University of British Columbia

Social Ecological Economic Development Studies (SEEDS) Sustainability Program

Student Research Report

USING LIDAR FOR ASSESSING BUILDINGS AT UBC FOR GREEN ROOF POTENTIAL

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1. INTRODUCTION

Green roof infrastructure has already been implemented in many major urban centres, providing a list of benefits for the residents, buildings, and overall well-being of the city (Asgarzadeh et al., 2010). Buildings with green roofs have shown to decrease thermal losses and ultimately spare internal heating expenses (Niachou et al., 2001; Zhao and Srebric, 2012); sequester carbon (Getter et al., 2009) and filter out other nasty urban pollutants (Baraldi et al., 2019; Van Metre and Mahler, 2003; Baik et al., 2012); mitigate the urban heat island effect (Ouldboukhitine et al., 2014; Gunawardena et al., 2017); harbor biodiversity and create ecological connections (Joimel et al., 2022; Wooster et al., 2022); and reduce stormwater runoff and flooding events (Shafique and Luo, 2019). Therefore, investing in green roof infrastructure at the University of British Columbia (UBC) can boost student morale, save money on heating/cooling buildings during peak temperatures, reduce airborne pollutants, and lessen the outflow of water from precipitation events.

However, actually implementing a green roof plot contains several variables that one must consider, especially if the green roof is to be built over a pre-existing building. Weight bearing capacity of the building, slope of the roof surface, and accessibility to the roof top are all key considerations before implementing green roof gardens. These must all be determined before moving forward with implementing either an intensive or extensive green roof, which differ between substrate depth. Extensive green roofs are shallower in substrate depth (8 cm) and can weigh between 12-14 kg/m² (Cascone 2019) with one study noting their saturated weight of green roof was equivalent to 150 kg/m³ (VanWoert et al,. 2005). Extensive green roofs are commonly implemented but limit the biodiversity and ecological connectivity potential that intensive green roofs may offer. However, intensive green roofs can weigh up to 600 kg/m², with a substrate depth between 50-60 cm (Cascone 2019). The slope of the roof surface must also be considered, as precipitation can cause sloughing on surfaces greater than 10° and further engineering will be required to navigate slopes greater than that angle (Greenroof Guide). Lastly, every green roof requires accessibility to the surface of the roof at the start of implementation and any subsequent weeding and irrigation that the green roof requires.

The objective of this study is to determine which buildings on UBC campus will be suitable for green roof infrastructure, and then analyse the top buildings and quantify the amount of stormwater run-off could be reduced by implementing extensive and intensive green roofs. This study also goes one step further to harmonize previous studies done for ecological connectivity (Nicholas Mantegna, 2021) and parkade retrofits for green roofs (Bankston et al., 2018) over UBC campus.

1.2 STUDY SITE

We examined the suitability of campus buildings at the University of British Columbia (UBC), located on xʷməθkʷəyə́ m (Musqueam) territory at 49.263591° N -123.246419°W. UBC is situated on the western coast of BC and experiences an average of 22.2°C in the summer, lows of 0.8°C in the winter, and up to 1152.8mm of precipitation per year (Environment and Climate Change Canada, 2022). Metro Vancouver predicts climate change to impact the city and surrounding area by increase of drought in the summers, warmer temperatures (longer summer, shorter winter), and more extreme precipitation events (Metro Vancouver, 2018).

