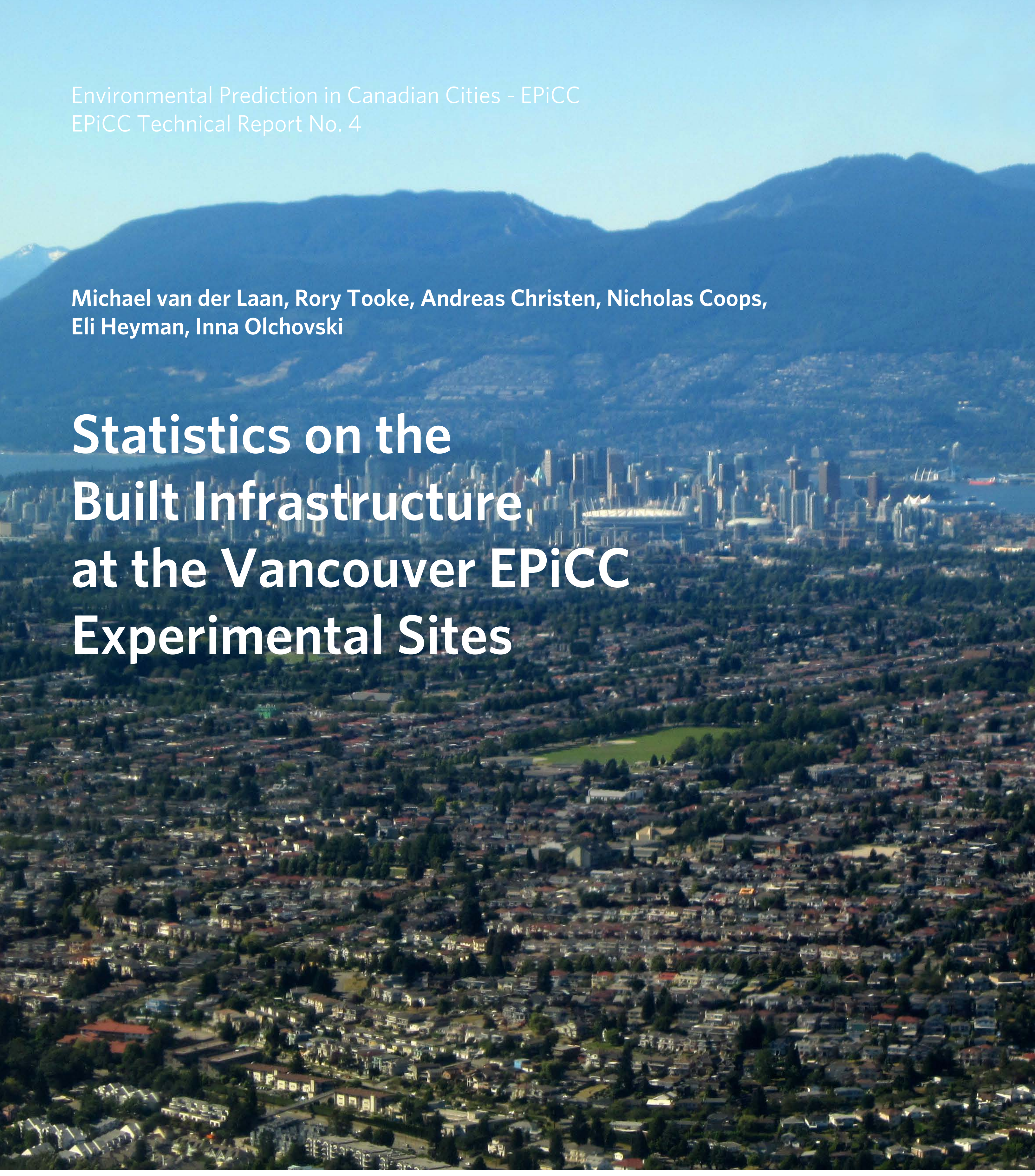
Environmental Prediction in Canadian Cities - EPiCC
EPiCC Technical Report No. 4

Michael van der Laan, Rory Tooke, Andreas Christen, Nicholas Coops, Eli Heyman, Inna Olchovski

Statistics on the Built Infrastructure at the Vancouver EPiCC Experimental Sites



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Cite this report as:

van der Laan, M., Tooke, R., Christen, A., Coops, N., Heyman, E., Olchovski, I. (2012): 'Statistics on the built infrastructure at the Vancouver EPiCC experimental sites'. EPiCC Technical Report No. 4, Technical Report of the Department of Geography, University of Britisch Columbia. http://circle.ubc.ca/, 30pp, Version 1.2

Cover Photo: Aerial view of the 'Sunset' neighborhood in Vancouver with Downtown in the background. Photo by A. Christen

The research network 'EPiCC' was supported by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)

Environmental Prediction in Canadian Cities

CFCAS Network 2006-2010

EPiCC Technical Report No. 4

Statistics on the built infrastructure at the Vancouver EPiCC experimental sites

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University of British Columbia

Version 1.2

March 2012

Introduction

This report includes summary statistics and descriptions of the built infrastructure and population in two study neighbourhoods that were part of the EPiCC network, namely the residential neighbourhoods of 'Vancouver-Oakridge' and 'Vancouver-Sunset'.

As part of the CFCAS network 'Environmental Prediction in Canadian Cities' (EPiCC, 2006-2010), the University of British Columbia / Department of Geography monitored energy, water and carbon balances in two suburban neighbourhoods in Vancouver, BC, Canada in 2008-2010. Two flux towers, 'Vancouver-Sunset' in South-East Vancouver, and 'Vancouver-Oakridge' in South Vancouver, were operated in extensive residential areas composed predominately of single detached homes.

Part 1 of this report lists the built cover (plan area ratios) and 3D-structure (height, sky view factor) of the urban surface in the neighborhoods as required for mesoscale urban parameterizations and ecosystem modeling. Part 2 details a building typology approach and describes building characteristics (building and roof materials, heights, footprint, floor area, etc.). Part 3 describes the population density and distribution.

Note - Details on soil and vegetation characteristics of the residential neighborhoods are given in separate EPiCC technical reports (Chirsten et al., 2010; Liss et al. 2010).

Part 1 – Built cover and three-dimensional structure

Urban surface cover

The building plan area fraction λ_b and the plan area fractions of impervious ground surfaces λ_I are shown in Table 1 and 2 respectively and visualized for Vancouver Sunset as maps in Figure 1. λ_b for Vancouver-Sunset was extracted through LiDAR data from which building footprints were estimated (Goodwin et al. 2009). The statistics for Vancouver-Oakridge are based on manually digitized plan areas traced from 2008 orthophotos provided through Vanmap's open-data catalogue[1].

Table 1 *– Building plan area fraction λ_b at the EPiCC residential sites for radii of various distances from the tower base. Longitude and Latitude refer to tower base. See FigA1.1a for the Vancouver-Sunset area and FigA1.1d for Vancouver-Oakridge area.*

	Lon (WGS-84)	**Lat** (WGS-84)	λ_b **250m radius**	λ_b **500m radius**	λ_b **1000m radius**
Vancouver-Oakridge [a]	-123.132894	49.230564	30%	25%	21%
Vancouver-Sunset	-123.078436	49.226125	23%	29%	29%

[a] 10 degree sector with median building plan area fraction (220 – 230º from geogr. North) instead of full 360º radius from tower

Plan area fractions of impervious ground λ_I was calculated as the residual of the building plan area fraction λ_b reported in Table 1 and the integral plan area fractions of vegetation (lawns and trees) reported in Technical report #3 (Table 1 in Liss et al., 2010), i.e. $\lambda_I = 1 – (\lambda_I + \lambda_v)$:

Table 2 *– Plan area fractions of impervious ground λ_i at the EPiCC residential sites for radii of various distances from the tower base. Longitude and Latitude refer to tower base.*

	Lon (WGS-84)	**Lat** (WGS-84)	λ_i **250m radius**	λ_i **500m radius**	λ_i **1000m radius**
Vancouver-Oakridge	-123.132894	49.230564	9%	20%	23%
Vancouver-Sunset	-123.078436	49.226125	46%	37%	32%

