Factors Affecting the Magnitude of Vancouver's Urban Heat Island

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0277-075

IB Geography HL Internal Assessment

Sir Winston Churchill Secondary School

May 2015

Word Count: 2478

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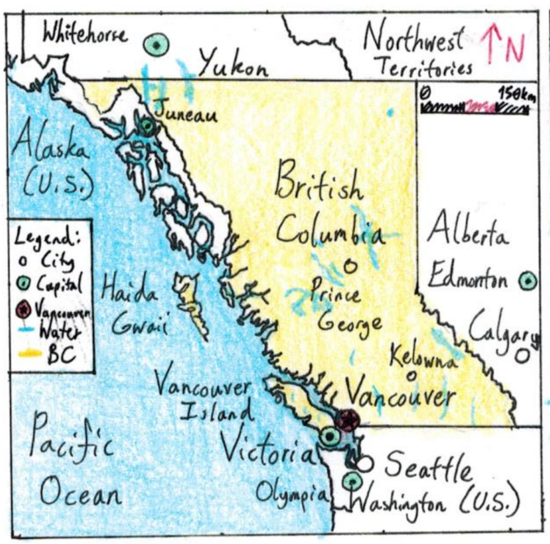
A: Fieldwork Question and Geographic Context

This paper addresses topic 3.1 in Option G: Urban Environments of the International Baccalaureate Geography curriculum by considering the factors that influence temperature patterns in urban microclimates. I have chosen to examine whether Vancouver has a heat island. If it does, how do temperatures in Vancouver correlate with distance from the central business district, vegetation, and building density?



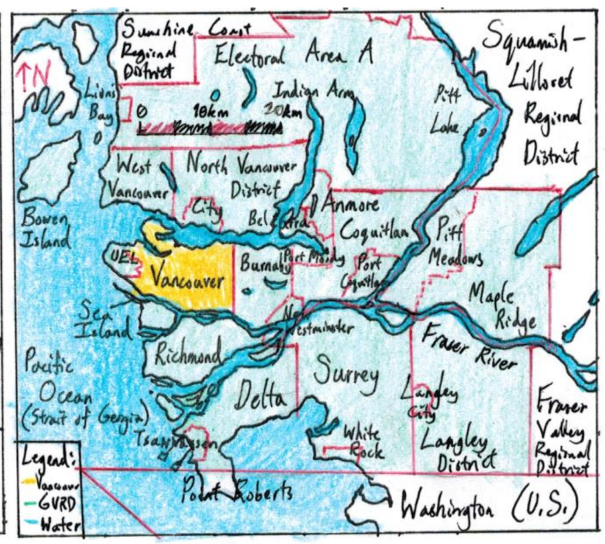


Figure 1. Sketch map of Vancouver's locational context within the province.

Figure 2. Sketch map of Vancouver within the Greater Vancouver Regional District.

Vancouver is a mid-latitude coastal city, shown in Figures 1 and 2, at approximately 123° W, 49° N by the Strait of Georgia. It is an appropriate choice because it is densely populated, heavily urbanized, and contains much variation in building density and vegetation, as seen in Figure 3. This variation allows fieldwork to give enough data to compare temperature with both vegetation and building density.

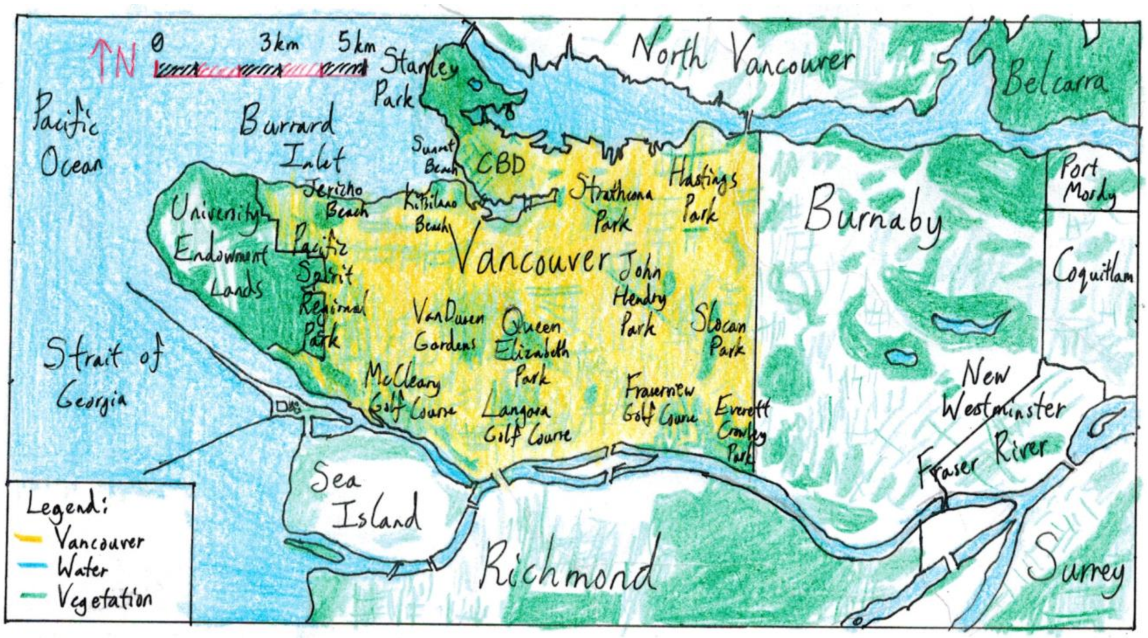


Figure 3. Sketch map of Vancouver's locational context, including vegetated areas.

My hypotheses are that areas with higher building density will have a higher temperature than areas with lower building density, that more heavily vegetated areas will have a lower temperature than less heavily vegetated areas, and that areas closer to the central business district will be warmer than areas further away. Furthermore, I believe that building density will show the highest correlation.

Compared to natural soils, urban built surfaces decrease albedo and increase heat capacity, which makes city centres significantly warmer than suburbs, especially at night; urban nonporous materials also increase runoff, so less water is present for evaporative cooling; the tall buildings of the central business district slow the escape of heat; and denser populations emit more concentrated waste heat than sparser populations (Arrau). These observations support the hypotheses and the claim that Vancouver, a heavily urbanized, densely populated city, is a good choice for a case study.

B: Method of Investigation

For this internal assessment, the IB Geography students in my school worked together to collect our data. To measure the temperatures patterns across Vancouver, we divided the city into the 87-cell grid of Figure 4 and assigned every pair of students to record the temperatures of 3 different cells. This division was systematic because we recorded the temperature at the centre of each cell, and the distance between centres of adjacent cells was the same. However, the people who took temperatures in cell groups 1, 2 and 3 chose their locations unsystematically within their grid (i.e. not in the centre), and several people took temperatures at other unsystematic locations too.

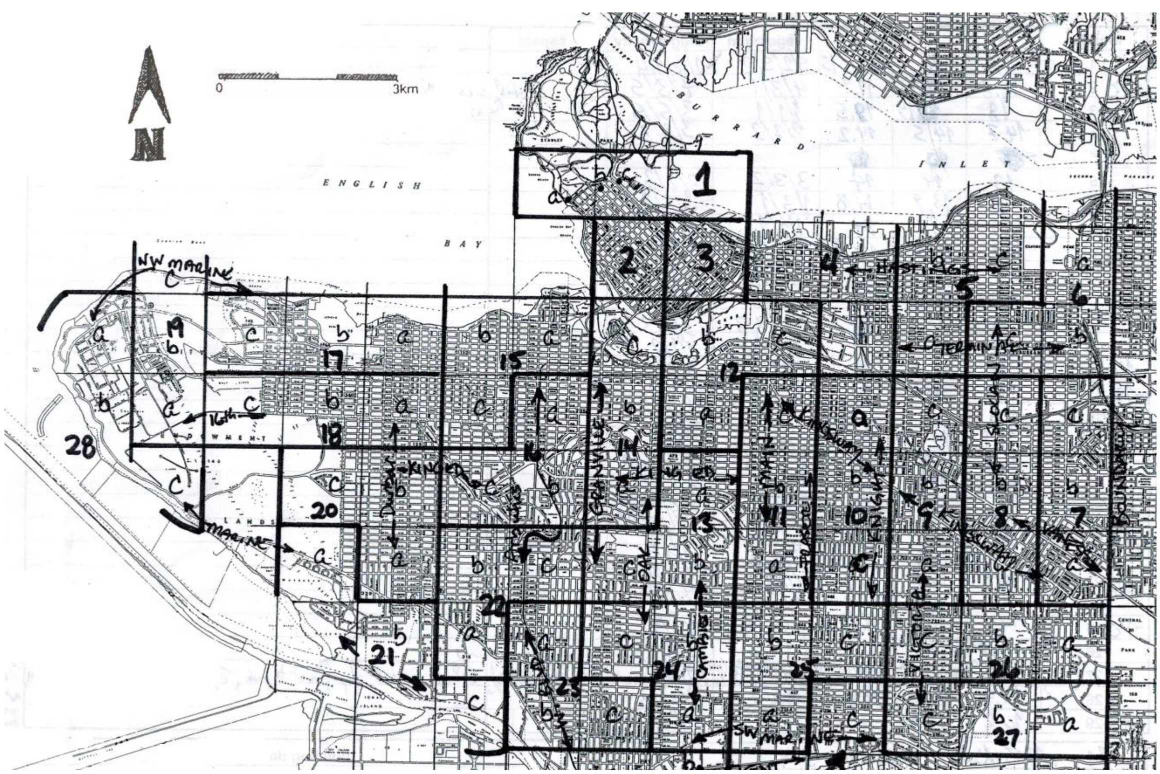


Figure 4. Systematic grid of Vancouver, divided into 87 cells.

To minimize the effect of cloud cover and wind, we decided to collect data on a calm night. The forecast predicted that 9 October would be cloudless and windless, which was largely true. So that the actual temperature would not fall considerably, we collected all data within half an hour, from 8:00 PM to 8:30 PM.

To minimize the effects of any prevailing wind, we all faced north while holding our thermometers. To minimize the impact of standing beside heat sources, we stood in the centre of the nearest intersection on quiet streets, or on the edge of the curb on busy streets, and held our thermometers between 1.2 and 1.5 metres away from the ground, at least 2 metres away from any buildings or waste heat sources, by its tip at arm's length, away from the human body. To gather more contextual qualitative data for factors that may affect temperature, we also quantified the vegetation and building density with a scale based on qualitative criteria agreed upon in class, in Appendix A. Some also recorded the aspect at their location, but not enough for any analysis. Finally, we calibrated all our thermometers beforehand by keeping them in a classroom away from windows in the same box for an afternoon, recording the differences rounded to the nearest 0.5 °C between the temperatures of outlier thermometers and the modal temperature, and then adding these differences to the temperature recorded by the outlier thermometers in Appendix B. We also all tested the time necessary for a thermometer to settle its temperature after a change of more than 5 °C—about 5 minutes—and all waited at least this long at each cell before recording the temperature. All our final data was then shared among all IB Geography students in our school.

