshold most closely matched the ABS definition of the Adelaide metro area defined from population density thresholds. A geo-referenced digital photograph of the Mt. Osmond area in the foothills of Adelaide shows

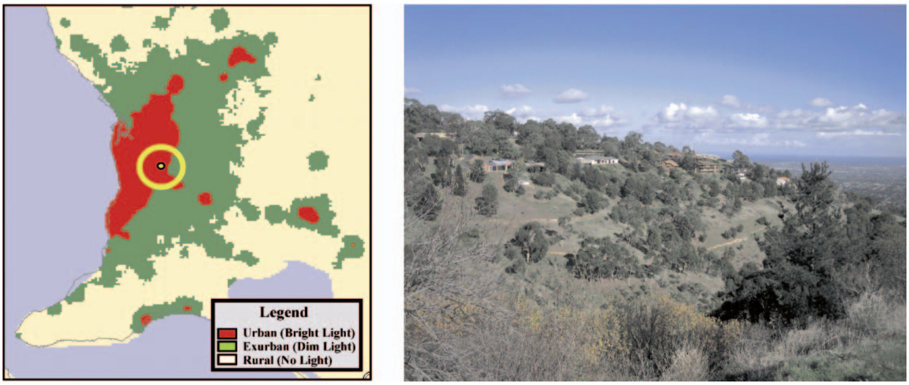


Figure 2 *Mt. Osmond area in foothills above Adelaide as an example of the urban–exurban boundary area and the limitations of the coarse spatial resolution of the DMSP OLS imagery.*

an area we would have preferred to have categorized as peri-urban to be classified as an urban area on the very edge of Adelaide (Figure 2). Despite the shortcomings inherent in the spatial and spectral resolution of the DMSP OLS imagery, we find the classification to be adequate for mapping urban, peri-urban, and rural areas for an area the size of Australia. The urban–peri-urban boundary is itself a very subjective concept and we have tried to develop the best possible delineation of this boundary from DMSP OLS and available data sources.

With this classification of urban, peri-urban, and rural areas of Australia, the urban and peri-urban areas are spatially clustered into urban and peri-urban agglomerations based on their spatial contiguity. A population for each agglomeration was determined by overlaying these urban areas on the population grid. Each agglomeration (contiguous pixels with a digital number [DN] of eleven or more) represents an urban area of Australia. This resulted in identifying 454 urban areas in the nighttime image with DN levels above ten. Of these 454 areas, 259 could be identified with a place name from the ABS populated places data set. The remaining 195 urban areas had a mean areal extent of 8.0 km^2 (less than 3 × 3 pixels) and an average population of 120 persons. These small urban areas that we could not affix a place name to are typically rural roadhouse and gas stations, mining operations (e.g., Roxby Downs), gas flares that were not successfully screened (e.g., the Woomba Gas Field), and small fragments of larger urban areas. In any case they represent less than 25,000 people in total. The focus of this part of the analysis is on the 259 urban areas for which we could identify a place name. The average population of these urban areas was 57,000 persons and the average size was 74 km^2. These named urban areas accounted for 14.8 million people or approximately 80 percent of the 2001 Australian population.

Using Urban Area and Population to Derive a Sprawl Index

This analysis easily produces a table of figures that contain the urban population, exurban population, urban area, and exurban area for well over 200 urban areas of Australia. This table of data with urban area and corresponding urban population is the source material for deriving a crude index of urban sprawl, which is merely a scale-adjusted (e.g., population-weighted) measure of land consumption per person for the people in a given urban area. The details of the sprawl index are related to the log-linear regression of the areal extent and the population of these urban areas of Australia (Figure 3). It is scale-adjusted to account for the fact that larger cities have higher aggregate population densities (lower land consumption per capita). The linear relationship between the natural log of the areal extent of a city and the natural log of its population has been identified by several researchers (Clark 1951; Stewart and Warntz, 1959; Tobler 1969).