2. DATA AND METHODS

2.1 CREATING 3D STRUCTURES

In 2021, the latest Light Detection and Ranging (LiDAR) dataset became available for UBC faculty and students to utilize. These data were downloaded from the UBC Dataverse and imported into ArcGIS Pro for further analysis. Data cleaning, LAS Dataset creation, 3D Building derivation, and the subsequent suitability analysis were all performed in ArcGIS Pro. ArcGIS Solutions has a package called 3D Basemaps that comes pre-equipped with workflows that help process and transform LiDAR point clouds into use-able features, such as ground elevation (digital terrain models or DTM) and 3D structures (https://doc.arcgis.com/en/arcgis-solutions/latest/reference/use-3d-basemaps.htm). Using this solution, we first extracted elevation surfaces from the LAS dataset, retrieving the DTM, a digital surface elevation (DSM) which depicts the top of the point cloud and contours of the buildings, and a normalized surface elevation (nDSM). Next, buildings were created by running the Extract Building Footprints and Preprocess Building Footprints tools, which created 3D rectangular representations of campus buildings with the elevation derived from the DSM. The Create Buildings tool then analyzed any further points and determined flat, gabled, or hipped roof features and the slope of the roof, and was followed by the Extract Roof Form tool. This tool uses the building footprints from the previous step and DTM, DSM, and nDSM to reconstruct roof form and create new attributes based on these values: 'BLDGHEIGHT' indicates the maximum height of the entire building; 'EAVEHEIGHT' indicates the minimum height of the roof form; 'ROOFFORM' represents the shape of the roof; 'BASEELEV' displays the elevation of the ground at the base of the building; 'ROOFDIR' represents the direction the roof faces in degrees; and 'RoofDirAdjust' which also provides information regarding direction the roof is facing in colloquial terms. In addition to this LiDAR set, we were also provided data regarding age, construction type, property management, and type of building (academic, student residence, operations, etc) which we used when designing the suitability criteria.

2.2 SUITABILITY CALCULATION

In order to determine which campus buildings are suitable for green roofs we created a weighted criteria of features:

1. Flatness: Green roofs are most commonly installed on flat surfaces with a slope between 2° and 10° as anything more than that risks sloughing and slippage (The Greenroof Centre, n.d.).
2. Structural Integrity: Green roofs also require a certain degree of structural integrity, as they can impose 13 - 30 lbs/sq.ft. of extra weight on the building (The Greenroof Centre, n.d.).
3. Size & Ownership: The client specified roof surfaces over 1000 m^2. (10763.9 sq.ft.) and owned by UBC (rather than private organizations) would be the most feasible and realistic way to implement green roof infrastructure.
4. Accessibility: Green roofs require a certain degree of maintenance and therefore accessibility to the roof. For this criteria, we went back to the LiDAR point cloud and examined any extra planar shapes that exceeded the roof surface and assumed those shapes represented ventilation, heating systems, and other mechanisms situated on the roof surfaces. We presumed that if there are machines on the roof, there must be accessibility to the roof in order to maintain the performance of the machines and therefore a relatively easy way to reach the roof surface for potential green roof maintenance. However, this also introduces contention in having *too much* machinery occupying the square footage of the roof surface, so

we further implemented a metric that would exclude buildings that had machinery covering more than 70% of the roof surface.

Therefore, the final suitability calculator re-assigned numerical values to the following attributes (Table 1), giving a score of ‘1’ to attribute features that were favourable given our criteria and a ‘0’ to features that were not.

Table 1 - Attributes derived from 3D Basemaps and campus building data that were reclassified to fit the suitability criteria as determined by literature, GIS team, and client. * ‘Systems’ and ‘Accessibility’ were presumed by further analysis of LiDAR data and delineated features.

ArcGIS Attribute	Classification	Reclassification
ROOF FORM	Flat	1
	Gable, Hip, etc.	0
CONSTR_TYPE (Integrity)	Concrete	1
	Wood	0
	OtherMixed	1
	Steel	1
Shape Area (Rooftop area)	< 1000 sqm	0
	> 1000 sqm	1
MANAGMENT (Building ownership)	UBC	1
	PRIVET	0
Systems* (Mechanics present)	Less than 30%	1
	More than 70%	0
Accessibility* (Mechanics Present)	Yes	1
	No	0