[1] http://www.vancouver.ca/vanmap

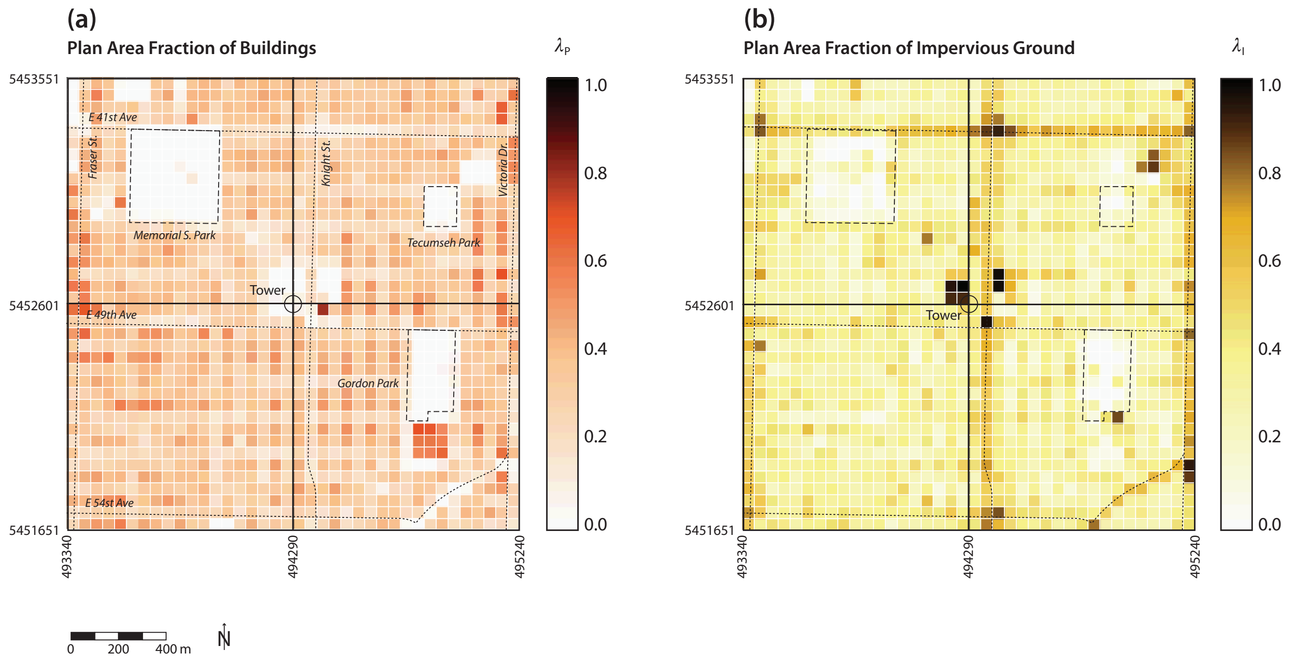


Figure 1 *– Maps of (a) plan area covered by buildings and (b) non-vegetated ground surfaces (streets, driveways, gravel etc.) in the Vancouver-Sunset area within 50 x 50 raster elements. This dataset can be downloaded in 1m and 50 m resolution as GEOTIFF from: http://www.geog.ubc.ca/~epicc/raster/*

Mean building height

The building height (z_H) metrics for "Vancouver-Sunset" were extracted from first-return LiDAR data classified as building (Goodwin et al. 2009). The statistics for "Vancouver-Oakridge" are based on BC-Assessment data from which 'built stories' data was available (See Table 5). This data was then merged with the manually digitized footprints to estimate z_H for "Vancouver-Oakridge". The heights presented in Table 3 for both sites are area-weighted heights of the 3D roofs, not the highest point of the roofs.

Table 3 *– The mean building roof height metrics for the Vancouver-Sunset and Vancouver-Oakridge sites. The standard deviation for values is provided in brackets. See FigA1.1a for Vancouver-Sunset area and FigA1.1d for Vancouver-Oakridge area.*

	Lon (WGS-84)	**Lat** (WGS-84)	**z_H (m) 250m radius**	**z_H (m) 500m radius**	**z_H (m) 1000m radius**
Vancouver-Oakridge [a]	-123.132894	49.230564	5.43	5.79	5.78
Vancouver-Sunset	-123.078436	49.226125	5.00 (1.74)	5.13 (1.85)	5.10 (1.85)

[a] 10 degree sector with median vegetation plan area fraction (220 – 230º from geogr. North) instead of full 360º radius from tower

Table 4 *– The average of the maximum height of roof structures in 50 x 50m grid cells for the Vancouver-Sunset site. The standard deviation is provided in brackets. This corresponds roughly to the average height of the highest roof elements. See FigA1.1a for Vancouver-Sunset area.*

	Lon (WGS-84)	**Lat** (WGS-84)	**Z_H (m) 250m radius**	**Z_H (m) 500m radius**	**Z_H (m) 1000m radius**
Vancouver-Sunset	-123.078436	49.226125	6.28 (2.38)	6.52 (2.44)	6.58 (4.10)

Table 5 *– Building height statistics for Vancouver-Sunset used to derive height estimates for Vancouver-Oakridge. The standard deviation is provided in brackets. See FigA1.1b for area on which statistics were based.*

	Mean height (m)
1 storey buildings	5.68 (0.84)
1.5 storey buildings	6.40 (0.85)
2 storey buildings	7.11 (0.85)
Garages [(a)]	2.50

[(a)] Estimated with less confidence

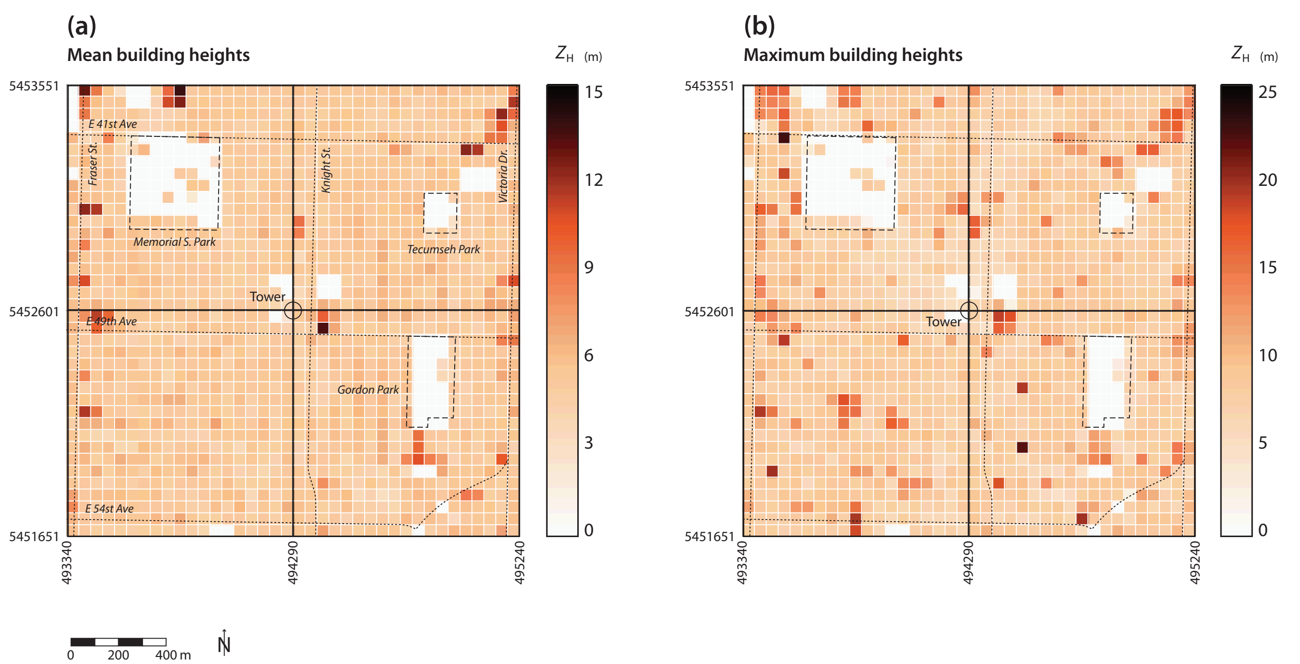


Figure 2 *– Maps of (a) mean building heights and (b) maximum building heights in the Vancouver-Sunset area within 50 x 50 raster elements (corresponds to Tables 2 and 3). This dataset can be downloaded as a GEOTIFF from: http://www.geog.ubc.ca/~epicc/raster/*

Vertical profile of building volumes

The vertical distribution of built volume for "Vancouver-Sunset" was extracted from first-return LiDAR data classified as building. Further details on building volume are presented in Part 2 where the statistics have been summarized according to building type. See FigA1.1b for the area on which statistics were based.

Table 6 *– Vertical distribution of built form within a 1900 x 1900 m box around the tower.*

Height layer (m)	**Average building volume density (m^3 m^{-3})**	**Relative building volume (%)**
0-1	0.2898	100.0%
1-2	0.2884	99.5%
2-3	0.2772	95.7%
3-4	0.2436	84.1%
4-5	0.1988	68.6%
5-6	0.1134	39.1%
6-7	0.0588	20.3%
7-8	0.0252	8.7%
8-9	0.0140	4.8%
9-10	0.0112	3.9%
10-11	0.0084	2.9%
11-12	0.0056	1.9%
12-13	0.0028	1.0%
13-14	0.0014	0.5%
14-15	0.0014	0.5%

Building density

Table 7 *– Building density for a 500 m radius around Vancouver-Sunset and Vancouver-Oakridge towers. Data presented does not include garages. See FigA1.1a for Vancouver-Sunset area extent.*

	Buildings/ha
Vancouver-Sunset	12.80
Vancouver-Oakridge [a]	8.03

[a] Vancouver-Oakridge statistics are based on City of Vancouver cadastral data.