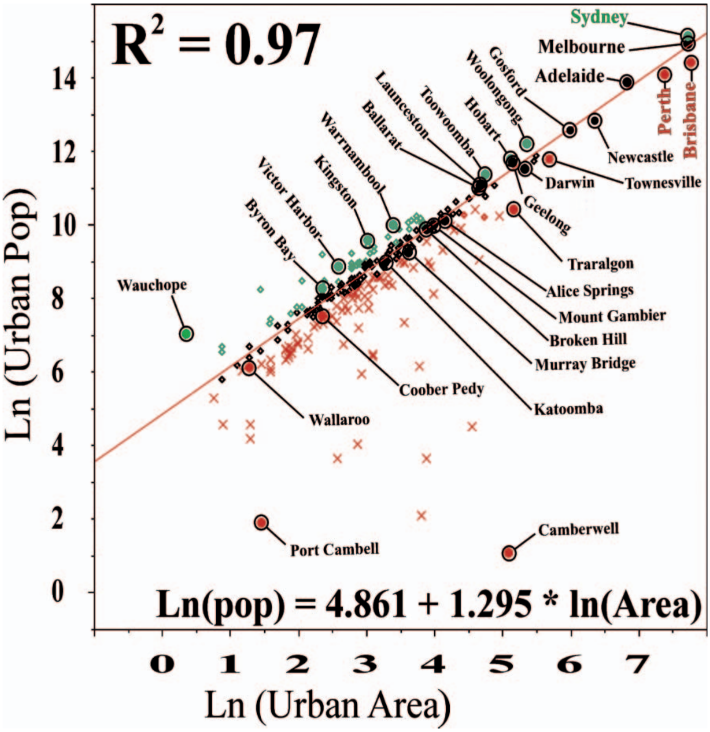


Figure 3 *Scatterplot and regression of Ln(Urban Area) on Ln(Urban Pop) for Australian urban areas identified by the nighttime imagery.*

We use this relationship in a simple regression model that predicts the natural log of an urban population from the natural log of the areal extent of the urban area as determined from the nighttime imagery. This regression is weighted by population to prevent small towns like Port Campbell and Wallaroo from having the same influence as major cities such as Sydney, Melbourne, and Brisbane in determining the regression parameters. We ran this regression on all the urban areas for which we could associate a place name ($n = 259$); however, the regression parameters and R^2 would not have changed much if we used all areas ($N = 454$) because of the population weighting. The scatterplot of Ln(Urban Area) versus Ln(Urban Population) is colored to symbolize the points (each of which represent a city or urban area of Australia) according to their score on the sprawl index (Figure 3; note that the Canberra Australian Capital Territory was excluded from our analysis.)

The essence of this index is this: For a given areal extent an urban area can contain more or less people than would be expected (expected population being the population corresponding to being exactly on the regression line). Sprawling cities have fewer people than would be expected and nonsprawling cities have more (below or above the line, respectively). The percentage by which a given urban area either exceeds or falls short of its expected population is our sprawl index. The sprawl index is simply the actual population of a given area minus the estimated or sprawl line population divided by the sprawl line population times 100 (e.g., the percentage by which a given urban area's population differs from the expected population). Green points represent urban areas above the sprawl line (regression line) that have populations higher than expected for a given areal extent, black points are urban areas close to the sprawl line that have populations within 25 percent of the expected sprawl line value, and red points are those urban areas that are below the sprawl line and have less than expected populations given their areal extent (e.g., higher land consumption per capita). Of the five most populous cities, Sydney was least sprawling (score = +32) and Brisbane was the most sprawling (score = –38). Perth also ranked as a sprawling city (score = –27), and Melbourne and Adelaide were in the middle range with scores of +8 and +20, respectively. The actual and expected population (and sprawl index) for the cities of Australia we identified as having a population in excess of 10,000 is provided in Table 1. Urban and peri-urban areas (and the corresponding populations) of Australia's five largest cities are provided in Figures 4 and 5.

Mapping Peri-Urban Areas with Low Light Levels of the DMSP Imagery

Mapping and analysis of the exurban areas of the five major cities (Sydney, Melbourne, Brisbane, Perth, and Adelaide) was accomplished by categorizing the contiguous low-light areas (DN values from one to ten) around each of these cities (Figures 4 and 5). Exurban area correlated positively with the total population of the core urban areas, as did total exurban population densities. The percentage of the metropolitan populations of these cities living in exurban areas was Sydney, 7 percent; Melbourne, 8 percent; Brisbane, 10 percent; Perth, 5 percent; and Adelaide, 7 percent. The population density (persons/km^2) of these exurban areas was Sydney, 41; Melbourne, 39; Brisbane, 39; Perth, 22; and Adelaide, 28.