D: Written Analysis

The data we collected is presented in Appendix B. As mentioned previously, the locations in cell groups 1, 2 and 3 were chosen unsystematically. When making Appendix C, I decided to omit all results from cell groups 30 and 31, whose data was all taken unsystematically: cell group 30 shows up as an anomalous blob in the middle of the map because of the elevation change in Queen Elizabeth Park, which was a former quarry; 31a and 31b were both specifically chosen to be inside parks; and 31c is the ocean temperature. However, I decided not to omit the results from cell groups 1, 2 and 3 because they are the only results available within 3 km of the central business district (CBD), and so are too important to omit. The locations in cell group 5 were not sampled because of coordination issues.

This data can be used to create an isotherm map of Vancouver, as I did in Appendix C. The isotherm map is on the next page, and supports the hypothesis that areas closer to the central business district will be warmer than areas further away, since the largest patch of red is in the central business district. However, there is also a warm spot around Dunbar and 41st, which is very far away from the central business district. Furthermore, there is one spot at Davie and Burrard which is only 13.2 °C, between two clumps of over 18 °C. Finally, the hotter spots in the southeast corner are much further away from the central business district than the cooler spots in Mount Pleasant. So distance from the central business district cannot explain all the patterns.

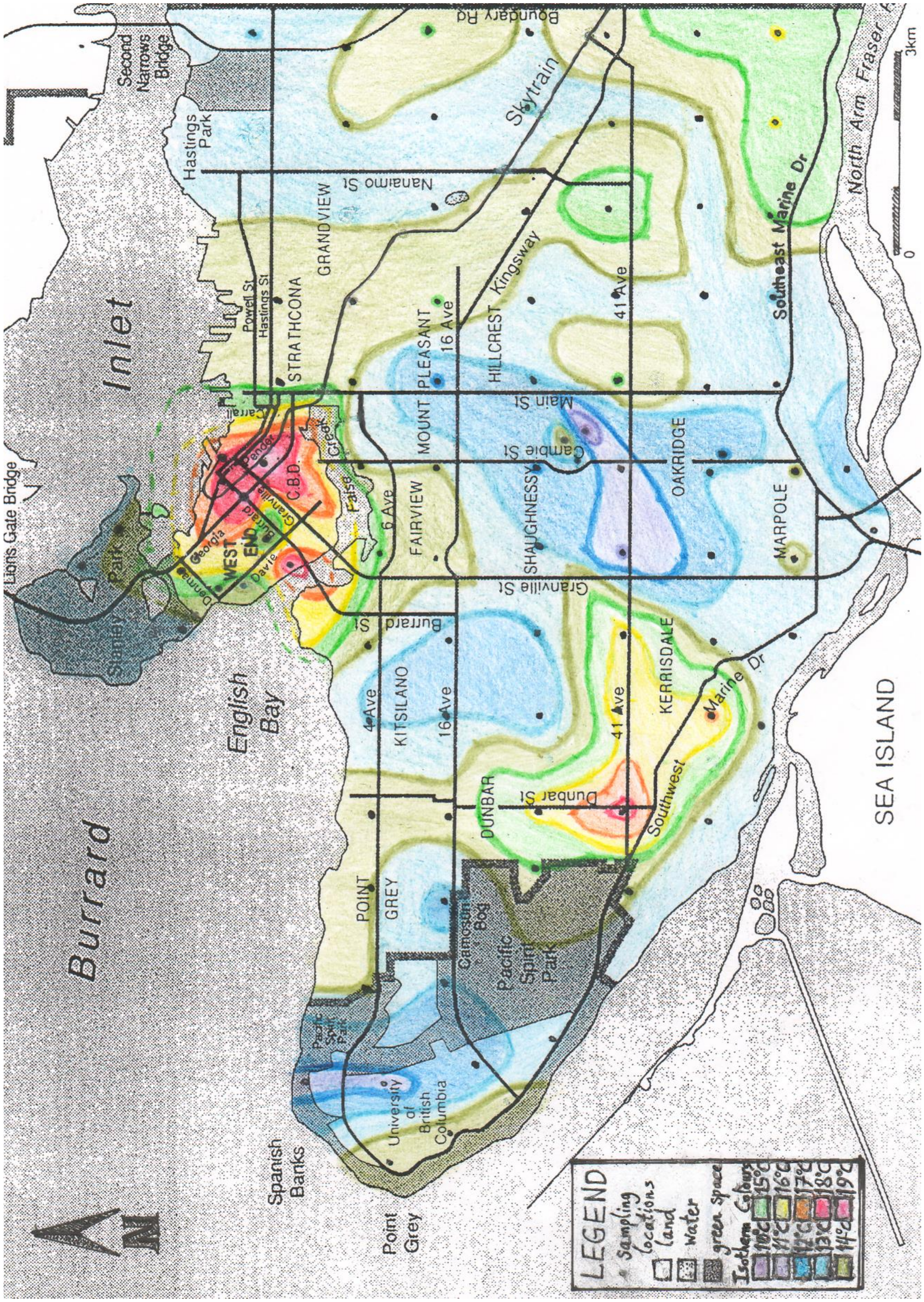


Figure 5. Isotherm map of Vancouver. A yellow isotherm has a temperature of 16 °C and yellow land has a temperature range of 16.0 °C to 16.9 °C.

I then compared the isotherm map to the sketch map in Figure 3, which supports the hypothesis that more heavily vegetated areas have lower temperature. Pacific Spirit Regional Park, Stanley Park, and Queen Elizabeth park are all areas of 14 °C and lower. However, the temperatures in Fraserview Golf Course and Everett Crowley Park are higher than their surroundings. So some other method of analysis is needed to explain these patterns.

I quantified the distance from the central business district, represented by the approximate peak land-value intersection of Burrard and Georgia, by measuring the distance from each point to Burrard and Georgia with a ruler. The scale is 3 km to 4.1 cm, or approximately 73000:1, so the conversion from the map scale to real life is to multiply each centimetre by 1.37 kilometres. I then checked each location to see if they bordered an official park or golf course. This data is in Appendix D.

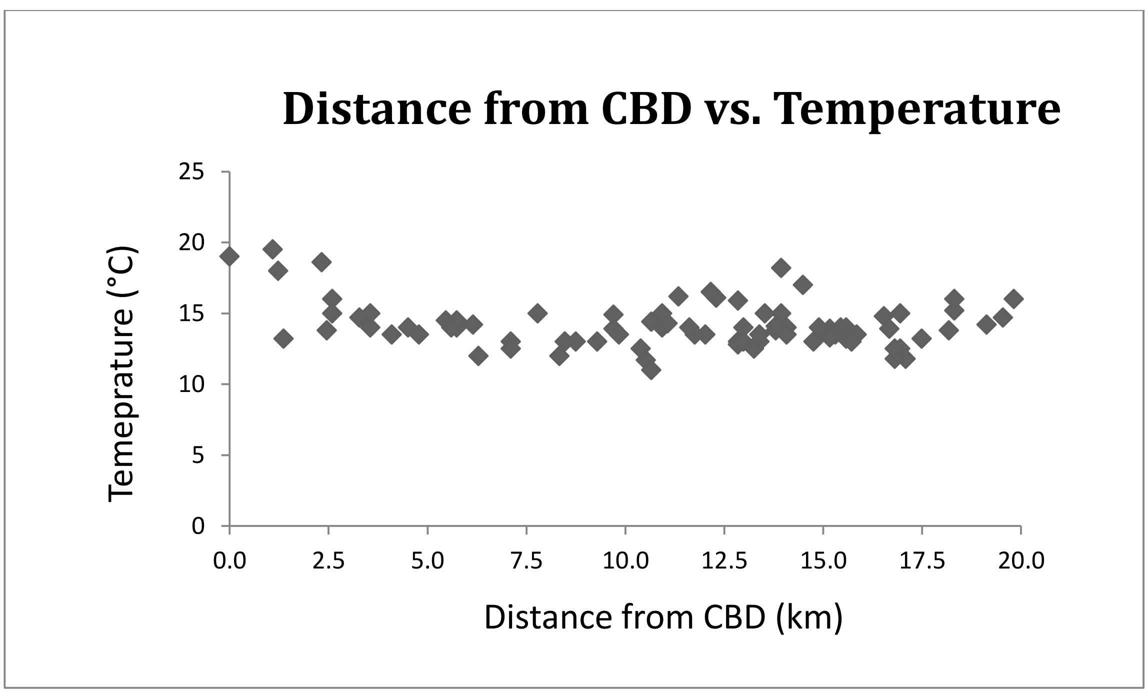


Figure 6. Graph of distance from the central business district vs. temperature.

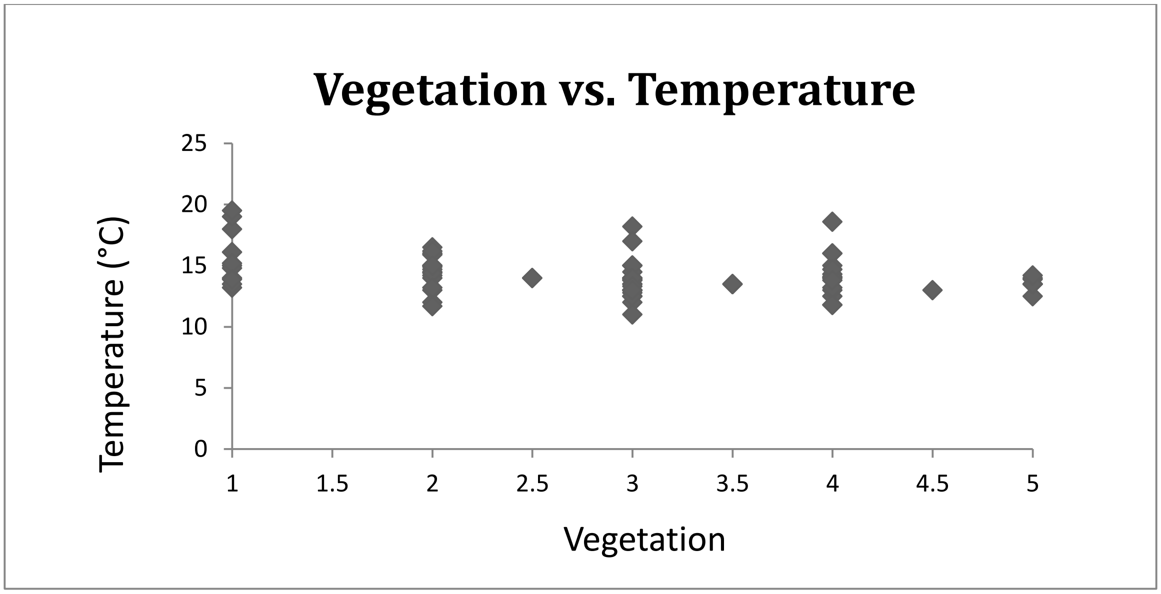


Figure 7. Graph of vegetation vs. temperature.