Sky view factor

The sky view factor ψ_{Sky} is defined as the fraction of radiant flux leaving a certain surface (or object) that is intercepted by the sky (Watson and Johnson, 1987). For instance, a ψ_{sky} of 1 describes a completely unobstructed view from a particular surface where all radiation emitted by a surface is reaching the sky. A ψ_{sky} of 0 describes a completely obstructed view, where all radiation emitted by a surface is intercepted by other facets of the urban surface (walls, trees, roofs etc.). The ψ_{sky} can bedetermined for any point (x,y,z) in an urban canopy but is typically reported for ground level for a horizontal receiving surface. The procedure and definitions that were used to calculate ψ_{sky} are described in Appendix 2.

Table 8 *– The average sky view factor ψ_{sky} at ground level and for all horizontal surfaces in Vancouver-Sunset for different radii around the tower. See FigA1.1a for Vancouver-Sunset area.*

Vancouver-Sunset	**Lon** (WGS-84)	**Lat** (WGS-84)	ψ_{Sky} **250 m radius**	ψ_{Sky} **500 m radius**	ψ_{Sky} **950 m radius**
Ground level only	-123.078436	49.226125	0.31	0.27	0.28
All horizontal surfaces	-123.078436	49.226125	0.60	0.60	0.60

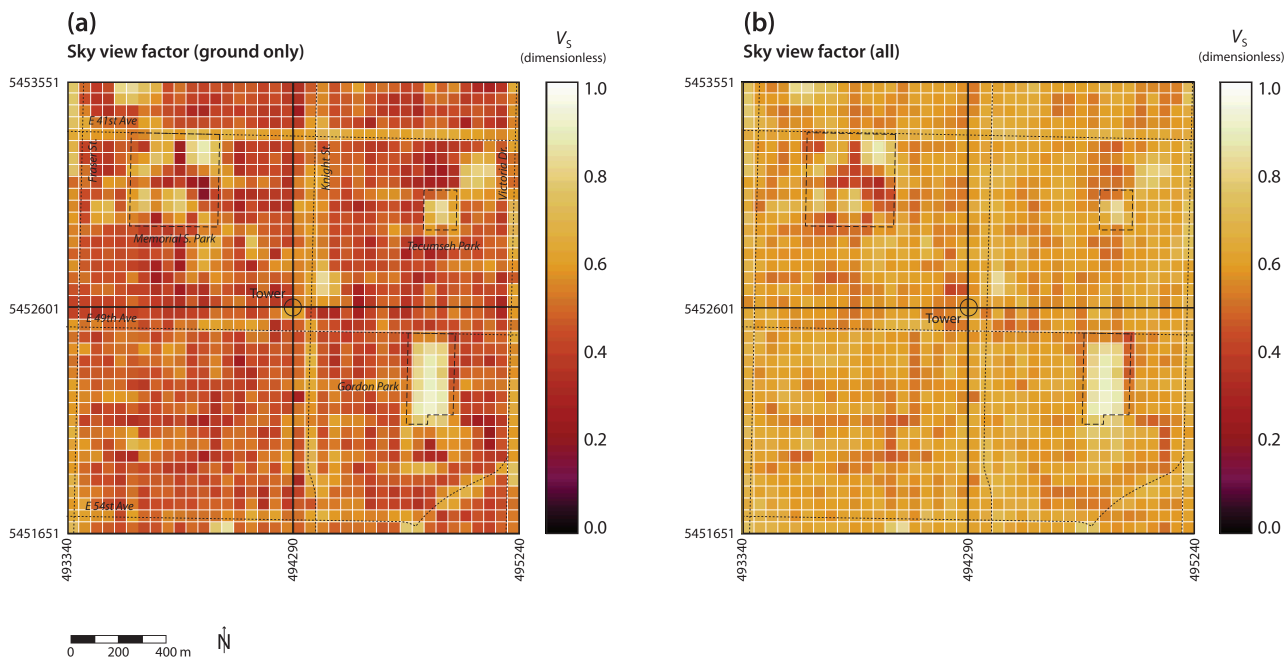


Figure 3 *– Maps of the sky view factor ψ_{sky} for all surfaces at ground level not including ψ_S within buildings or trees (left) and the sky view factor of all horizontal surfaces including roof and tree elements (right) for the Vancouver-Sunset area within 50 x 50 raster elements. This dataset can be downloaded as a GEOTIFF from:* [*http://www.geog.ubc.ca/~epicc/raster/*](http://www.geog.ubc.ca/~epicc/raster/)

Figure 4 *– Map of the sky view factor ψ_{sky} at ground level, from ψ_{sky} =1 (white) to ψ_{sky} =0 (black). Values within buildings or trees are included, drawn black) or for the Vancouver-Sunset area within 1 x 1 m raster elements. This dataset can be downloaded as a GEOTIFF from: http://www.geog.ubc.ca/~epicc/raster/*

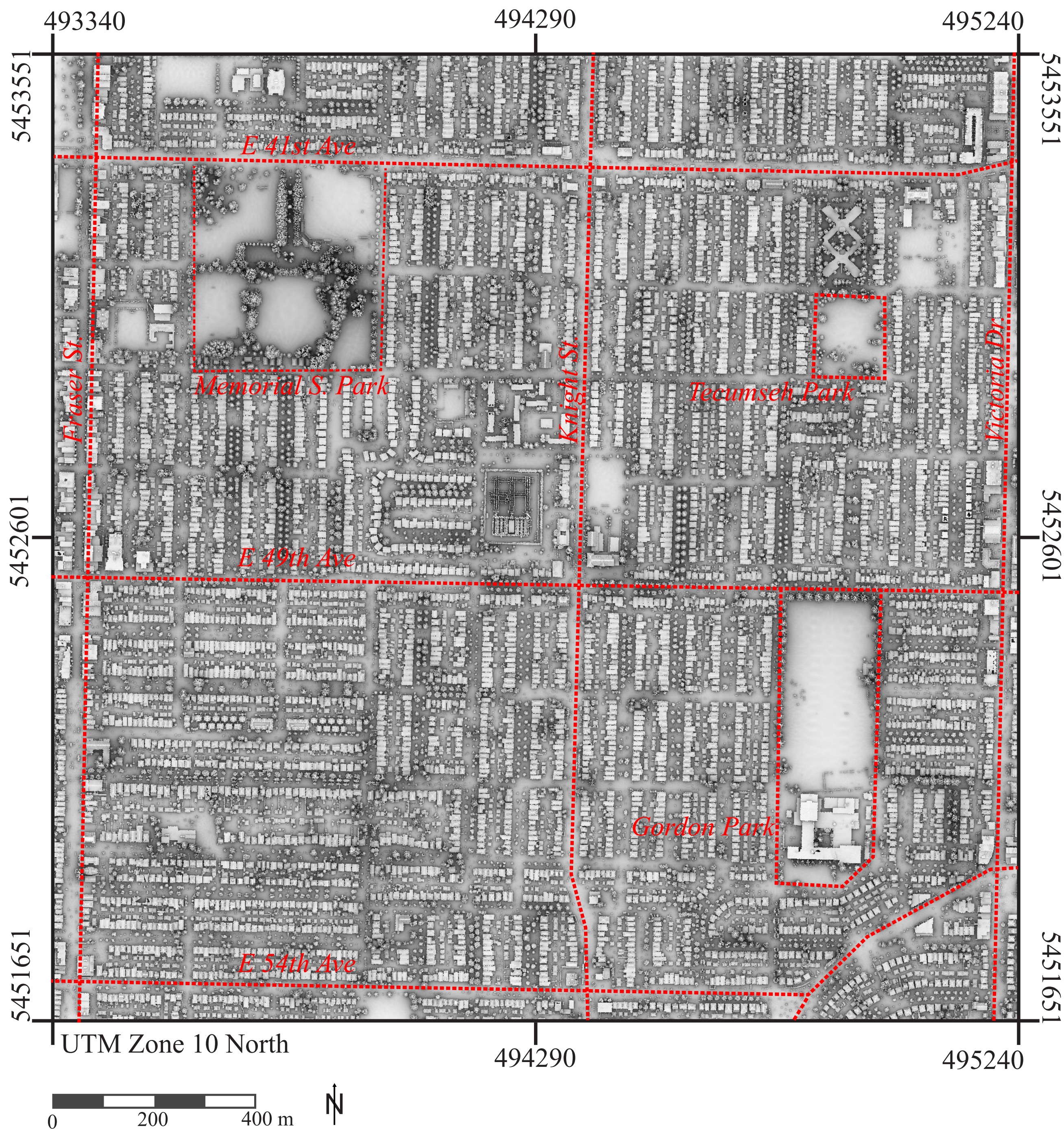


Figure 5 *– Map of the sky view factor ψ_{Sky} for all horizontal surfaces including roof and tree elements for the Vancouver-Sunset area within 1 x 1 m raster elements. A value of ψ_{sky} =1 is displayed in white, ψ_{sky} =0 is black. This dataset can be downloaded as a GEOTIFF from: http://www.geog.ubc.ca/~epicc/raster/*

Part 2 – Building typology

What is a building typology?