Results and Discussion

Various definitions of urban sprawl have been proposed, ranging from Whyte's (1958) "Leapfrog nature of development" to simple aggregate measures of population density (Kolankiewicz and Beck 2001). This research is limited to characterizing two aspects of urban sprawl for the urban areas of Australia and contrasting them with similar measurements in the United States. One is a scale-adjusted measure of per capita land consumption as an aggregate indicator for each urban area. The second is an investigation of the exurban or peri-urban areas that surround most major urban areas, which we assert are an important aspect of urban form in the developed world today. A complete discussion of urban sprawl is beyond the scope of this research and certainly beyond the scope of a journal article; however, we provide these admittedly simple characterizations of urban and exurban sprawl in the hope that it sheds light on understanding some aspects of contemporary urban form and growth in the world today as it pertains to global demographic and economic dynamics.

The scale-adjusted measure of urban sprawl presented here is unique in that it allows the comparison of apples and oranges with respect to small and large urban areas. Simply comparing the aggregate population density of Sydney to a much smaller city like Murray Bridge is an inappropriate comparison for assessing the degree to which these two cities sprawl. Even the comparison of the aggregate population density of large cities like Sydney to Melbourne is unfair due to their real differences in total population. The scale adjustment we determined with our sprawl-line regression suggests that the average areal extent of theoretical Australian cities with these standard populations would be as follows: A population of 10,000 occupies ~28 km^2 (population density = 357 persons/km^2), a population of 100,000 occupies ~172 km^2 (population density = 581 persons/km^2), and a population of 1 million occupies ~766 km^2 (population density = 2,801 persons/km^2). Population density increases nonlinearly with scale or total population of a city. This is true everywhere in the world; however, the relationship is relatively constant within nations and sprawls with increasing levels of national income (e.g., gross domestic product per capita; Sutton et al. 2001). Consequently, cities of equivalent population in the United States occupy larger areal extents, suggesting that Australian cities do not sprawl as much as American cities. Australia undoubtedly fares well by this comparison because its major cities are coastal, which is a geographic constraint that tends to increase population density. Nonetheless, the difference would remain (albeit somewhat diminished) if we limited the comparison to coastal U.S. cities. We argue that the scale adjustment enables a fairer comparison of sprawl for all the urban areas of Australia. The actual population, actual areal extent, sprawl-line population, and sprawl

Table 1 *Australian cities with actual population of 10,000 or more*

City name	Actual population	Areal extent (km^2)	Sprawl line population	Sprawl index
Sydney	3,760,490	2,258	2,841,313	32
Melbourne	3,042,890	2,245	2,818,879	8
Brisbane	1,852,350	2,346	2,985,309	−38
Perth	1,318,010	1,596	1,813,558	−27
Adelaide	1,062,100	917	886,191	20
Newcastle	378,656	568	476,597	−21
Gosford	290,540	403	305,447	−5
Woolongong	199,891	211	132,611	51
Caloundra	144,697	242	158,309	−9
Hobart	133,021	166	96,820	37
Townsville	126,961	289	198,766	−36
Cairns	123,411	233	150,408	−18
Geelong	120,722	172	101,839	19
Darwin	102,616	204	126,794	−19
Toowoomba	86,968	114	59,806	45
Ballarat	67,137	109	56,104	20
Launceston	65,169	107	54,904	19
Albury	64,679	131	71,785	−10
Bendigo	59,748	103	52,523	14
Rockhampton	55,986	102	51,406	9
Mackay	48,343	115	60,552	−20
Wagga Wagga	44,836	90	44,002	2
Bundaberg	41,230	75	34,699	19
Traralgon	34,054	173	102,298	−67
Mooroopna	33,388	67	29,810	12
Bunbury	32,293	98	48,996	−34
Dubbo	30,829	78	36,386	−15
Mildura	30,203	71	32,263	−6
Tamworth	29,891	60	25,766	16
Geraldton	29,046	84	40,246	−28
Melton	28,466	42	16,421	73
Gladstone	27,524	139	77,415	−64
Kalgoorlie	27,235	113	59,332	−54
Orange	26,385	44	17,645	50
Port Macquarie	25,100	42	16,421	53
Alice Springs	25,030	64	28,142	−11
Coffs Harbor	24,805	39	14,673	69
Lismore	23,946	46	18,212	31
Sunbury	23,819	37	14,036	70
Hervey Bay	22,835	45	17,851	28
Mount Gambier	22,414	53	22,402	0
Warrnambool	22,306	29	10,353	115
Whyalla	20,565	68	30,564	−33
Tewantin	19,957	47	18,940	5
Mount Isa	19,798	79	37,297	−47
Maryborough	19,758	38	14,329	38
Ballina	19,718	32	11,646	69
Broken Hill	19,479	48	19,675	−1
Nowra	19,387	50	20,788	−7
Armidale	19,212	42	16,421	17
Bathurst	19,042	54	22,728	−16
Mittagong	18,696	71	32,617	−43
Eumundi (Nambour)	15,754	27	9,407	67
Devonport	15,551	38	14,329	9
Cessnock	15,326	36	13,308	15
Goulburn	15,159	44	17,337	−13
Kingston	14,598	20	6,454	126
Grafton	13,800	31	10,995	26
Port Pirie	13,770	33	12,021	15
Port Augusta	13,640	48	19,307	−29
Taree	13,338	38	14,329	−7
Griffith	12,753	32	11,739	9
Albany	12,588	20	6,454	95