Figure 6 shows that although there is a clear trend that, within 5 km of the central business district, areas closer to the central business district are warmer than areas further away, the trend disappears or even reverses in areas more than 5 km away from the central business district. Similarly, Figure 7 shows no clear trend between vegetation and temperature. These two graphs do not support the hypotheses.

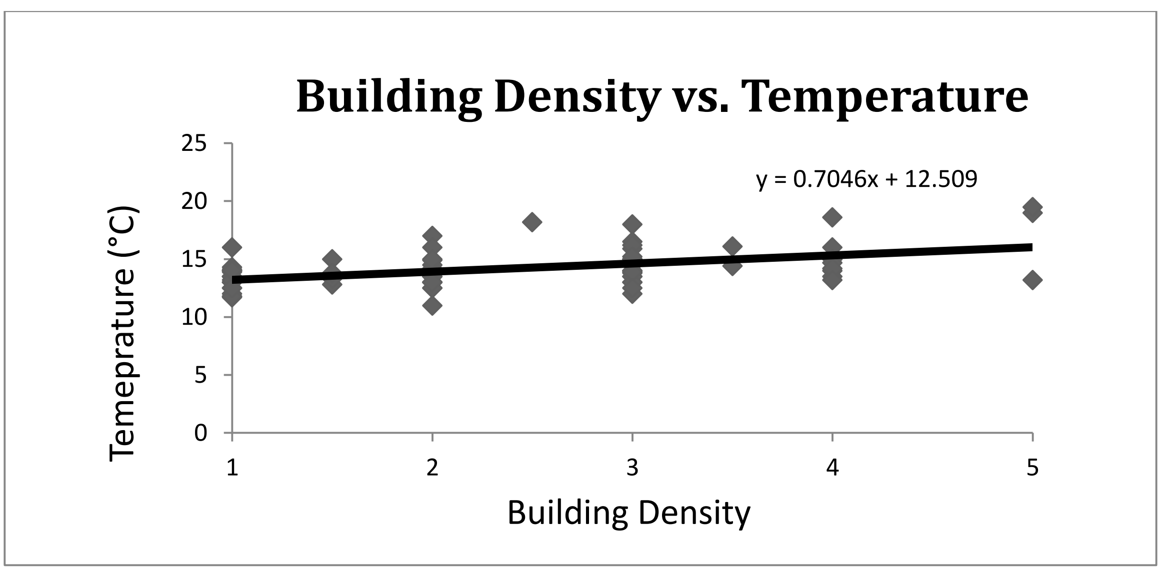


Figure 8. Graph of building density vs. temperature, with linear best-fit line.

However, Figure 8 does support the hypothesis that areas with higher building density will have a higher temperature than areas with lower building density, since there is a clear linear trend. I found the best-fit line with Excel and displayed its equation on the graph. The equation has a slope of 0.70, which suggests that the temperature increases by 0.70 C° every time the building density increases by 1. This sounds like a reasonable conclusion, but there is no reason to assume that temperature is linearly correlated with an arbitrary qualitative scale of building density. All six graphs relating the four variables are presented in Appendix E, but more quantitative analysis is necessary to find the correlation between vegetation or distance and temperature.

Many statistical tools become available if the distribution of temperatures fits a normal distribution. I tested if they were by using William Huber's technique of ranking the temperatures from 1 to n, where $n = 85$, proportionally converting the temperatures to values between 0 and 1 by using the formula $(\text{rank} + 1/6)/(n + 1/3)$, and then using Excel's NormSInv function to find the normal score of each temperature. If temperature were distributed perfectly normally, then plotting temperature vs. normal score should show a perfectly straight line (Huber). However, when I plotted temperature vs. normal score, I instead got a curve that markedly differed from its best-fit line, as seen in Figure 9. This means that the distribution of temperatures is not normal, and that nonparametric statistics must be used to analyze it.

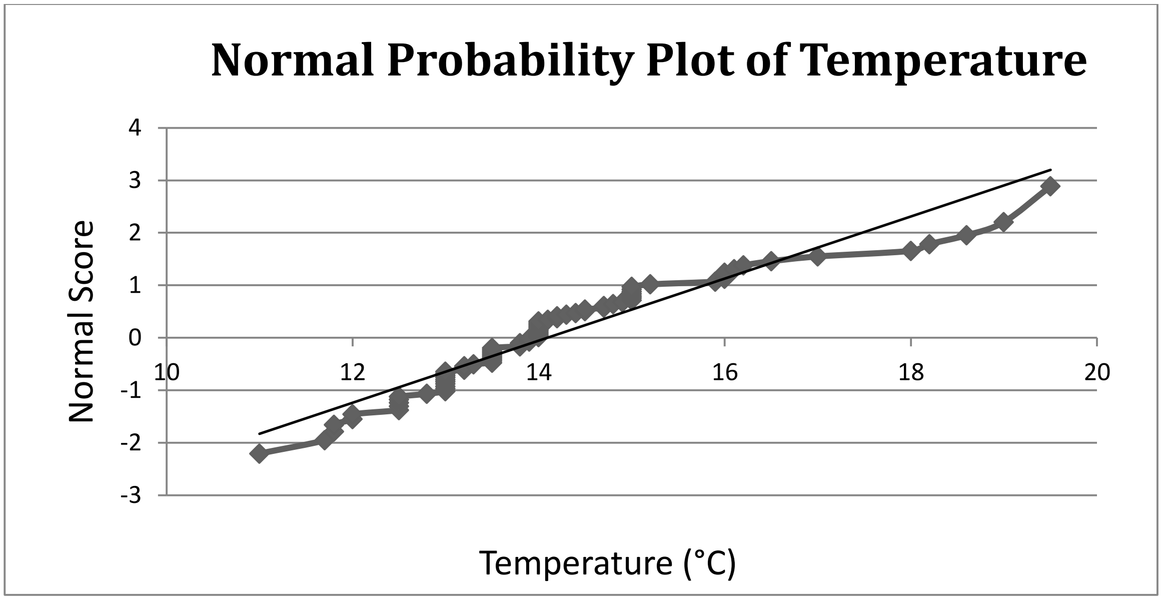


Figure 9. Normal probability plot of temperature, whose curve is markedly curved.

One quantitative nonparametric method for assessing correlation is to compute Spearman's rank correlation coefficient by solving the equation:

$$\rho = 1 - \frac{6\sum(x_i - y_i)^2}{n(n^2 - 1)}$$

Where (x_i, y_i) represents one data point at rank x_i in set X and rank y_i in set Y. This requires first that all data sets be ranked in order, which I have done in Appendix F, by assigning 1 to the highest value, $n = 85$ to the lowest value, and by taking the average of all ranks when there are ties. After that, I calculated $(x_i - y_i)^2$ between all sets of data by squaring the difference between the two ranks; the data is in Appendix G.

	Temperature	Vegetation	Building Density	Distance from CBD
Temperature	1.00000	-0.25793	0.45876	-0.12332
Vegetation	-0.25793	1.00000	-0.53028	0.31824
Building Density	0.45876	-0.53028	1.00000	-0.24482
Distance from CBD	-0.12332	0.31824	-0.24482	1.00000

Figure 10. Table of Spearman's rank correlation coefficient between all pairs of sets.

These results support all of my hypotheses: temperature is negatively correlated with vegetation (more vegetated areas are cooler); temperature is positively correlated with building density (more heavily built areas are warmer); and temperature is negatively correlated with distance from the central business district (more peripheral areas are cooler). However, a significance test is required before accepting these results.

n	$p = 0.20$	$p = 0.10$	$p = 0.05$	$p = 0.02$	$p = 0.01$	$p = 0.001$
25	0.265	0.337	0.398	0.466	0.511	0.630
30	0.240	0.306	0.362	0.425	0.457	0.580
50	0.184	0.235	0.279	0.329	0.363	0.456
60	0.168	0.214	0.255	0.300	0.331	0.418
70	0.155	0.198	0.235	0.278	0.307	0.388
80	0.145	0.185	0.220	0.260	0.287	0.363
100	0.129	0.165	0.197	0.233	0.257	0.326

Figure 11. Table of critical values of Spearman's rank correlation coefficient (Zar).

This table shows that when $n = 80$, the absolute value of Spearman's rank correlation coefficient must be greater than 0.220 for a $p = 0.05$ level of statistical significance. Comparing 0.220 to Figure 10 shows that all the relationships between the data sets are statistically significant except for the correlation between distance from the CBD and temperature, which is not statistically significant even if n were at 100. Thus, distance from the central business district does not have any significant effect on temperature.

We also see that building density is the most strongly correlated with temperature, which supports the hypothesis that building density increases the urban heat island effect more than anything else. The strongest correlation overall is the negative correlation between vegetation and building density.

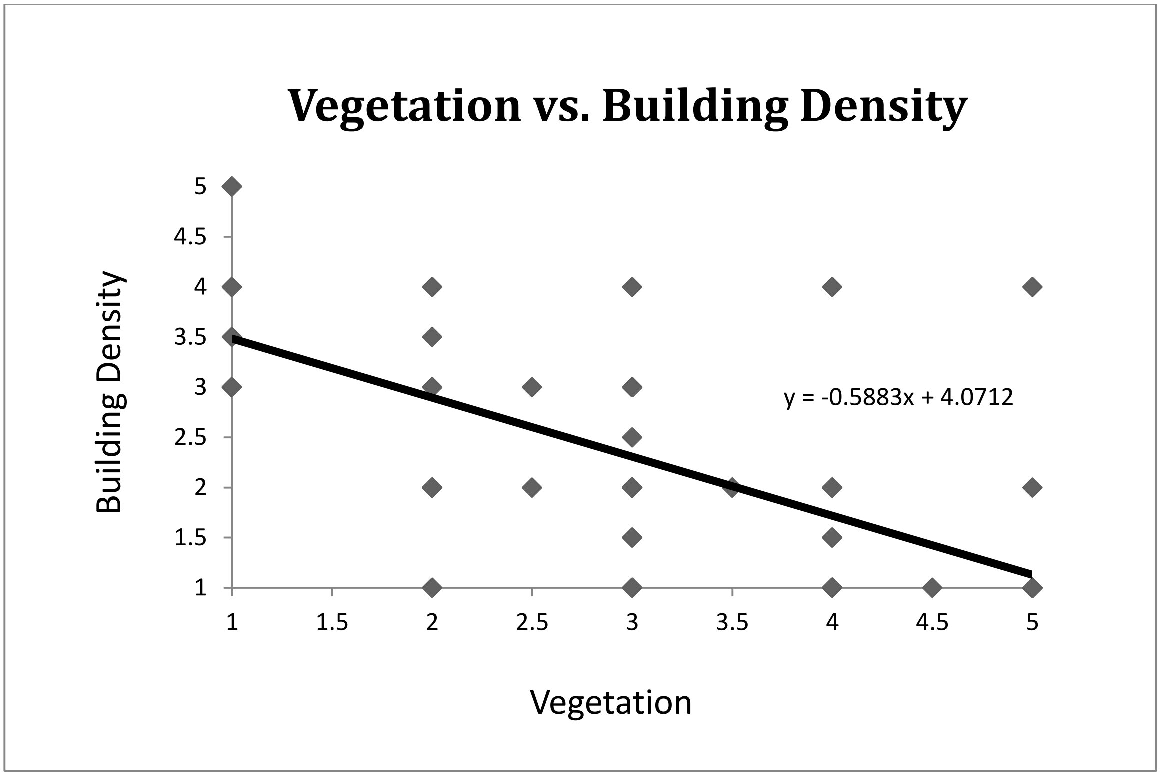


Figure 12. Graph of vegetation vs. building density, with linear best-fit line.