A building typology is a classification of the built environment according to one or several criteria. Common typologies group buildings according to their use, vintage and morphology (e.g. detached, attached and stacked dwelling types). This type of classification is helpful when outlining potential development patterns or when characterizing the existing urban form. It is advantageous to energy mapping exercises if classifications not only capture patterns in built morphology but also anticipate other characteristics such as the energy intensity differences amongst building types.

Building energy use is a product of space heating, cooling, lighting, domestic hot water use, ventilation and auxiliary equipment loads. The energy required for the above proposes can be supplied by a variety of sources – including coal-fired electricity, hydro electricity, natural gas, biomass, solar thermal, solar voltaic, sewage heat recovery, ocean, wind and nuclear power. The amount of energy consumed by a building depends on its use, local climate and context, system and equipment efficiencies, materials, construction, and occupant behavior.

What is an urban archetype?

An urban archetype is an extension of the building typology approach, where common characteristics of a neighbourhood are grouped together. Using this approach, it is assumed that a city is not only made up of repeated building types but also of repeated patterns of development. The characteristics of an individual neighbourhood may include land use, building type, urban morphology and other important attributes (e.g. energy consumption and travel behaviour). An archetype is typically constructed through the synthesis of several data sources - such as census, municipal, utility and survey data.

Vancouver-Sunset Building Archetypes

A total of 18 building archetypes were selected for the Vancouver-Sunset neighbourhood. Data for the selected archetypes was compiled by first merging 2009 BC-Assessment data with City of Vancouver municipal cadastral data. This was done through a unique property identifier, linking non-geospatial data with geospatial parcel data in ARCGIS. This data was then merged with LiDAR information to provide the built infrastructure statistics presented in Table 9. The statistics presented in Table 9 do not include garages and the mean floor area statistics are based on regression analysis of BC-Assessment data (See FigA1.1b for area). For further reference on the building archetypes presented in Tables 9-13 see Appendix 2.

Table 9 *– The built infrastructure statistics for individual building archetypes in Vancouver-Sunset.* [(a)] *See FigA1.1b for area on which statistics were based.*

	No of Buildings	**Mean Bldg. height (m)**	**Mean Bldg. Footprint (m^2)**	**Mean Bldg. Volume (m^3)**	**Mean Floor Area (m^2)** [(b)]
Single Detached pre 1965	868	5.4	109	580	149
Single Detached pre 1965 (with suite)	649	5.5	113	612	158
Single Detached 1965-90	510	5.7	154	875	226
Single Detached 1965-90 (with suite)	1034	5.8	162	943	243
Single Detached post 1990	469	7.1	122	850	219
Single Detached post 1990 (with suite)	615	6.9	128	879	227
Single Detached other	11	5.3	135	694	179
Duplex	22	6.4	121	743	192
Row-house	2	6.1	846	5,194	1,338
Multi-family conversion	21	7.2	118	846	216
Apartment	7	6.6	1145	1,839	2,965
Mixed-use	73	6.4	309	2,011	518
Commercial retail	81	5.3	403	2,246	578
Commercial office	16	5.8	470	3,163	815
Commercial other	6	4.7	443	2,253	582
Extended care	3	8.9	305	3,326	857
Industrial / Warehouse	2	5.5	530	2,925	753
Civic	26	7.2	1604	11,937	3,075
Total [(c)]	**4,421**		**667,594**	**4,024,884**	**1,040,455**
Per urban area	**12.2** Build. ha^{-1}		**0.18** $m^2\ m^{-2}$	**1.11** $m^3\ m^{-2}$	**0.28** $m^3\ m^{-2}$

[(a)] Statistics do not include garages.
[(b)] Floor area estimate are estimated through regression analysis based on 2009 BC Assessment data and do not include garages.
[(c)] Total values have been based on all buildings (partial values included for those clipped) within 1900 x 1900 m of the Sunset tower, and therefore vary from values reported in Part 1 (which considers various radii around tower).

Building surface properties

Building surface properties were documented for single detached dwellings in Vancouver-Sunset – the dominant building archetype found within the neighbourhood. Statistics in Tables 10-13 are based on field survey data collected in the spring of 2010. This dataset contains the visual documentation of façade and roofing materials for 281 single detached buildings in the Vancouver-Sunset area (See FigA1.1c for area). For further reference on the building archetypes presented in Tables 9-13 see Appendix 3.

Table 10 *– Percentage of built area consisting of various roofing materials for single detached dwellings in Vancouver-Sunset. See FigA1.1c for area on which statistics are based.* [a]

	Asphalt	Clay	Slate	Gravel	Metal
Single detached Post 1990	56	43	1	0	0
Single detached 1965-90	43	25	0	14	19
Single detached Pre 1965	96	0	0	0	4

[a] Statistics are based on a visual survey of 281 buildings was conducted in the spring of 2010

Table 11 *– Percentage of roof area (See Table2.10) consisting of various colours for single detached dwellings in Vancouver-Sunset. See FigA1.1c for area on which statistics are based.* [a]

	Beige	Black	Blue	Brown	Green	Grey	Grey (light)	Grey (dark)	Red
Single detached Post 1990	1	11	0	29	0	19	0	14	25
Single detached 1965-90	0	6	0	14	0	27	12	5	36
Single detached Pre 1965	2	31	5	18	4	15	13	6	4

[a] Statistics are based on a visual survey of 281 buildings was conducted in the spring of 2010

Table 12 *– Percentage of built area consisting of various facade materials for single detached dwellings in Vancouver-Sunset. See FigA1.1c for area on which statistics are based.* [a]

	Wood	Brick	Stucco	Concrete	Vinyl
Single detached Post 1990	2	8	79	0	11
Single detached 1965-90	12	11	59	0	18
Single detached Pre 1965	23	3	64	0	11

[a] Statistics are based on a visual survey of 281 buildings was conducted in the spring of 2010

Table 13 *– Percentage of facade area (See Table2.10) consisting of various colours for single detached dwellings in Vancouver-Sunset. See FigA1.1c for area on which statistics are based.* [a]

	Beige	Blue	Brown	Green	Grey	Pink	Red	White	Yellow
Single detached Post 1990	34	4	9	9	15	22	1	5	0
Single detached 1965-90	19	3	2	3	10	1	1	58	4
Single detached Pre 1965	18	1	3	0	39	1	0	33	5

[a] Statistics are based on a visual survey of 281 buildings was conducted in the spring of 2010

Part 3 – Population density

Accurate distribution of population[2] is important for a variety of applications, including the calculation the energy load and the spatial estimation of the sources of human respiration and anthropogenic heat. Statistics Canada provides population and housing data as fine as a census dissemination area (DA) (approximately 150 homes), which does not allow for population to be assessed at the dwelling level. Using LiDAR data, the spatial resolution of the census population densities (Statistics Canada, 2006 census) has been resampled to 50 x 50m grid cell elements. Firstly, average fractional population were assigned to individual buildings, this data was then up-scaled to create a map of 50 x 50m grid-cells of population density (Figure 9). These uniform grid cells make it possible to assign average population densities to areas of different radii around the Tower (Table 7) as well as for use in source area models. Statistics Canada census data, British Columbia Assessment data and LiDAR volume data were combined in order to complete this task. Appendix 3 lists a detailed description of the resampling methodology.

Because LiDAR Data was not available for Oakridge, these population densities were calculated simply by dividing the total area of DAs within various distances of the tower by their population in the 2006 Canadian census.

Table 14 *- Nighttime population densities of different radii around Oakridge and Sunset towers. See FigA1.1a for Vancouver-Sunset area.*

	Lon (WGS-84)	**Lat** (WGS-84)	**Inh./ha 250m radius**	**Inh./ha 500m radius**	**Inh./ha 1000m radius**
Vancouver-Oakridge [(a)]	-123.132894	49.230564	26.9	29.3	27.6
Vancouver-Sunset	-123.078436	49.226125	49.2	65.9	63.1

[(a)] Vancouver Oakridge data is based on Statistics Canada data (2006) and involved no LiDAR attribution steps

[2] It is important to note that census data provides *nighttime* residential population only, so in Part 3 "population" must always be read as "nighttime residential population".

Table 15 *- Population densities for areas of different radii around Sunset Tower (Fig 9a).* See FigA1.1a for Vancouver-Sunset area.