(Continued on next page)

Table 1 *Australian cities with actual population of 10,000 or more (Continued)*

City name	Actual population	Areal extent (km^2)	Sprawl line population	Sprawl index
Wangaratta	12,472	29	10,081	24
Gympie	12,261	39	15,019	−18
Echuca	12,124	36	13,453	−10
Moe	12,046	22	7,199	67
Burnie	11,827	32	11,459	3
Sale	11,306	28	9,810	15
Tuncurry	10,890	22	7,283	50
Singleton	10,708	60	26,158	−59
Murray Bridge	10,625	37	14,036	−24
Kiama	10,203	16	4,790	113
Kurri Kurri	10,123	31	10,995	−8
Horsham	10,097	28	9,541	6
Furnissdale	10,053	21	6,700	50

index are summarized for all urban areas of Australia in Table 1.

Of the five major cities of Australia, Sydney by design, historical development, and geographic and environmental conditions sprawls the least, whereas Brisbane sprawls the most. It should be noted that the urban core of Brisbane included the Gold Coast, whereas the urban core of Sydney did not include major urban areas north and south of Sydney such as Newcastle, Gosford, and Woolongong. Clearly, many of Australia's urban areas are growing together and forming conurbations of smaller cities in which the in-between spaces can often be characterized as exurban. For Sydney it is the conurbation of Newcastle, Gosford, and Woolongong with Sydney—perhaps not complete yet but likely in a matter of time. For Melbourne the metro area could eventually span from Traralgon to Geelong. Brisbane is probably the farthest along in the conurbation progression in that the area between Brisbane and the Gold Coast is increasingly urban in its form and function as our classification of the nighttime imagery did capture. Areas south of Perth such as Mandurah are becoming increasingly developed, and Freemantle and Perth were seen by the DMSP OLS imagery as one urban area already. Adelaide is second only to Sydney (of the most populous five cities) for green score on the sprawl index; however, it has essentially merged with Gawler to the north and Port Noarlunga to the South and will probably merge with Mt. Barker to the east if it experiences any significant population growth. Nonetheless, Australian cities do not sprawl as much as American cities based on the indexes of this methodology. In fact, Australia is significantly more urban than the United States by these measures, which raises interesting questions regarding the economic and demographic aspects of the fundamental causes of urban sprawl.

Previous studies and characterizations of exurban areas focus on the United States and rely primarily on census data (Berry and Gillard 1977; Long and Nucci 1997; Nelson, and Sanchez 1997, 1999; Burchell et al. 2002). This study provides an alternative perspective on exurbia by focusing primarily on the comparison of ABS census data with remotely sensed satellite imagery of Australia. The nighttime satellite imagery over Australia shows significant areas of low light surrounding many of the major metropolitan areas. These areas would be primarily characterized as bare soil or vegetation by 30-meter resolution Landsat imagery, yet they contain significant numbers of people who have social, economic, and ecological impacts (e.g., traffic congestion, bush fire hazard exposure, and other problems associated with the urban–bush interface). In Australia many of these exurbanites are dairy farmers, "sea change" and "tree change" retirees and migrants, people working in the tourism industry, and people who choose to live outside the big city and commute in for work. In the United States these exurbanites have historically been considered to be rich commuters who choose to live in natural settings beyond the city and suburbia (Spectorsky 1955); however, recent large increases in urban real