Correlation is not causation; perhaps vegetation is only negatively correlated with temperature because higher building densities raise the temperature but also remove vegetation in construction. This would explain why vegetation and temperature are only mildly correlated while both are strongly correlated with building density.

Perhaps distance from the CBD and temperature will have a statistically significant relationship if we use some other method of quantifying correlation. The Pearson product-moment correlation coefficient also measures linear correlation, but instead of using ranks, it divides the covariance of two populations by both of their standard deviations: $\rho = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$. However, the calculation becomes more involved when only considering samples, to correct for the biased sample standard deviation.

	Temperature	Vegetation	Building Density	Distance from CBD
Temperature	1	-0.31551	0.48302	-0.25584
Vegetation	-0.31551	1	-0.61724	0.274136
Building Density	0.48302	-0.61724	1	-0.33985
Distance from CBD	-0.25584	0.274136	-0.33985	1

Figure 13. Table of Pearson's product-moment correlation coefficient.

Thankfully, Excel has a function $\mathrm{PEARSON}$, that computes the Pearson product-moment correlation coefficient between any two sets of data. I used this function to generate Figure 13 using the data in Appendices A and B. Figure 14 now shows that for $n = 80$, 0.242 is significant to $p = 0.02$. Since $n = 85 > 80$ and $|-0.256| > 0.242$, the negative correlation between the distance from the CBD and temperature is statistically significant to at least $p = 0.02$.

n	$p = 0.20$	$p = 0.10$	$p = 0.05$	$p = 0.02$	$p = 0.01$	$p = 0.001$
25	0.255	0.323	0.381	0.445	0.487	0.597
30	0.234	0.296	0.349	0.409	0.449	0.554
50	0.181	0.231	0.273	0.322	0.354	0.443
60	0.165	0.211	0.250	0.295	0.325	0.408
70	0.153	0.195	0.232	0.274	0.302	0.380
80	0.143	0.183	0.217	0.256	0.283	0.357

Figure 14. Table of critical values of Pearson's correlation coefficient (Weathington).

Since the statistical significance of correlations depends somewhat on which correlation coefficient is used, vegetation may or may not correlate with temperature.

E: Conclusion

Spearman's rank correlation coefficient supported the hypotheses that less vegetation and higher building density are correlated with greater temperatures. However, Spearman's rank correlation coefficient did not return a statistically significant result for the correlation between distance from the CBD and temperature, which I expected had a pattern from inspecting the graph of distance vs. temperature. Pearson's product-moment correlation coefficient, on the other hand, showed that there was a correlation between distance from the CBD and temperature at $p = 0.02$. Nevertheless, for both Spearman's and Pearson's correlation coefficients, the negative correlation between building density and vegetation was the greatest, followed by the positive correlation between building density and temperature, which supported the hypothesis that increased building density is the key factor in making urban heat islands. In conclusion, because urban areas have a higher building density than rural areas, and because data taken from Vancouver show that higher building density is significantly correlated with higher temperatures, Vancouver does exhibit an urban heat island effect, centered at its central business district. The isotherm map of Figure 5 makes this clear.

F: Evaluation

Primary data was controlled fairly well. We could have all held the thermometer out at 1.2 m, rather than at shoulder level, which varies depending on the person. Perhaps there was some variation in temperature over time; I wanted to see if temperatures decreased substantially over that half hour but I could not because I did not know the order in which people took their data. Perhaps there was some variation in temperature due to aspect; however, I could not do anything meaningful with the few data points on aspect I had. This study could be extended by collecting data on aspect and slope in the future, and by traversing each cell group in alphabetical order.

Perhaps we should have excluded areas with parks from our study, since the cooling effect of parks does not extend outwards throughout its entire cell. After re-ranking the data without parks ($n = 64$) and then without cell groups 1, 2 and 3 ($n = 75$) in Appendix H, I put the numbers and squared ranks through Pearson's and Spearman's.

	Original, n = 85		No Parks, n = 64		No Groups 1–3, n = 75	
	Spearman's	Pearson's	Spearman's	Pearson's	Spearman's	Pearson's
Temperature vs. Vegetation	-0.25793	-0.31551	-0.42183	-0.48685	-0.19624	-0.21816
Temperature vs. Building Density	0.45876	0.48302	0.53152	0.55049	0.37281	0.32241
Vegetation vs. Building Density	-0.53028	-0.61724	-0.44774	-0.62026	-0.47145	-0.55352

Figure 15. Table comparing correlation coefficients among different groups of data.

By using Figure 11 and Figure 14, I calculated the statistical significance of these correlations, which are shown in Figure 16.

	Original, n = 85		No Parks, n = 64		No Groups 1–3, n = 75	
	Spearman's	Pearson's	Spearman's	Pearson's	Spearman's	Pearson's
Temperature vs. Vegetation	$p = 0.01$	$p = 0.01$	$p = 0.001$	$p < 0.001$	$p = 0.10$	$p = 0.10$
Temperature vs. Building Density	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.001$	$p = 0.01$
Vegetation vs. Building Density	$p < 0.001$	$p < 0.001$	$p = 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.01$

Figure 16. Table comparing correlation significances among different groups of data.

Figure 16 shows that omitting parks from the calculation increases the statistical significance of all correlations, while omitting cell groups 1, 2 and 3 actually decreased their statistical significance, especially that of temperature vs. vegetation. So although cell groups 1, 2 and 3 were unsystematically sampled, they were critical in ensuring a correlation between temperature and vegetation.

Instead of calibrating all the thermometers manually, it would have been more uniform to use an identical set of 29 thermometers. Even though my thermometer did not need to be calibrated and I waited long enough outside for its temperature to stop falling, I felt that the temperatures I recorded were still too high. This could be because of the angle at which I held the thermometer, or because the temperature inside the car was extremely high, or because heat was transferred from my hand despite only touching the tip of the thermometer. Ultimately, variations in individual measurement probably accounted for most of the variations in the map, especially at Dunbar and 41st. The best way to improve the accuracy and consistency of the data is to give all students precise, unambiguous instructions.

Appendix A: Qualitative Scales

Vegetation

1	minimal	< 20%	CBD, paved, ext. commercial / industrial
2		20–40%	business, comm. ind., high dens. res.
3	moderate	40–60%	residential
4		60–80%	low dens. res. / parks / green space
5	mostly	> 80%	extensive green space / golf / parks

Building Density

1	low	ext. green space, low density single detached
2		residential, mainly single detached, some apt./condo
3	moderate	higher density residential; some commercial
4		many 3–5 storeys; some 5+; commercial
5	high	CBD, most buildings above 5 storeys, ext. comm. / ind.

Appendix B: Raw Data

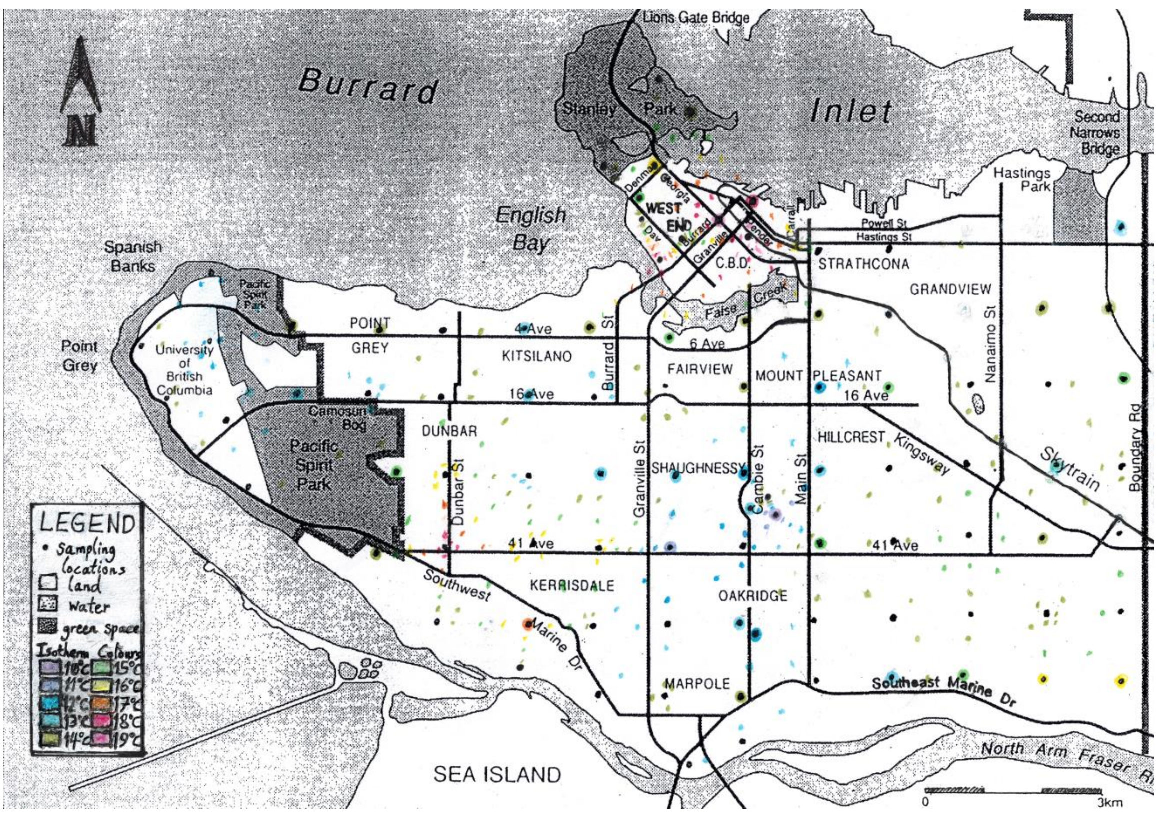
Location	Temperature (°C)	Vegetation	Building Density	Additional Notes	
01a	13.5	5	1		unsystematic
01b	16	2	4		unsystematic
01c	13.5	5	1		unsystematic
01d	15	2	4		unsystematic
02a	18.6	4	4	added +2 °C	unsystematic
02b	13.8	3	3	added +2 °C	unsystematic
02c	13.2	1	5	added +2 °C	unsystematic
03a	18	1	3		unsystematic
03b	19	1	5		unsystematic
03c	19.5	1	5		unsystematic
04a	14.7	2	3		
04b	14.5	2	2		
04c	14.2	2	2		
06a	13	3	2		
06b	14	3	2		
06c	14	2	3		
07a	15	1	3		
07b	13.9	3	2		aspect: slight N
07c	14.8	1	3		
08a	13.5	1	4		
08b	13	2	3		
08c	14	1	4		
09a	15.9	2	3	added -1 °C	
09b	14.3	4	1	added -1 °C	
09c	13.9	5	1	added -1 °C	
10a	15	3	3		
10b	13.5	3	3		
10c	13.5	3	3		