Circle of radius (m) from tower base	Total residential population (Inh.) within circle	Residential population density (Inh. ha^{-1})
100	27	8.7
200	421	33.5
300	1637	57.9
400	3026	60.2
500	5176	65.9
600	7555	66.8
700	9975	64.8
800	12305	61.2
900	16032	63.0

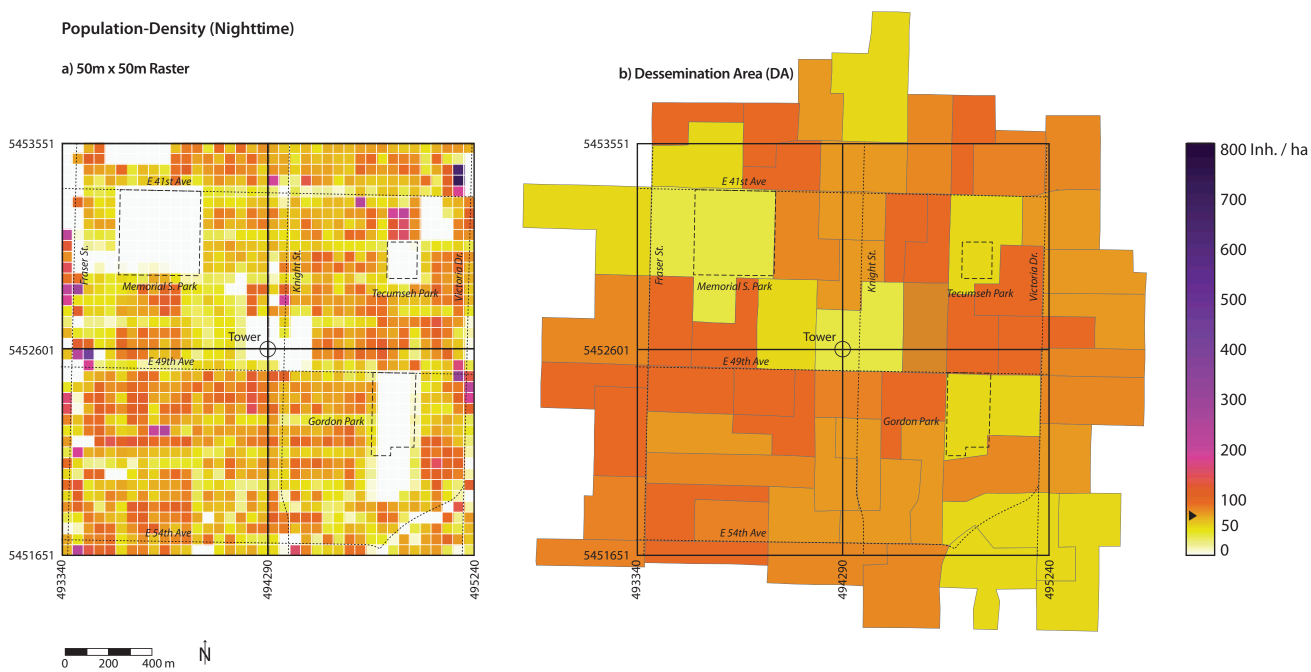


Figure 7 *– (a) 50m x 50m raster of nighttime population density (inh./ha) in the Sunset area using the steps outlined above (sec 3.1 and sec. 3.2) and (b) population densities displayed using only Statistics Canada census data. Although the DA map shown in (b) is for Vancouver- Sunset, this is the method used for Vancouver-Oakridge.*

Appendix 1 – Study areas for building statistics

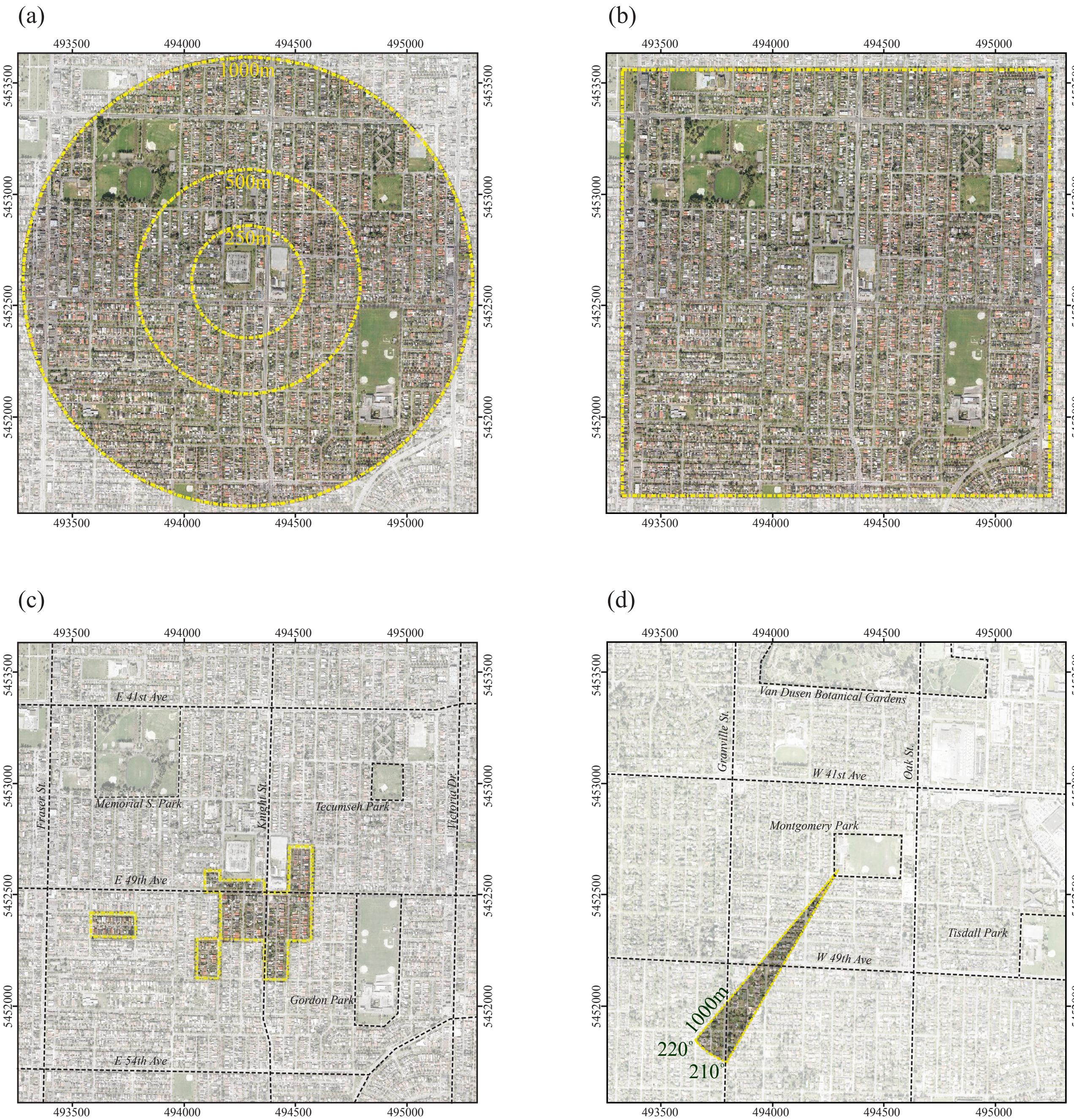


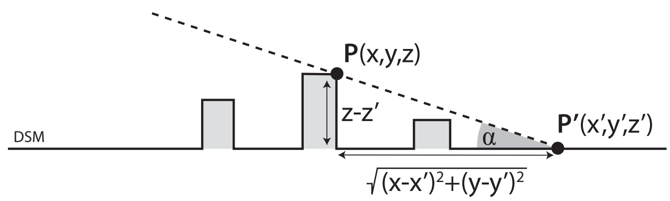
Figure A1.1 *– (a) radii of 250 m, 500m and 1000 m around the Vancouver Sunset tower (b) 1900 m x 1900 m LiDAR extent around the Vancouver Sunset tower (c) field survey extent (d) 220 – 210 degree sector extent extending 1000 m from the Vancouver Oakridge tower*

Appendix 2 – Calculation of sky view factor maps

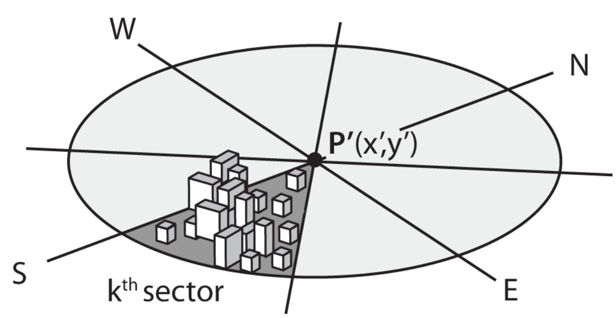
The sky view factor ψ_{sky} can be calculated a number of ways - for example through idealized geometries, using building height to width ratios (Oke, 1981), fish eye photographs (Brown et al., 2001) or 3D surface data (Ratti et al., 2003). Here an approach based on a digital surface model (DSM) in raster format is used.

For each raster element *P'(x',y')* of the DSM at 1m resolution, the horizon obstruction around the point was calculated by determining the element *P(x,y)* that causes the highest obstruction angle α. This was calculated for point clouds *P(x,y)* within narrow sectors originating at *P'(x',y')*:

$$\alpha = \arctan\left[\max\left(\frac{\sqrt{(x-x')^2+(y-y')^2}}{z-z'}\right)\right]$$



Objects were all treated opaque (including trees) and no holes were expected below the highest return (the height in the DSM): This procedure was repeated to determine α*(k)* for *N* different sectors around the point *P'(x',y')* in different directions (in the figure below there are 8 sectors, but calculations were done with 16 sectors):



With known $\alpha(k)$, the sky view factor was then determined using the following equation, which is a sectorial approach based on Oke 1987 (p.353, the 'basin case'):

$$\psi_{sky} = \frac{1}{N}\sum_{k=1}^{N}\cos^2\left(\alpha\left(k\right)\right)$$

The area average of ψ_{sky} (‘all horizontal surfaces’) was calculated as the average ψ_{sky} (x’y’) of all pixels located within the region of interest and includes pixels on roofs and trees.