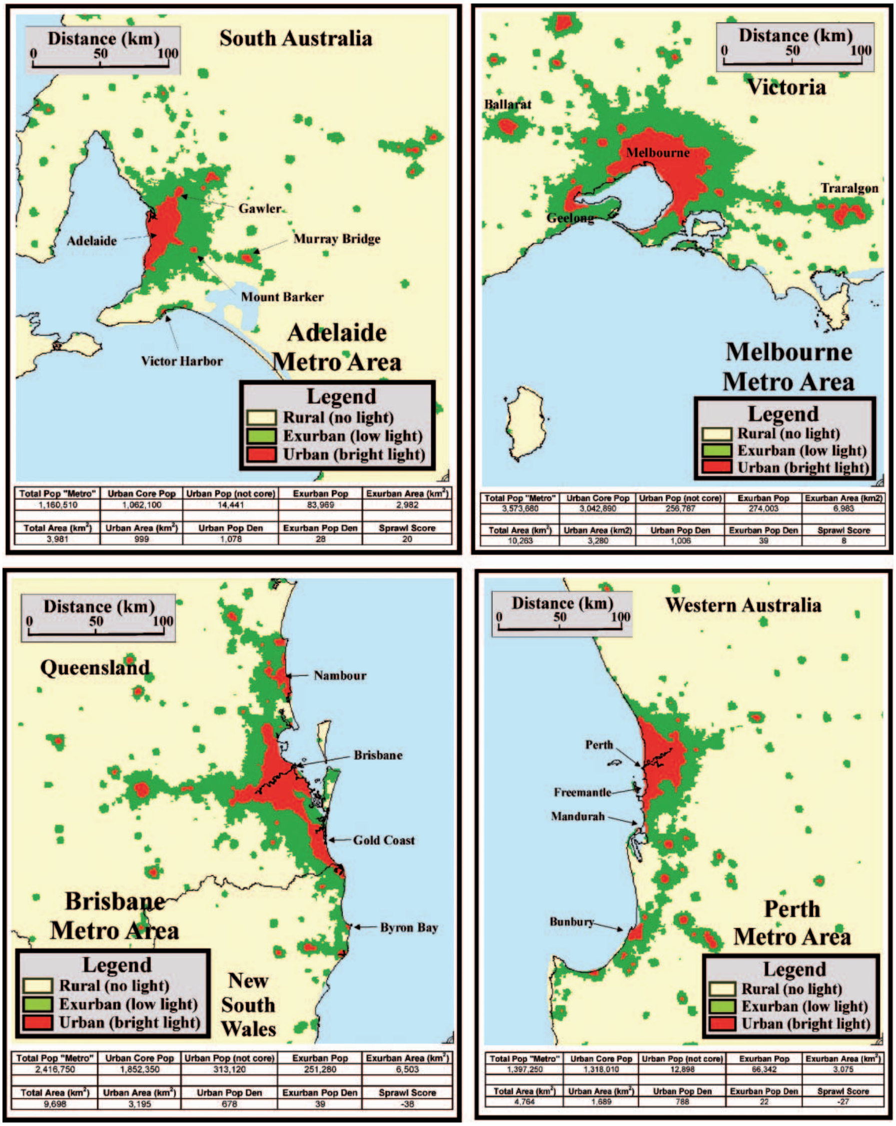
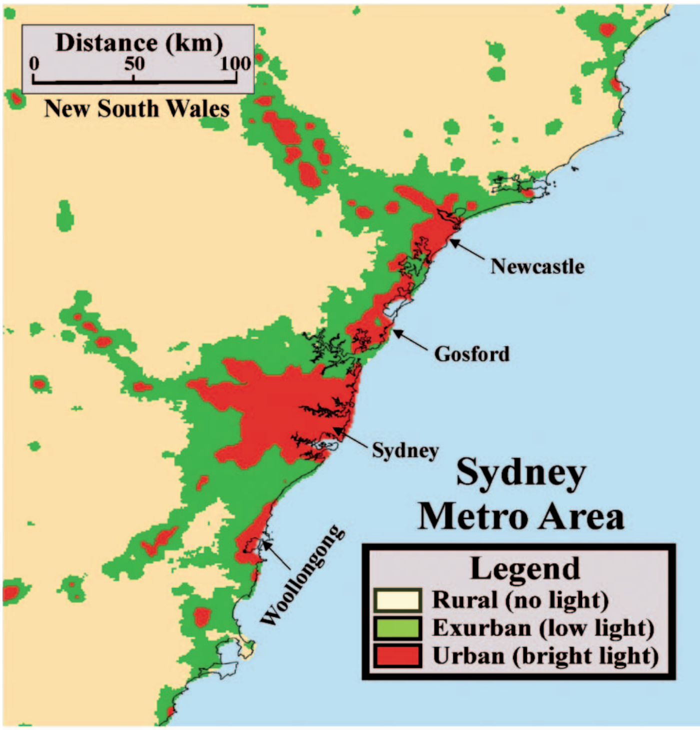