11a	12	3	3		
11b	13	3	3		
11c	15	3	4		
12a	14	2.5	3		
12b	14	2.5	2		
12c	14	3	3		
13a	12	2	1		
13b	11.7	2	1		
13c	11	3	2		
14a	13	3	2	added -1 °C	
14b	14.5	3	3	added -1 °C	
14c	15	3	3	added -1 °C	
15a	14	3	2	added -1 °C	
15b	13	3	1	added -1 °C	
15c	13	3	1	added -1 °C	
16a	12.5	4	2		
16b	13	4	2		
16c	12.5	3	2		
17a	14.9	2	2		
17b	14	4	1		
17c	14	4	1		
18a	14.4	2	3.5		aspect: NE
18b	12.8	3	1.5		aspect: E
18c	13	4.5	1		aspect: N
19a	12.5	5	1		
19b	11.8	4	1		
19c	11.8	4	1		
20a	15	4	1.5	added -1.5 °C	
20b	16.1	1	3.5	added -1.5 °C	
20c	18.2	3	2.5	added -1.5 °C	
21a	14	5	1	added -1 °C	
21b	13.5	5	1	added -1 °C	

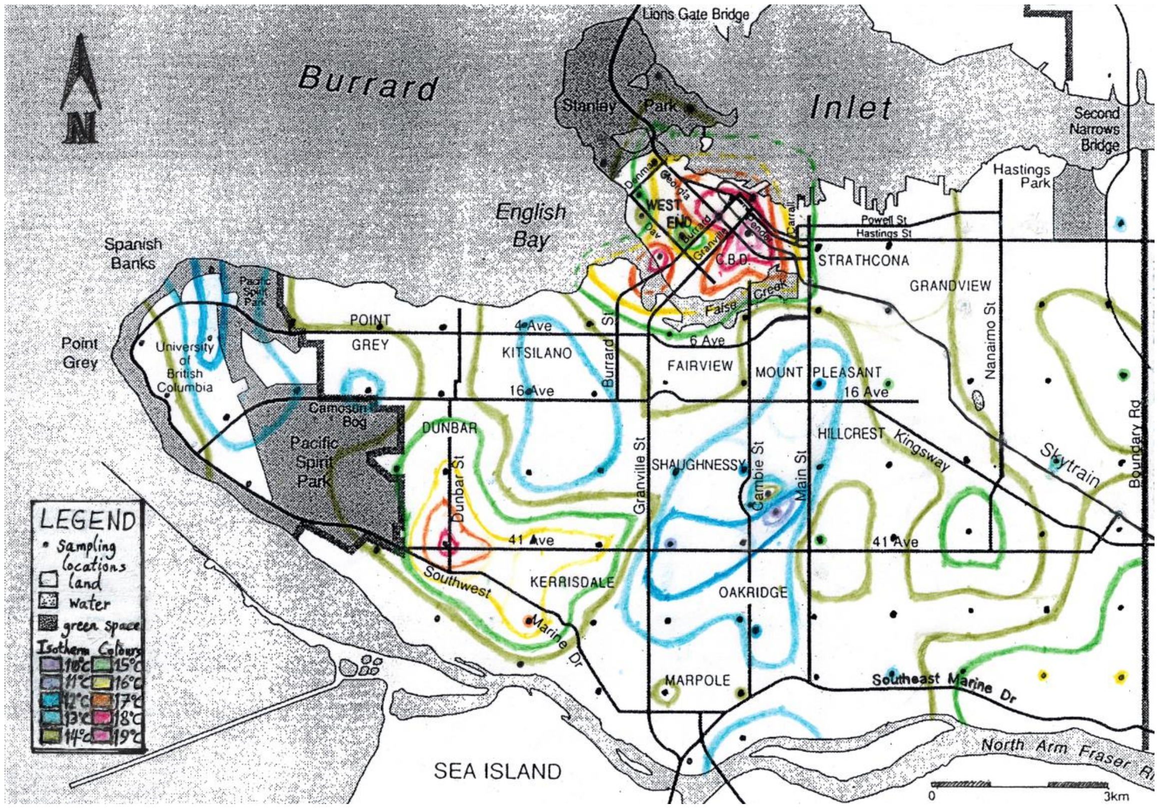
21c	13.5	5	1	added -1 °C	
22a	17	3	2		
22b	16.5	2	3		
22c	16.2	2	3		
23a	13.8	3	2	added -1 °C	aspect: flat
23b	13.2	4	1	added -1 °C	aspect: SW
23c	14.1	4	1	added -1 °C	aspect: flat
24a	14	3	1		aspect: S
24b	13	3	2		aspect: S
24c	12.5	3	1		aspect: flat
25a	13.5	3.5	2	added -1 °C	aspect: S
25b	13.5	3.5	2	added -1 °C	aspect: S
25c	13.5	3.5	2	added -1 °C	aspect: S
26a	15.2	1	3		
26b	13.9	1	3		
26c	13.3	3	1.5		
27a	16	4	1		
27b	16	4	2		
27c	15	2	2		
28a	14.7	4	4		
28b	14.2	5	4		
28c	13.8	4	1.5		
29a	13.2	2	4	added -1 °C	aspect: flat
29b	12.5	3	3	added -1 °C	aspect: flat
29c	13	3	2	added -1 °C	aspect: S
30a	14.5	5	2		unsystematic
30b	10	5	1		unsystematic
30c	13	5	1		unsystematic
31a	14				unsystematic
31b	12	5	1		unsystematic
31c	10.5			ocean temperature	

Appendix C: Isotherm Map

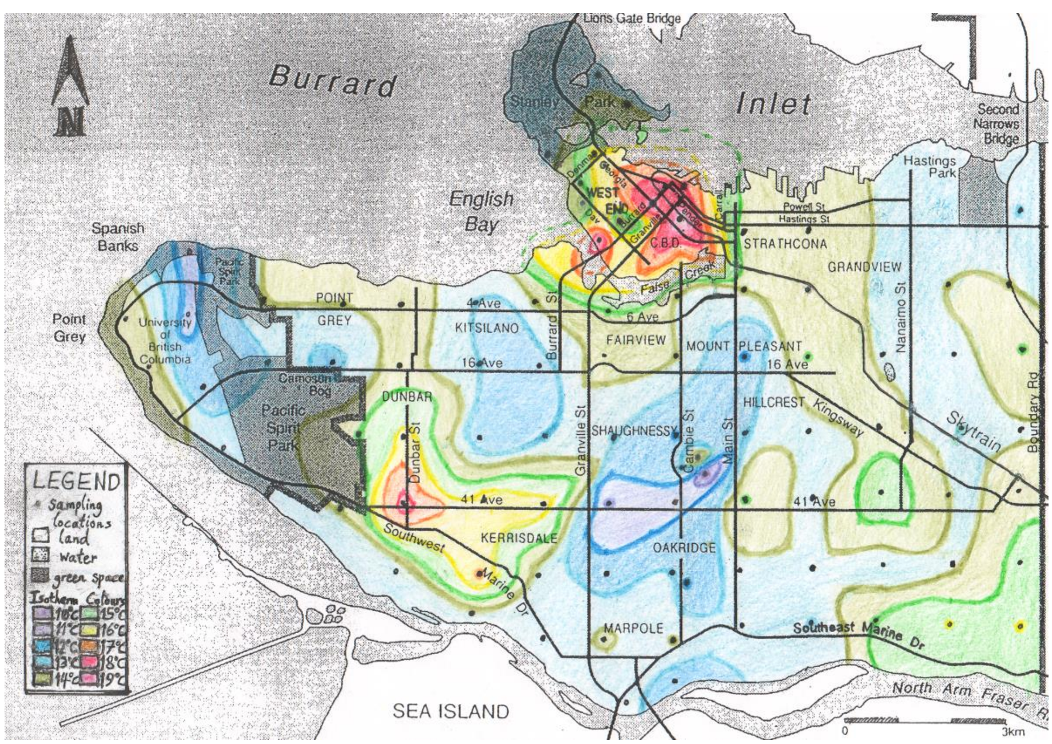
First, draw points on a map of Vancouver showing the location of each data point. Second, measure the distance between each point and its nearest points, and divide up this distance to mark dots of integral degree temperature. This assumes that the temperature gradient between two neighbouring points is constant. This is not true; however, it is more systematic and objective to find integral degrees mathematically than to gauge it by eye. Because this may cause conflicts if two distances intersect, where conflicts occur, the southwest–northeast pair of points have priority.



Third, connect all the points of the same degree together to create isotherms. I colour-coded my points and isotherms for ease of interpretation.



Finally, colour in the spaces between isotherms, so that all temperatures between, for example, 16 °C and 16.9 °C are coloured like the 16 °C isotherm is, in yellow.