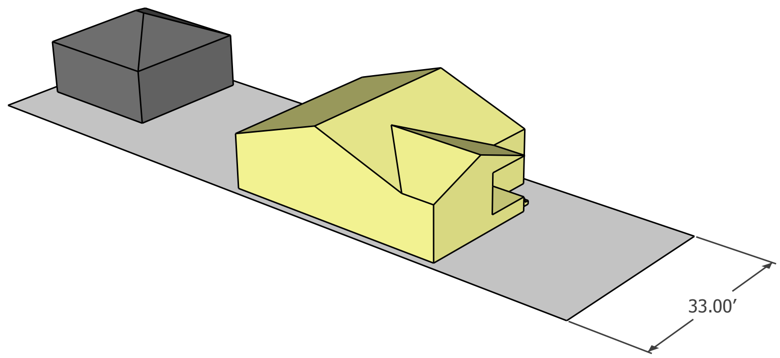
The area average ψ_{sky} over an area at ground level (‘Ground only’) was calculated as the average ψ_{sky} (x’y’) of only pixels located at the ground level (z < 0.5m) within the region of interest but excluding pixels with z > 0.5 in the average (i.e. the interior of buildings or trees).

Appendix 3 – Building archetype data

Figure A2.1 *– Vancouver-Sunset building archetypes (a) Row-house (b) Duplex (c) & (d) Single detached post 1990 (e) & (f) Single detached 1965-90 (g) & (h) Single detached pre 1965*

Figure A2.2 *– Vancouver-Sunset building archetypes (a) Extended care (b) Industrial/Warehouse (c) Civic (d) Commercial office (e) Commercial retail (f) Commercial other (g) Apartment (h) Mixed-use*

Archetype - Single Detached Dwelling Pre 1965



Vintage: constructed prior to 1965
Roof shape: low to medium complexity typically of high slope
Building height: larger variation in height amongst buildings
Building footprint: lower building footprint to lot area ratios
Building volume: lower building volumes with typically no attached garages

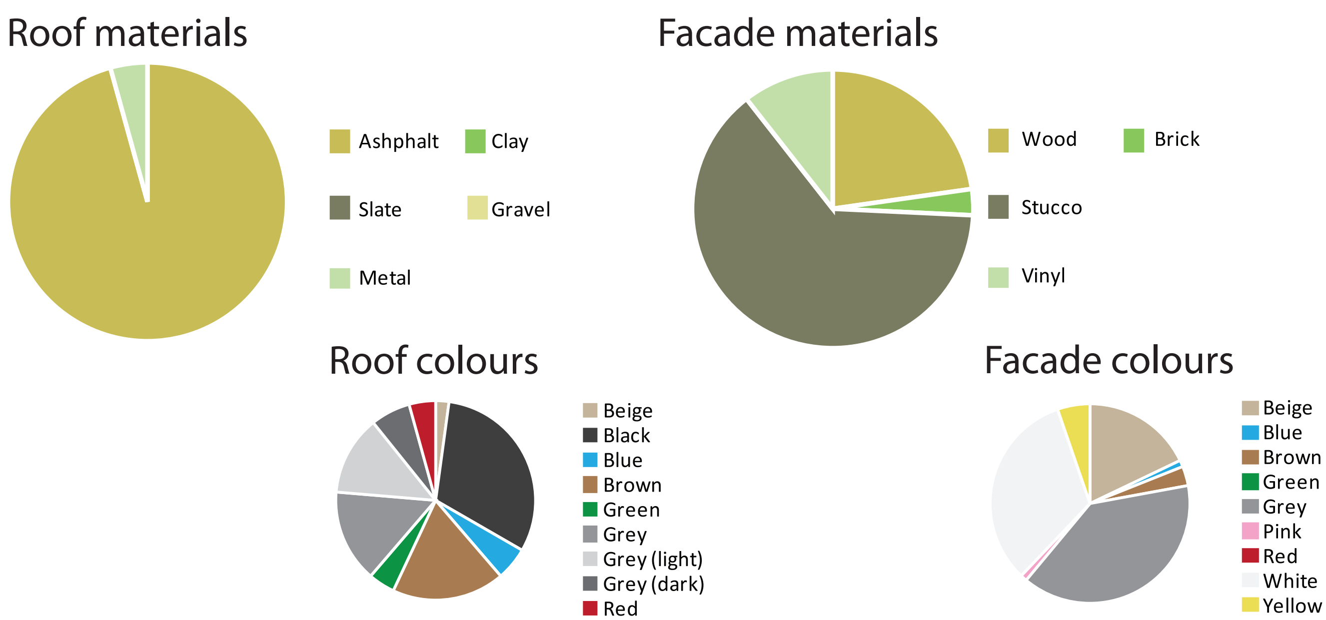
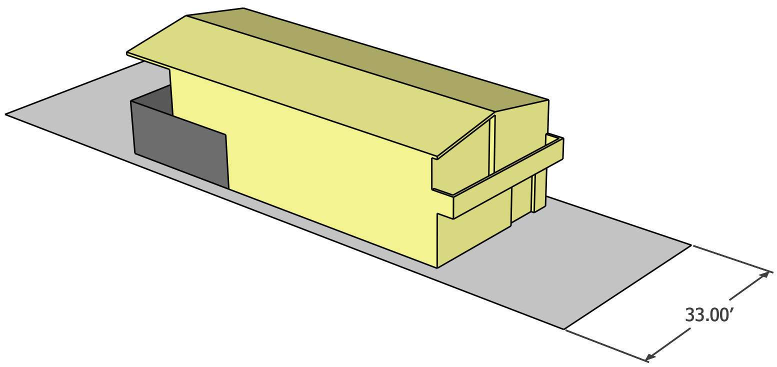


***Figure A2.3** – Building metrics for the Single detached dwelling (pre 1965). Statistics are based on a field survey conducted in February and March of 2010. See appendix for survey extent.*

Archetype - Single Detached Dwelling 1965-90



Vintage: constructed between 1965 and 1990
Roof shape: simple low slopping gable roof
Building height: medium height typically two stories slab on grade
Building footprint: maximized building footprint to lot area ratios
Building volume: large volume which often includes attached garage or tuck under parking

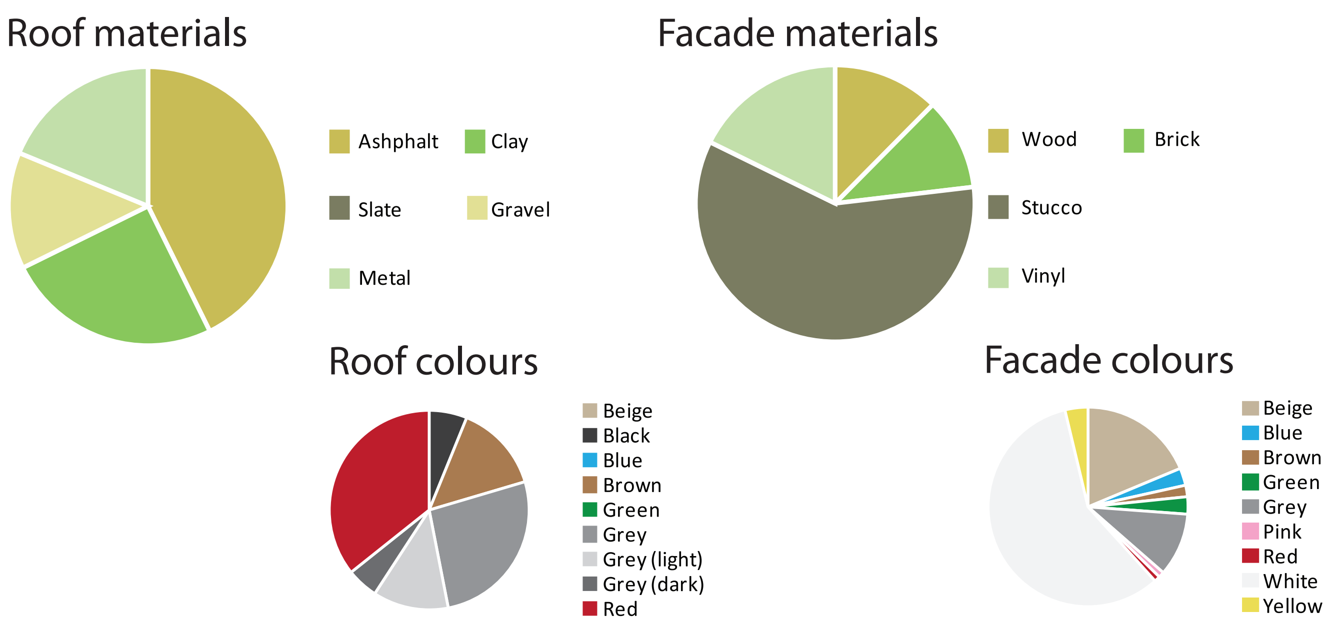
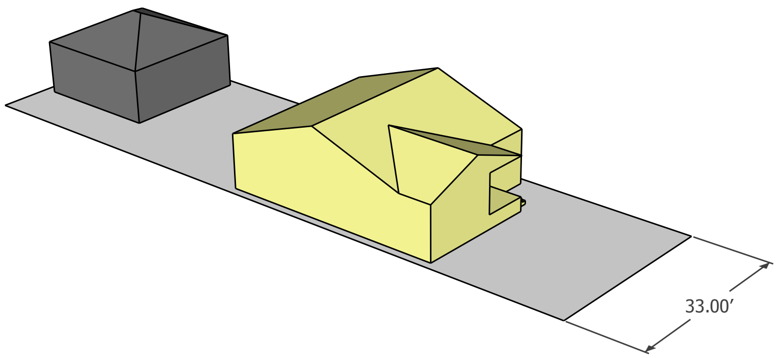