Figure 4 *Urban, exurban, and rural areas of Melbourne, Brisbane, Perth, and Adelaide.*

estate prices suggest that many U.S. exurbanites might be middle-income teachers, police officers, and nurses trying to find affordable real estate in environments with schools, crime rates, and environments they find acceptable. Burnley and Murphy (2004) also note that many retirees and welfare recipients in Australia move to these peri-urban areas for lower real estate costs and because they are not necessarily tied to urban job centers. An interesting question for future exploration is to what extent these factors are influencing the residential location decisions of Australians.

Contrasting the rural or dark areas in the nighttime satellite imagery between the United States and Australia is problematic for several



Total Pop "Metro"	Urban Core Pop	Urban Pop (not core)	Exurban Pop	Exurban Area (km2)
5,137,760	3,760,490	1,000,750	376,520	9,232

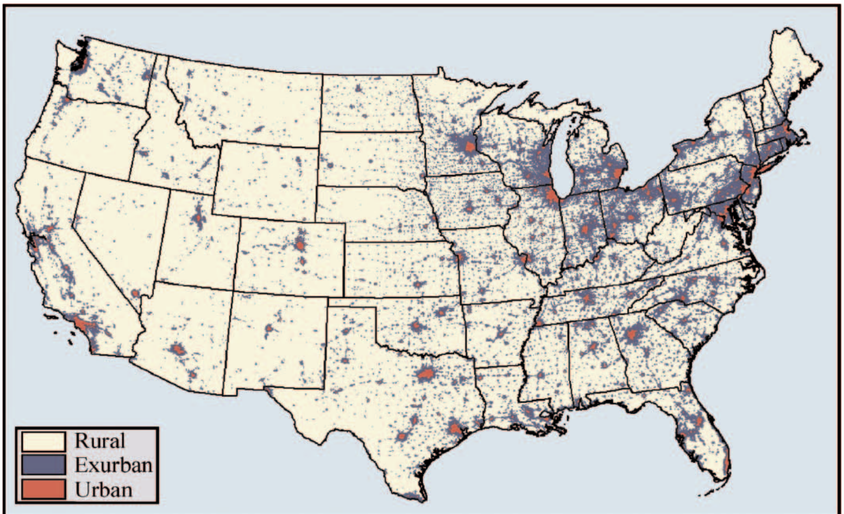
Total Area (km^2)	Urban Area (km2)	Urban Pop Den	Exurban Pop Den	Sprawl Score
13,501	4,269	1,115	41	32