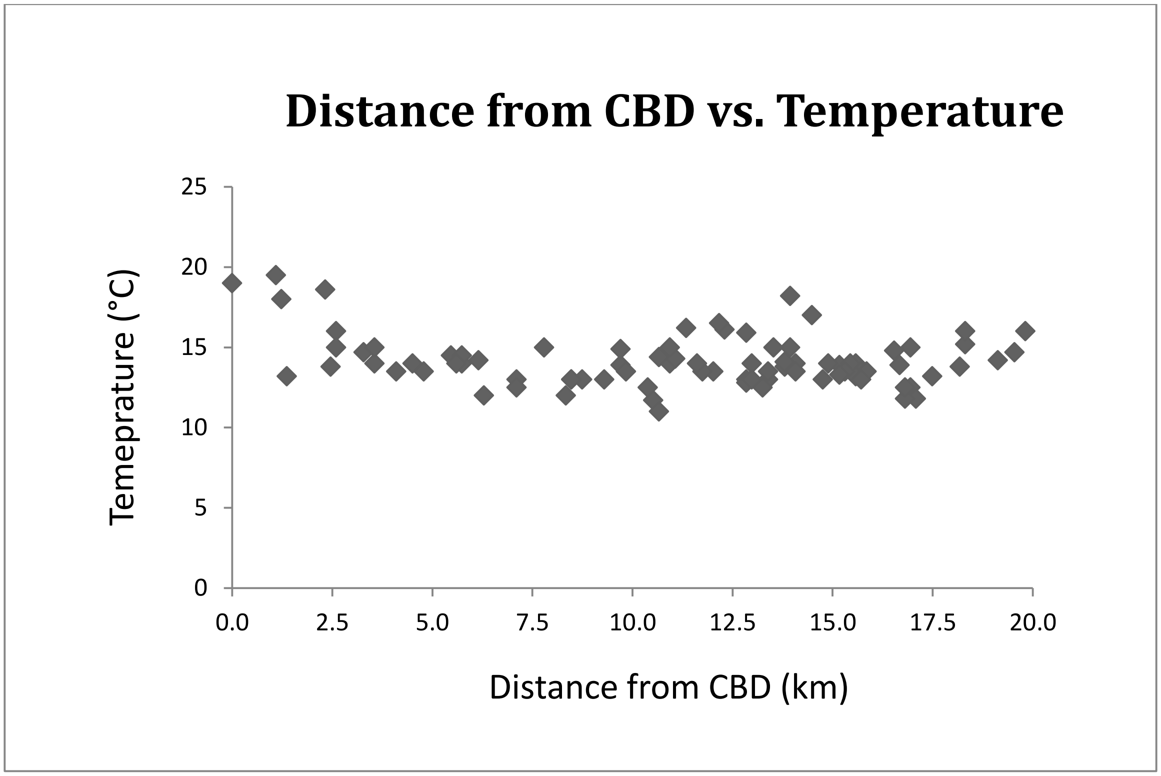


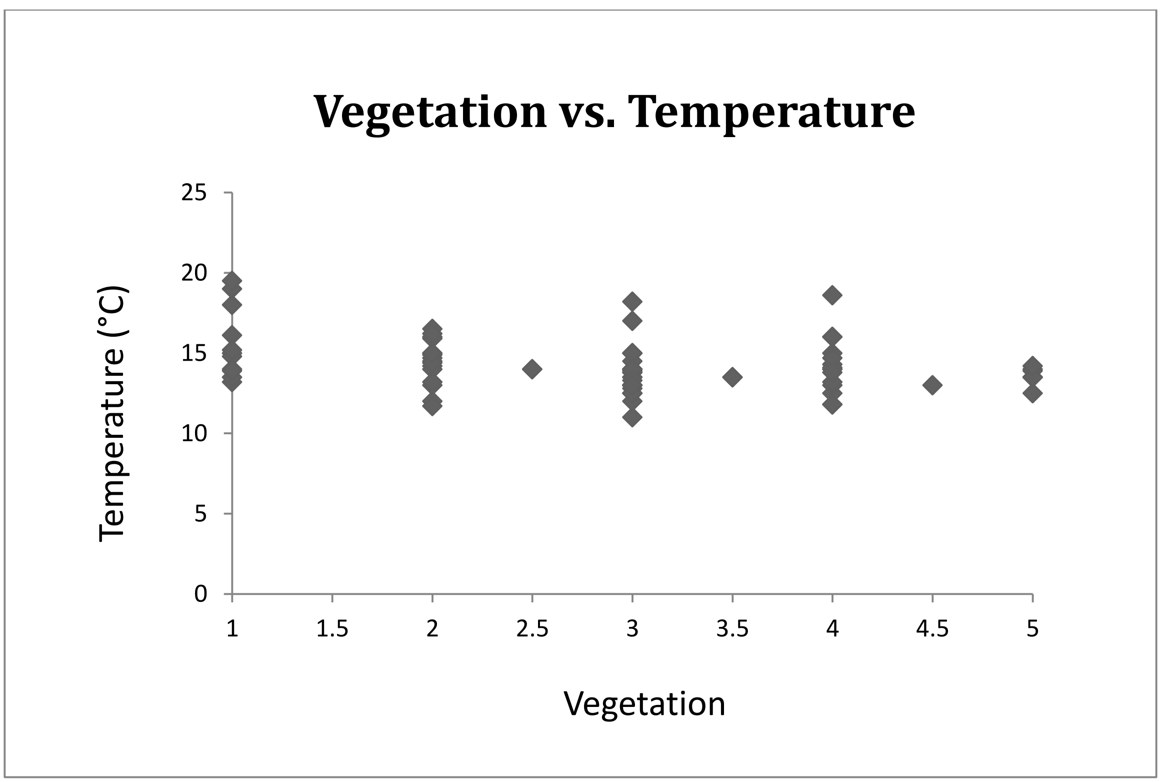
Appendix D: Secondary Data

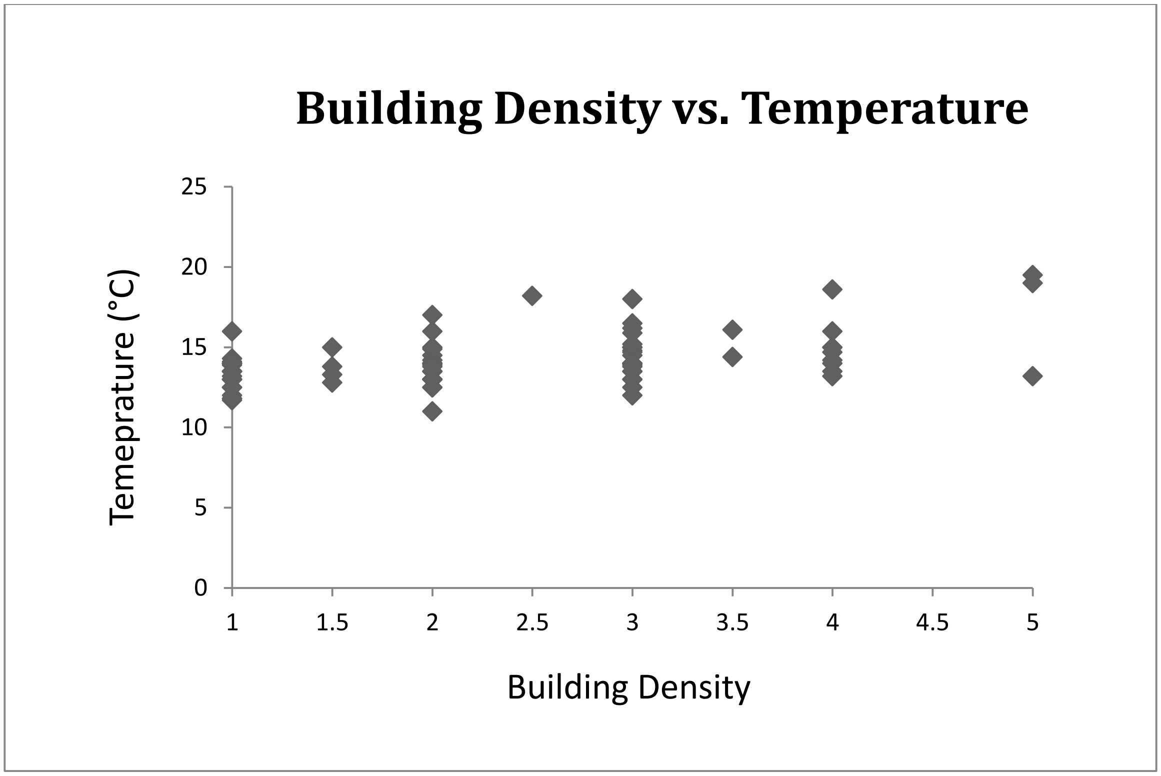
Location	Notes	Green Space	Distance from PLVI (cm)	(km)
01a	unsystematic	in Stanley Park	3.5	4.8
01b	unsystematic		1.9	2.6
01c	unsystematic	in Stanley Park	3.0	4.1
01d	unsystematic		1.9	2.6
02a	unsystematic	in Sunset Beach Park	1.7	2.3
02b	unsystematic		1.8	2.5
02c	unsystematic	in Nelson Park	1.0	1.4
03a	unsystematic		0.9	1.2
03b	unsystematic		0.0	0.0
03c	unsystematic		0.8	1.1
04a			2.4	3.3
04b			4.0	5.5
04c			4.5	6.1
06a			9.4	12.8
06b			9.5	13.0
06c			8.0	10.9
07a			10.2	13.9
07b			11.1	15.2
07c			12.1	16.5
08a			8.8	12.0
08b			9.8	13.4
08c			10.9	14.9
09a			9.4	12.8
09b		in Brewers Park	8.1	11.1
09c			7.1	9.7
10a			5.7	7.8
10b			7.2	9.8
10c			8.6	11.8
11a			4.6	6.3
11b			6.4	8.7
11c			8.0	10.9
12a			4.2	5.7
12b			2.6	3.6
12c			3.3	4.5
13a			6.1	8.3
13b			7.7	10.5
13c			7.8	10.7
14a			6.2	8.5
14b			4.2	5.7
14c			2.6	3.6
15a			4.1	5.6

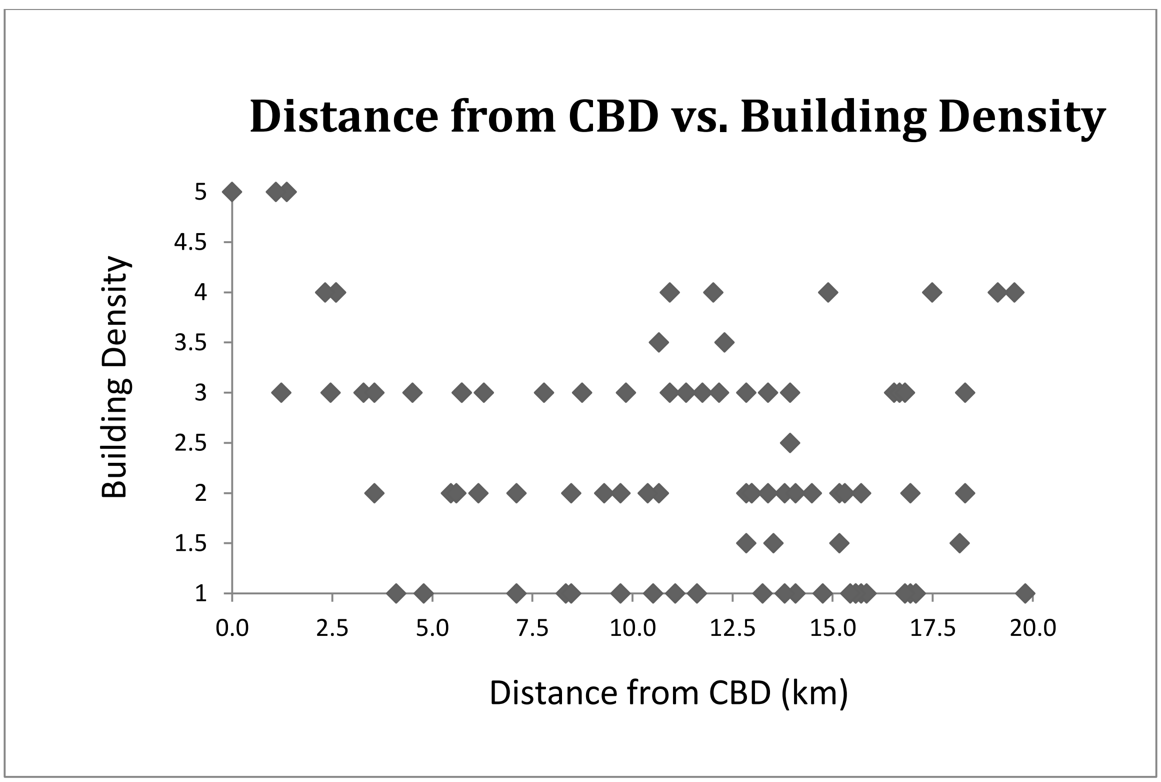
15b		5.2	7.1
15c		6.2	8.5
16a		5.2	7.1
16b		6.8	9.3
16c		7.6	10.4
17a		7.1	9.7
17b	in Jericho Beach Park	8.5	11.6
17c	in Pacific Spirit Regional Park	10.3	14.1
18a		7.8	10.7
18b	in Camosun Park	9.4	12.8
18c	in Pacific Spirit Regional Park	10.8	14.8
19a		12.4	16.9
19b	in Pacific Spirit Regional Park	12.5	17.1
19c	in Pacific Spirit Regional Park	12.3	16.8
20a	in Pacific Spirit Regional Park	9.9	13.5
20b		9.0	12.3
20c		10.2	13.9
21a	in the University Endowment Lands Ecological Reserve	11.4	15.6
21b	in Point Grey Golf Course	11.5	15.7
21c	in McCleery Golf Course	11.6	15.9
22a		10.6	14.5
22b		8.9	12.2
22c		8.3	11.3
23a		10.1	13.8
23b		11.4	15.6
23c		10.1	13.8
24a		11.3	15.4
24b		9.5	13.0
24c		9.7	13.3
25a		11.2	15.3
25b		9.8	13.4
25c		10.3	14.1
26a		13.4	18.3
26b	in Killarney Park	12.2	16.7
26c		11.1	15.2
27a	in Everett Crowley Park	14.5	19.8
27b	in Fraserview Golf Course	13.4	18.3
27c		12.4	16.9
28a	in Pacific Spirit Regional Park	14.3	19.5
28b	in Totem Park	14.0	19.1
28c	in Pacific Spirit Regional Park	13.3	18.2
29a		12.8	17.5
29b		12.3	16.8
29c		11.5	15.7