Figure A2.4 *– Building metrics for the Single detached dwelling (1965-1990). Statistics are based on a field survey conducted in February and March of 2010. See appendix for survey extent.*

Archetype - Single Detached Dwelling Pre 1965



Vintage: constructed prior to 1965
Roof shape: low to medium complexity typically of high slope
Building height: larger variation in height amongst buildings
Building footprint: lower building footprint to lot area ratios
Building volume: lower building volumes with typically no attached garages

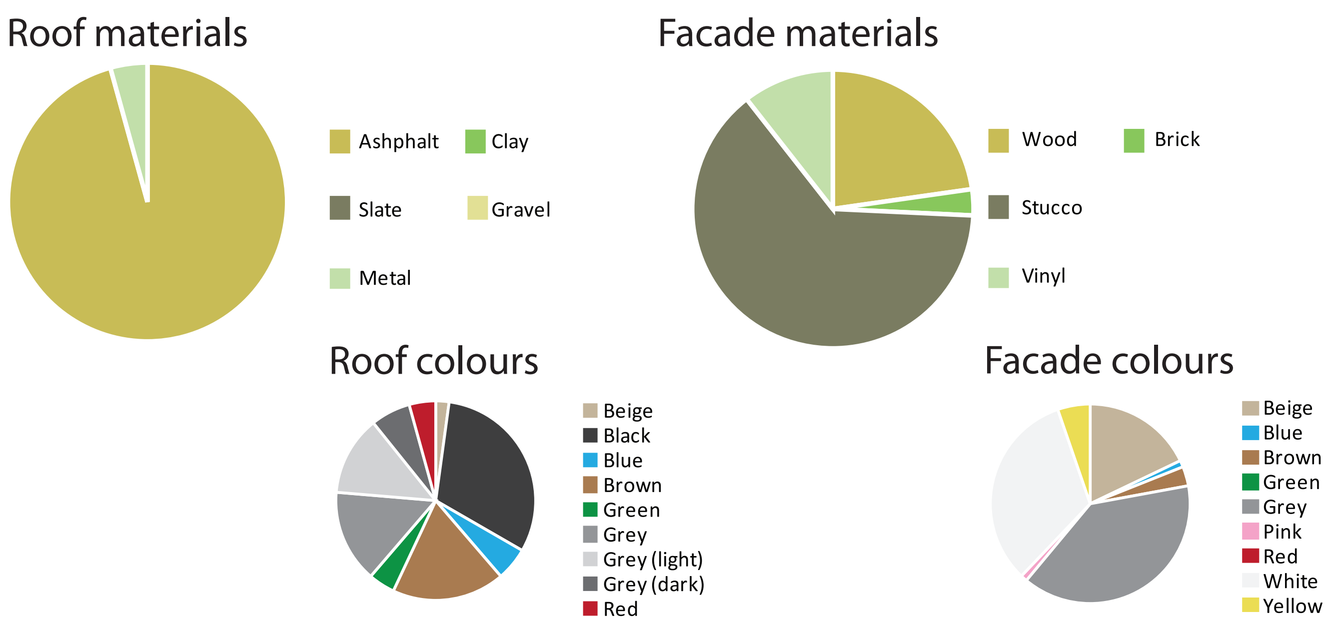


***Figure A2.5** – Building metrics for the Single detached dwelling (post 1990). Statistics are based on a field survey conducted in February and March of 2010. See appendix for survey extent.*

Appendix 4a – Procedure for down-sampling population density using LIDAR

Attribution of population to individual buildings

1) Census data was used to separate population based on *dwelling type*. Residential buildings were separated into two categories; either ground-oriented or apartment (see Tab. A4.1). Census data gives us total population (P_{total}) for each DA, but the number of inhabitants living in apartment dwellings (P_{apt}) vs. ground-oriented dwellings (P_{GO}) is not directly provided by the census data and needed to be calculated separately for each DA:

$$P_{total} = P_{apt} + P_{GO} \tag{1}$$

Census data, however provides the total number of dwellings (D_{total}) and the number for different dwelling types D_{appt} and D_{go} for each DA:

$$D_{total} = D_{apt} + D_{GO} \tag{2}$$

A linear regression through P_{total}/D_{total} vs. D_{apt}/D_{total} with data from all 61 DAs in the study area (Fig. A4.1) showed that on average for the study area

$$P_{apt}/D_{apt} = 2.3 \text{ Inhab.} / \text{apartment} \tag{3}$$

and

$$P_{GO}/D_{GO} = 3.5 \text{ Inhab.} / '\text{ground} - \text{oriented}' \text{ dwelling} \tag{4}$$

Table A4.1 *- Simplified residential building classification based on census data and BC land use assessment data.*

Ground-oriented dwellings		**Apartment dwellings**	
Type of dwelling (census data)	*Land use type (BC assessment data)*	*Type of dwelling (census data)*	*Land use type (BC assessment data)*
Single-detached house	SFD no suite, SFD with suite, or Section 19	Apartment, building that has five or more storeys	Mixed use, or Multi-storey
Semi-detached house	SFD no suite, SFD with suite, or Section 19	Apartment, building that has fewer than five stories	Mixed use or Multi-storey
Row house	Row house		
Apartment, duplex	Duplex		

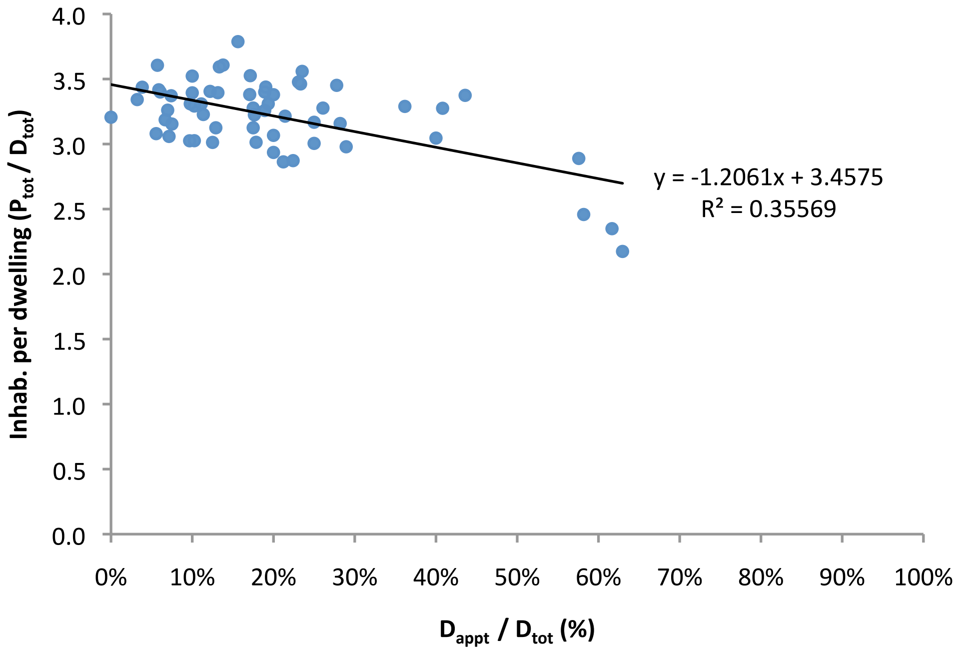


Figure A4.1 *- Regression of P_{total} /D_{total} vs. D_{appt} /D_{total} for all 61 dissemination areas (DAs) districts in the Study area of Vancouver Sunset (1900 x 1900m).*

Those relationships are only valid on average for the study area. Assignments in individual DAs might depart, but we postulate that for all DAs the ratio stays constant, i.e.

$$\mathbf{r} = \frac{P_{apt}/D_{apt}}{P_{GO}/D_{GO}} = \frac{2.25}{3.46} = 0.651 = \frac{P_{apt}D_{GO}}{D_{apt}P_{GO}} \tag{5}$$

This means that, on average, it is expected that the number of inhabitants in an apartment is 65.1% of the number of inhabitants in a ground-oriented dwelling. Solving for P_{apt} and use Eq. (1) to replace $P_{GO} = P_{total} - P_{apt}$ leads to

$$P_{apt} = \mathbf{r} \cdot \frac{D_{apt}}{D_{GO}}(P_{total} - P_{apt}) \tag{6}$$

rearrangement gives:

$$P_{apt} = \frac{\mathbf{r}P_{total}}{\left(\frac{D_{GO}}{D_{apt}} + \mathbf{r}\right)} \tag{7}$$

and similarly

$$P_{GO} = \frac{1}{\mathbf{r}} \cdot \frac{D_{GO}}{D_{apt}}(P_{total} - P_{GO}) \tag{8}$$

$$P_{GO} = \frac{P_{total}}{\left(\mathbf{r}\frac{D_{apt}}{D_{GO}} + 1\right)} \tag{9}$$

Eq. 7 and 9 were used to calculate P_{apt} and P_{GO}.