Figure 5 *Urban, exurban, and rural areas of Sydney.*

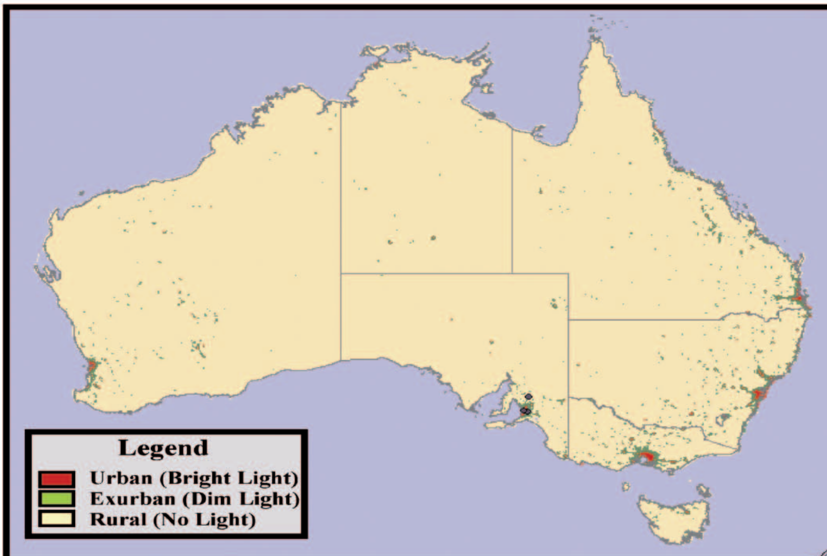
reasons, including the fact that Australia has a huge "no-man's land" in its great outback center and because of the profound difference in the total population of the two nations of approximately equivalent areal extent and level of economic development. Nonetheless, comparison of the urban and exurban populations strikes us as rational and justified because of those similar levels of economic development, relatively similar cultures, and similar levels of energy consumption, gross domestic product per capita (U.S. ~$46,000 and Australia ~$37,500 in 2007), and use of automobiles.

In the United States roughly 37 percent of the population live in these exurban areas as defined by the nighttime imagery (Sutton, Cova and Elvidge 2006); yet, in Australia only 15 percent live there (Figure 6). In contrast, roughly 82 percent of the Australian population live in urban areas, whereas only about 55 percent of Americans do (Figure 6). Clearly, an analysis that does not use nighttime satellite imagery would also suggest that U.S. urban areas sprawl more than Australian urban areas; nonetheless, this analysis demonstrates this reality in significant ways that would be difficult to track with census data alone.

An important question beyond the scope of this article is the future trajectory or dynamics of urban growth patterns in both Australia and the United States. Increasing petrol prices put significant pressure on the viability of living in exurban areas, particularly if the residents of these areas intend to commute to the urban core. The United States has enjoyed relatively low petrol prices for several



Class	Area (km2)	Population	Pop Den	% of Area	% of Population
Rural	6,528,385	23,115,941	4	84.0	8.3
Exurban	1,108,408	102,725,552	93	14.3	37.0
Urban	131,809	151,492,560	1,149	1.7	54.7



Class	Area (km2)	Popualtion	Pop Density	% Area	% Population
Rural	7,027,550	586,612	0.1	98.35	3.3
Exurban	97,261	2,609,560	26.8	1.36	14.5
Urban	20,823	14,832,600	712.3	0.29	82.3

Figure 6 *Contrasting the urban, exurban, and rural areas of Australia and the United States.*

decades, which has probably encouraged exurban sprawl. (In 2004, U.S. average price per gallon was $2.18, whereas Australia's average price per gallon was $5.58.) Australian petrol prices have been higher in both real and relative terms over these years and clearly a smaller fraction of the Australian population has chosen to live in these areas. However, what is the future of peri-urban or exurban sprawl in Australia? Have communities such as Mandurah (outside of Perth) and Mt. Barker (outside of Adelaide) served as nodes for exurban development based on similar American rationales and opportunities? Is Australia ready to sprawl into "exurbia" as the United States already has? What impact will rising petrol prices have on the viability of communities like Mandurah and Mt. Barker?

Conclusion

Nighttime satellite imagery has been used to map urban and an exurban population in the United States and this article demonstrates that the same methods are reasonable for mapping similar urban and exurban environments in Australia. Comparing these results with prior studies of U.S. cities shows that Australia is significantly more urban than the United States and Australia's urban areas do not sprawl in either an urban or peri-urban way relative to those in the United States. Within Australia, Sydney sprawls the least and Brisbane sprawls the most. Perth sprawls a bit, but Melbourne and Adelaide do not. Comparing the peri-urban populations and areal extent of these five big cities is problematic due to the differing degree of conurbation they have with nearby large cities (e.g., Sydney with Newcastle and Woolongong; Brisbane with the Gold Coast; Perth with Freemantle and Mandurah; Melbourne with Geelong; and Adelaide with Mt. Barker). Future demographic, economic, social, political, and ethical decisions and nondecisions will determine whether Australia will move toward or away from the urban and exurban sprawl that presently exists in the United States.

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