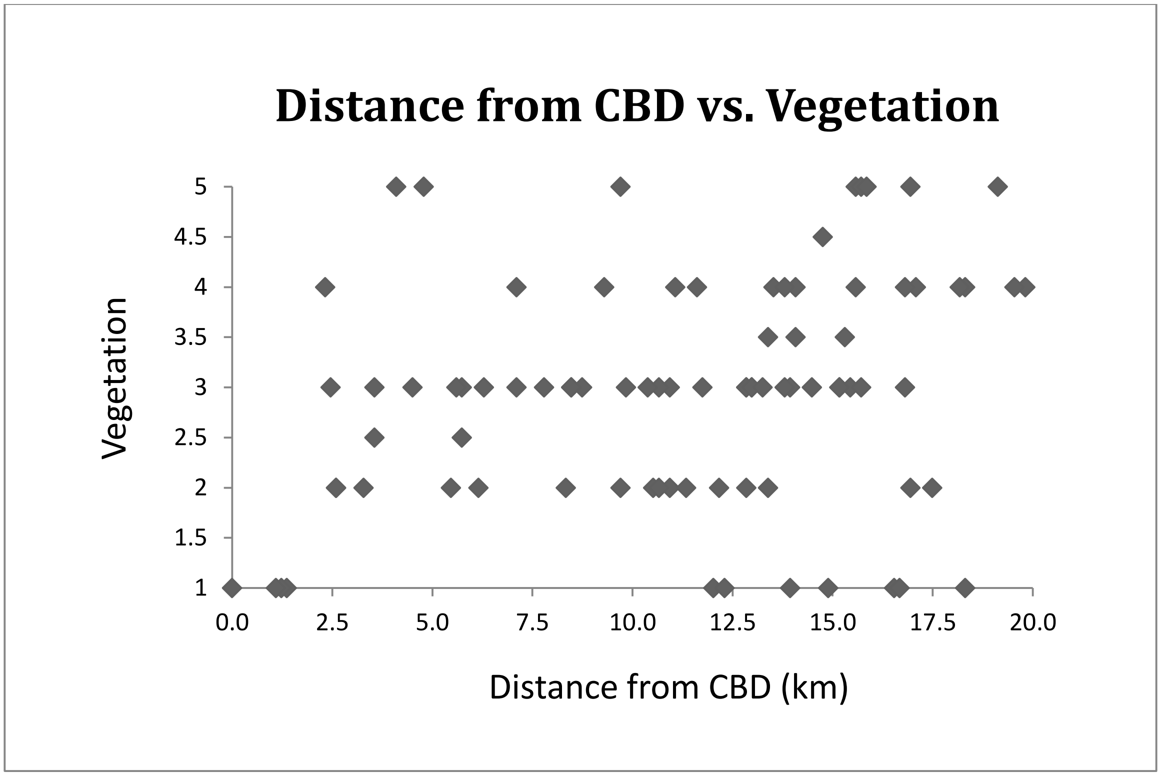
Appendix E: Excel Graphs

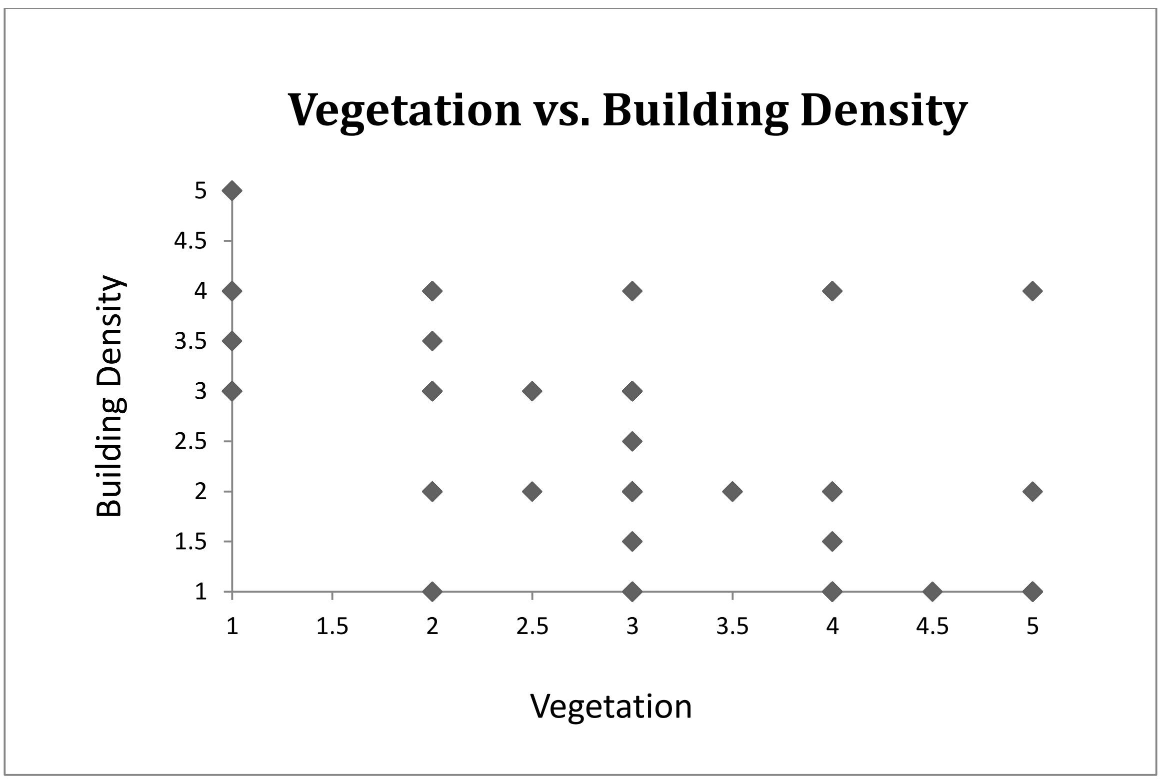





Building Density vs. Temperature
Temepratureа (°C)
25
20
15
10
5
0
1
1.5
2
2.5
3
3.5
4
4.5
5
Building Density


Distance from CBD vs. Building Density
Building Density
5
4.5
4
3.5
3
2.5
2
1.5
1
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Distance from CBD (km)


Distance from CBD vs. Vegetation
Vegetation
5
4.5
4
3.5
3
2.5
2
1.5
1
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Distance from CBD (km)


Vegetation vs. Building Density
Building Density
5
4.5
4
3.5
3
2.5
2
1.5
1
1
1.5
2
2.5
3
3.5
4
4.5
5
Vegetation

Appendix F: Ranked Data

Location	Temperature	Vegetation	Building Density	Distance from CBD
01a	54.5	4.5	74.5	72
01b	11	66.5	8	78.5
01c	54.5	4.5	74.5	74
01d	18	66.5	8	78.5
02a	3	17	8	81
02b	48	42	25.5	80
02c	62	80	2	82
03a	5	80	25.5	83
03b	2	80	2	85
03c	1	80	2	84
04a	24.5	66.5	25.5	77
04b	26.5	66.5	48.5	71
04c	30.5	66.5	48.5	67
06a	68.5	42	48.5	40
06b	38	42	48.5	37.5
06c	38	66.5	25.5	49.5
07a	18	80	25.5	29.5
07b	45	42	48.5	22.5
07c	23	80	25.5	14
08a	54.5	80	8	44
08b	68.5	66.5	25.5	34.5
08c	38	80	8	24
09a	13	66.5	25.5	40
09b	29	17	74.5	48
09c	45	4.5	74.5	56.5
10a	18	42	25.5	63
10b	54.5	42	25.5	55
10c	54.5	42	25.5	45
11a	80.5	42	25.5	66
11b	68.5	42	25.5	59
11c	18	42	8	49.5
12a	38	57.5	25.5	68.5
12b	38	57.5	48.5	75.5
12c	38	42	25.5	73
13a	80.5	66.5	74.5	62
13b	84	66.5	74.5	53
13c	85	42	48.5	51.5
14a	68.5	42	48.5	60.5
14b	26.5	42	25.5	68.5
14c	18	42	25.5	75.5
15a	38	42	48.5	70