2) BC Assessment data was then used to classify all buildings in the study areas as one of three *building types*: (a) Non-residential (all commercial and institutional buildings), (b) residential apartment and (c) residential ground-oriented buildings (includes single-family detached homes, duplexes and row houses). It is assumed that the three classes go with different population densities per floor area or volume. Non-residential buildings are assumed to have no population. Similar classes to (b) and (c) exist in the census data (unit type) for each DA (see Tab. 3.1). In certain cases BC Assessment data was not available or incorrect, so information was confirmed or reassigned manually by using aerial photos. The number of each building type was then counted in each complete DA.

3) The LiDAR analysis (see Part 2) assigned a volume to each building. This allowed in combination with the BC assessment data to calculate an average (or total) volume per building type in each of the DA.

4) A subset of the DAs were selected that were (i) completely within the study area (i.e. LiDAR data available) and (ii) contained at least one apartment building according to the BC Assessment data. The partial DAs on the border may contain significant changes in urban form or land use mix in an area that is not included in the LiDAR data and were therefore not used to derive the relationships. DAs without apartments were excluded because this was a requirement for the calculation of adjusted volume (step 5). For complete DAs with apartments, the total number of inhabitants per dwelling type (step 1) and the corresponding total volume per building type (step 3) were extracted. The resulting numbers were summed for all complete DAs (see Tab. 3.2).

5) Using the totals for all complete DAs from step 4, a series of global (study area-wide) parameters were extracted in order to establish the average volume occupied by a person (m^3 Inh^{-1}) living in either an apartment or ground-oriented dwelling (Tab. 3.2). This was done by dividing the total volume of each building type by the total number of inhabitants in the corresponding dwelling type (both from step 4). For example, for ground-oriented dwellings:

$$\begin{aligned} Average\ building\ vol./inhab. &= \frac{Total\ building\ vol.\ in\ complete\ DAs}{Total\ population\ in\ complete\ DAs} \\ &= \frac{1\ 350\ 270 m^3}{7\ 990 inh.} = 169.0 m^3 inh.^{-1} \end{aligned} \tag{10}$$

These values were then used to create attribution factors f_a:

$$\begin{aligned} f_a\ (G.O.) &= \frac{Avg.\ vol./apartment\ inhab.}{(Avg.\ vol./G.O.\ inhab.) + (Avg.\ vol./apartment\ inhab.)} \\ &= \frac{90.12}{90.12 + 169.0} = 0.70 \end{aligned} \tag{11}$$

Where f_a is a 'volume adjustment'. It is assumed that a person in an apartment occupies less space than someone living in a ground oriented dwelling. Essentially the 'volume adjustment' is increasing the volume of apartments and decreasing the volume of ground-oriented dwellings so that the number of inhabitants in a building can be assigned based on its percentage of DA 'adjusted volume' regardless of its type (see steps 6 and 7).

Table 2 *– Global parameters of population statistics for all dissemination areas (DAs) that are contained completely by the LiDAR transect and have at least one apartment building.*

Building type	**Total building volume (m^3)**	**Percentage of volume (%)**	**Total population**	**Percentage of population in building type**	**Average volume per inhabitant (m^3 Inh^{-1})**	f_a
Ground-oriented	1,350,270	70.5%	7,990	85.1%	169.0	0.70
Apartment	182,533	9.5%	2,025	14.9%	90.12	1.30
Non-residential	381,241	19.9%	0	0%	0	0

6) The LiDAR volume of each individual building in the study area, including those excluded in step 4, was multiplied ('adjusted') by the attribution factor f_a based on the building's type. As a result, all non-residential buildings were assigned a volume of zero, while the volume of apartments was increased by a factor of 1.30 and the volume of all GOs decreased by a factor of 0.70. For example:

$$\hat{v}_{GO}(n) = v_{GO}(n) \cdot f_a = v_{GO}(n) \cdot 1.30 \tag{11}$$

Where v_{GO} is the LiDAR extracted building volume and $\hat{v}_{GO}$ is the adjusted ground-oriented building volume. The adjusted volumes for each building type were totaled for each DA, complete or incomplete so that:

$$\hat{V}_{GO} = \sum_{n=1}^{B_{GO}} \hat{v}_{GO}(n) \tag{12}$$

Where B_{GO} is the total number of ground-oriented buildings in a DA (not individual dwellings), and $\hat{V}_{GO}$ is the total adjusted volume of all ground-oriented buildings in a DA.

Similarly for apartment buildings (not individual dwellings):

$$\hat{V}_{apt} = \sum_{n=1}^{B_{apt}} \hat{v}_{apt}(n) \tag{13}$$

7) The adjusted volume of each residential building was divided by the total adjusted volume of all buildings in the particular DA

$$\dot{p}_{GO}(n) = \frac{\hat{v}_{GO}(n)}{\hat{V}_{GO} + \hat{V}_{apt}} \tag{14}$$

Where $\dot{p}_{GO}$ corresponds to the modeled fractional population of the ground-oriented building in the DA.

Similarly for apartment buildings

$$\dot{p}_{apt}(n) = \frac{\hat{v}_{apt}(n)}{\hat{V}_{GO} + \hat{V}_{apt}} \tag{15}$$

As a result, large apartment buildings are assigned more population than smaller ones. Also, as socio-economic variables change, it can be expected that household size will change as well, even if the number of people in the average home does not.

8) For all buildings in each complete DA, the fractional population $\dot{p}_{GO}$ or $\dot{p}_{apt}$ were multiplied by the census total population for the corresponding building type in the entire DA (either P_{GO} or P_{apt}) to obtain a value for the population of the building

$$p_{GO}(n) = \dot{p}_{GO}(n) \cdot P_{GO} \tag{16}$$

and

$$p_{apt}(n) = \dot{p}_{apt}(n) \cdot P_{apt} \tag{17}$$

For buildings in incomplete DAs, the adjusted volume of the building was divided by the global volume/inhabitant value (Table 3.2, second last column) to obtain an estimate.

Upscaling from building population to 50 x 50m raster

Individual nighttime building populations were upscaled to 50 x 50m raster elements in order to be represented in the same format as other surface properties in the EPiCC database (e.g. fractional vegetation cover, modeled emissions, etc.). First, the entire 1900 x 1900 m study area was split into 1 x 1m pixels. If a portion of a populated building covered the majority of a pixel, the pixel was assigned a fraction of the building's total population (calculated in step 8, above). Pixels that lied outside of buildings were assigned a population of zero. The 1 x 1 m raster was then summed over a 50 x 50m cell, and divided by the cell's area to give a population density. This upscaling was done for all 50 x 50m raster cells that covered the study area. The modeled resulting 50 x 50m raster cells are shown in (Fig. 9a), thus improving the spatial attribution of population densities.

Appendix 4b – Procedure for down-sampling population density in Vancouver-Oakridge where LiDAR data was not available

1) All DAs that were within (either partially or fully) a selected distance (r) of the tower were selected. The area of the complete DAs was calculated. Even if a DA is only partially within the 500m, the area of the entire DA is calculated first.

2) DA Population density (N) is calculated by

$$N(inh./ha) = \frac{p}{a} \tag{18}$$

3) The DAs within 500m of the tower were clipped to the exact shape of a 500m radius from the tower.

4) The result is layer with the same number of DAs, but some of them have been reduced in size. The new areas of the partial DAs are then re-calculated giving the new fractional area ($\hat{a}$).

5) The new area is multiplied by the original population density to give the new fractional population ($\hat{p}$) of the partial DA.

$$\hat{p} = \hat{a} \times N \tag{19}$$

6) Finally, the populations of all DAs or partial DAs is summed and divided by the total area given by a circle with the appropriate radius to give the approximated population density ($\hat{N}$) over the area of the given radius around the tower.

$$\hat{N} = \frac{\sum_{n=1}^{n} \hat{p}}{\pi r^2} \tag{20}$$

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