15b	68.5	42	74.5	64.5
15c	68.5	42	74.5	60.5
16a	77	17	48.5	64.5
16b	68.5	17	48.5	58
16c	77	42	48.5	54
17a	22	66.5	48.5	56.5
17b	38	17	74.5	46
17c	38	17	74.5	27.5
18a	28	66.5	13.5	51.5
18b	74	42	61.5	40
18c	68.5	9	74.5	25
19a	77	4.5	74.5	9.5
19b	82.5	17	74.5	8
19c	82.5	17	74.5	11.5
20a	18	17	61.5	33
20b	9	80	13.5	42
20c	4	42	37	29.5
21a	38	4.5	74.5	18.5
21b	54.5	4.5	74.5	16.5
21c	54.5	4.5	74.5	15
22a	6	42	48.5	26
22b	7	66.5	25.5	43
22c	8	66.5	25.5	47
23a	48	42	48.5	31.5
23b	62	17	74.5	18.5
23c	32	17	74.5	31.5
24a	38	42	74.5	20
24b	68.5	42	48.5	37.5
24c	77	42	74.5	36
25a	54.5	26	48.5	21
25b	54.5	26	48.5	34.5
25c	54.5	26	48.5	27.5
26a	14	80	25.5	4.5
26b	45	80	25.5	13
26c	60	42	61.5	22.5
27a	11	17	74.5	1
27b	11	17	48.5	4.5
27c	18	66.5	48.5	9.5
28a	24.5	17	8	2
28b	30.5	4.5	8	3
28c	48	17	61.5	6
29a	62	66.5	8	7
29b	77	42	25.5	11.5
29c	68.5	42	48.5	16.5

Appendix G: Squared Rank Differences

Location	Distance from CBD vs. Temp.	Vegetation vs. Temp.	Building Density vs. Temp.
01a	306.25	2500	400
01b	4556.25	3080.25	9
01c	380.25	2500	400
01d	3660.25	2352.25	100
02a	6084	196	25
02b	1024	36	506.25
02c	400	324	3600
03a	6084	5625	420.25
03b	6889	6084	0
03c	6889	6241	1
04a	2756.25	1764	1
04b	1980.25	1600	484
04c	1332.25	1296	324
06a	812.25	702.25	400
06b	0.25	16	110.25
06c	132.25	812.25	156.25
07a	132.25	3844	56.25
07b	506.25	9	12.25
07c	81	3249	6.25
08a	110.25	650.25	2162.25
08b	1156	4	1849
08c	196	1764	900
09a	729	2862.25	156.25
09b	361	144	2070.25
09c	132.25	1640.25	870.25
10a	2025	576	56.25
10b	0.25	156.25	841
10c	90.25	156.25	841
11a	210.25	1482.25	3025
11b	90.25	702.25	1849
11c	992.25	576	100
12a	930.25	380.25	156.25
12b	1406.25	380.25	110.25
12c	1225	16	156.25
13a	342.25	196	36
13b	961	306.25	90.25
13c	1122.25	1849	1332.25
14a	64	702.25	400
14b	1764	240.25	1
14c	3306.25	576	56.25
15a	1024	16	110.25

15b	16	702.25	36
15c	64	702.25	36
16a	156.25	3600	812.25
16b	110.25	2652.25	400
16c	529	1225	812.25
17a	1190.25	1980.25	702.25
17b	64	441	1332.25
17c	110.25	441	1332.25
18a	552.25	1482.25	210.25
18b	1156	1024	156.25
18c	1892.25	3540.25	36
19a	4556.25	5256.25	6.25
19b	5550.25	4290.25	64
19c	5041	4290.25	64
20a	225	1	1892.25
20b	1089	5041	20.25
20c	650.25	1444	1089
21a	380.25	1122.25	1332.25
21b	1444	2500	400
21c	1560.25	2500	400
22a	400	1296	1806.25
22b	1296	3540.25	342.25
22c	1521	3422.25	306.25
23a	272.25	36	0.25
23b	1892.25	2025	156.25
23c	0.25	225	1806.25
24a	324	16	1332.25
24b	961	702.25	400
24c	1681	1225	6.25
25a	1122.25	812.25	36
25b	400	812.25	36
25c	729	812.25	36
26a	90.25	4356	132.25
26b	1024	1225	380.25
26c	1406.25	324	2.25
27a	100	36	4032.25
27b	42.25	36	1406.25
27c	72.25	2352.25	930.25
28a	506.25	56.25	272.25
28b	756.25	676	506.25
28c	1764	961	182.25
29a	3025	20.25	2916
29b	4290.25	1225	2652.25
29c	2704	702.25	400

Location	Distance from CBD vs. Building Density	Distance from CBD vs. Vegetation	Building Density vs. Vegetation
01a	6.25	4556.25	4900
01b	4970.25	144	3422.25
01c	0.25	4830.25	4900
01d	4970.25	144	3422.25
02a	5329	4096	81
02b	2970.25	1444	272.25
02c	6400	4	6084
03a	3306.25	9	2970.25
03b	6889	25	6084
03c	6724	16	6084
04a	2652.25	110.25	1681
04b	506.25	20.25	324
04c	342.25	0.25	324
06a	72.25	4	42.25
06b	121	20.25	42.25
06c	576	289	1681
07a	16	2550.25	2970.25
07b	676	380.25	42.25
07c	132.25	4356	2970.25
08a	1296	1296	5184
08b	81	1024	1681
08c	256	3136	5184
09a	210.25	702.25	1681
09b	702.25	961	3306.25
09c	324	2704	4900
10a	1406.25	441	272.25
10b	870.25	169	272.25
10c	380.25	9	272.25
11a	1640.25	576	272.25
11b	1122.25	289	272.25
11c	1722.25	56.25	1156
12a	1849	121	1024
12b	729	324	81
12c	2256.25	961	272.25
13a	156.25	20.25	64
13b	462.25	182.25	64
13c	9	90.25	42.25
14a	144	342.25	42.25
14b	1849	702.25	272.25
14c	2500	1122.25	272.25
15a	462.25	784	42.25
15b	100	506.25	1056.25

15c	196	342.25	1056.25
16a	256	2256.25	992.25
16b	90.25	1681	992.25
16c	30.25	144	42.25
17a	64	100	324
17b	812.25	841	3306.25
17c	2209	110.25	3306.25
18a	1444	225	2809
18b	462.25	4	380.25
18c	2450.25	256	4290.25
19a	4225	25	4900
19b	4422.25	81	3306.25
19c	3969	30.25	3306.25
20a	812.25	256	1980.25
20b	812.25	1444	4422.25
20c	56.25	156.25	25
21a	3136	196	4900
21b	3364	144	4900
21c	3540.25	110.25	4900
22a	506.25	256	42.25
22b	306.25	552.25	1681
22c	462.25	380.25	1681
23a	289	110.25	42.25
23b	3136	2.25	3306.25
23c	1849	210.25	3306.25
24a	2970.25	484	1056.25
24b	121	20.25	42.25
24c	1482.25	36	1056.25
25a	756.25	25	506.25
25b	196	72.25	506.25
25c	441	2.25	506.25
26a	441	5700.25	2970.25
26b	156.25	4489	2970.25
26c	1521	380.25	380.25
27a	5402.25	256	3306.25
27b	1936	156.25	992.25
27c	1521	3249	324
28a	36	225	81
28b	25	2.25	12.25
28c	3080.25	121	1980.25
29a	1	3540.25	3422.25
29b	196	930.25	272.25
29c	1024	650.25	42.25

Appendix H: Re-Ranked Data

	No Trees, n = 64			No Groups 1–3, n = 75		
Location	Temperature	Vegetation	Building Density	Temperature	Vegetation	Building Density
01b	9	47.5	5.5			
01d	14.5	47.5	5.5			
02b	36.5	23.5	21			
03a	4	60	21			
03b	2	60	1.5			
03c	1	60	1.5			
04a	20	47.5	21	18.5	61.5	18.5
04b	21.5	47.5	43	20.5	61.5	40.5
04c	24	47.5	43	24.5	61.5	40.5
06a	51	23.5	43	58.5	38.5	40.5
06b	29.5	23.5	43	32	38.5	40.5
06c	29.5	47.5	21	32	61.5	18.5
07a	14.5	60	21	12.5	72	18.5
07b	34.5	23.5	43	39	38.5	40.5
07c	19	60	21	17	72	18.5
08a	40.5	60	5.5	54.5	72	3.5
08b	51	47.5	21	58.5	61.5	18.5
08c	29.5	60	5.5	32	72	3.5
09a	10	47.5	21	8	61.5	18.5
09b				23	14.5	65.5
09c	34.5	1.5	59.5	39	3.5	65.5
10a	14.5	23.5	21	12.5	38.5	18.5
10b	40.5	23.5	21	54.5	38.5	18.5
10c	40.5	23.5	21	47.5	38.5	18.5
11a	61.5	23.5	21	70.5	38.5	18.5
11b	51	23.5	21	58.5	38.5	18.5
11c	14.5	23.5	5.5	12.5	38.5	3.5
12a	29.5	38.5	21	32	53.5	18.5
12b	29.5	38.5	43	32	53.5	40.5
12c	29.5	23.5	21	32	38.5	18.5
13a	61.5	47.5	59.5	70.5	61.5	65.5
13b	63	47.5	59.5	74	61.5	65.5
13c	64	23.5	43	75	38.5	40.5
14a	51	23.5	43	58.5	38.5	40.5
14b	21.5	23.5	21	20.5	38.5	18.5
14c	14.5	23.5	21	12.5	38.5	18.5
15a	29.5	23.5	43	32	38.5	40.5
15b	51	23.5	59.5	58.5	38.5	65.5

15c	51	23.5	59.5	58.5	38.5	65.5
16a	58	4.5	43	67	14.5	40.5
16b	51	4.5	43	58.5	14.5	40.5
16c	58	23.5	43	67	38.5	40.5
17a	18	47.5	43	16	61.5	40.5
17b				32	14.5	65.5
17c				32	14.5	65.5
18a	23	47.5	9.5	22	61.5	7.5
18b				64	38.5	53.5
18c				58.5	7	65.5
19a	58	1.5	59.5	67	3.5	65.5
19b				72.5	14.5	65.5
19c				72.5	14.5	65.5
20a				12.5	14.5	53.5
20b	8	60	9.5	5	72	7.5
20c	3	23.5	32	1	38.5	29
21a				32	3.5	65.5
21b				47.5	3.5	65.5
21c				47.5	3.5	65.5
22a	5	23.5	43	2	38.5	40.5
22b	6	47.5	21	3	61.5	18.5
22c	7	47.5	21	4	61.5	18.5
23a	36.5	23.5	43	41.5	38.5	40.5
23b	45.5	4.5	59.5	52.5	14.5	65.5
23c	25	4.5	59.5	26	14.5	65.5
24a	29.5	23.5	59.5	32	38.5	65.5
24b	51	23.5	43	58.5	38.5	40.5
24c	58	23.5	59.5	67	38.5	65.5
25a	40.5	8	43	47.5	23	40.5
25b	40.5	8	43	47.5	23	40.5
25c	40.5	8	43	47.5	23	40.5
26a	11	60	21	9	72	18.5
26b				39	72	18.5
26c	44	23.5	54	51	38.5	53.5
27a				6.5	14.5	65.5
27b				6.5	14.5	40.5
27c	14.5	47.5	43	12.5	61.5	40.5
28a				18.5	14.5	3.5
28b				24.5	3.5	3.5
28c				41.5	14.5	53.5
29a	45.5	47.5	5.5	52.5	61.5	3.5
29b	58	23.5	21	67	38.5	18.5
29c	51	23.5	43	58.5	38.5	40.5

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