2.3 STORMWATER RUNOFF WATER CALCULATION

We calculated stormwater runoff using an application designed by Wu et al. (2021) that incorporates area of roof, impervious surfaces, green space, and returns a monthly breakdown of runoff spared from hypothetical low-impact development (LID) ideas. For the purpose of this study, we used open-source shapefiles from UBC Geodata (Table 2; https://github.com/UBCGeodata) and shape area values as they are represented in the Canada Albers Equal Area Conic (ESRI: 102001) in QGIS for calculating stormwater runoff. Green roof area was hand-drawn over ESRI Satellite basemap within QGIS (QGIS Development Team, 2022) with Google Earth Pro as 3D reference, as to avoid large machinery present on rooftops. Site area was determined by a squared-off 20 m buffer around the suitable building or around the complex of buildings deemed suitable by the above calculation. The stormwater calculator utilizes curve numbers which capture the effect different substrates and surface materials have on stormwater discharge and runoff events (Wu et al., 2021). Curve numbers have been widely used in landscape ecology and urban planning to approximate runoff over a particular area, and double as being easy to calculate and incorporate (Wu et al., 2021). Wu et al. (2021) give an example calculation which was conveniently based over UBC in Vancouver, BC; therefore, curve numbers for 'Lawn' and 'Impermeable paving' were retained for the purpose of our study at 61 and 98, respectively. Extensive (50 - 150 mm medium depth) and Intensive (150 - 1000 mm medium depth) green roof plots (Hui and Chan, 2011) were determined with crop coefficient (Kc) values of 0.3 and 0.6, respectively (Wu et al., 2021).

Table 2 - Factors and features included when calculating storm water run off. Curve numbers (CN) taken from the stormwater calculator application developed by Wu et al. (2021).

Calculator Field	Shapefile Used	Curve Number (CN)	Source
TOTAL SITE AREA	ubcv_legal_boundary	-	UBC Geodata on github
TOTAL ROOF AREA	ubcv_buildings	-	2021 LiDAR dataset
IMPERMEABLE PAVING	ubcv_softlandscape	98	UBC Geodata on github; dissolved
LAWN	ubcv_softlandscape	61	UBC Geodata on github

2.4 IMPERMEABILITY ANALYSIS

This phase examined the water-permeable surfaces across the UBC campus on average per parcel. A study by Yunyani Li (2021) examined different types of land use and classified these across campus. As a result of this classification, it was possible to estimate impervious surfaces such as buildings, roads, and parking lots. This information would allow us to understand the extent of impact our derived green roof layers would have over these parcels of UBC campus, and works alongside the stormwater runoff quantification.

First, the Urban Green Space Analysis study file was imported. Next, the segmentation layer was converted to Raster in ArcGIS PRO, which helped understand the different land-use types. The segmented Raster was then 'Reclassified' to help understand the types of non-permeable surfaces. Next, to determine the area of impervious and permeable surfaces within each plot of land on campus, a calculation of the impervious area compared to each parcel was done using the Tabulate Area tool in ArcGIS PRO. Using this calculation allows saving the results in a new table. The table results were then merged with the Campus Parcel Layer, making it possible to add a new column and calculate the percentage of the impervious areas in each area division. These calculations were displayed using the Symbology tab. Finally, the same process was performed to test the effect of the green roofs found in this study. This time, the suitable buildings in this study were marked as water-permeable areas, which allowed recalculation and presentation of the new results with the relevant green roofs.

Lastly, a comparison was made using a raster calculation to understand the percentage change in each parcel across campus.

2.5 PLANT SELECTION

Selecting the most suitable plant species for green roofs depends on the desired outcome. Based on previous literature, it is evident that sedum species are most commonly used for green roofs due to their shallow roots, drought resistance, and low maintenance requirements (Schrieke & Farrell, 2021). However, sedums are not native to Vancouver, making them less useful for improving biodiversity on campus.

For this study, plants with high water retention abilities are preferred as a key aim is to reduce stormwater runoff. Further, to improve the biodiversity on the UBC Vancouver campus, native plant species should be predominantly used, however this is most important for lower roofs which may increase connectivity on campus. Our plant recommendations were taken from a comprehensive list of plants suitable to green roofs in Vancouver, provided by Holly Horne (Head of Design and Project Manager at Gingko Sustainability, Appendix A). From this list, plants were chosen based on criteria, such as stormwater retention, ability to improve biodiversity, and aesthetic considerations.

Additionally, the most suitable plant species will vary depending on the roof. Low maintenance plants will be most appropriate for all roofs, but particularly for roofs that are more difficult to access. Environmental factors, such as light and wind, will control which plants are able to survive on certain roofs as some roofs may be heavily shaded by other buildings. Aesthetically pleasing plants will be most suitable for highly visible roofs or roofs that are commonly used by the public. Plants that provide key ecosystem benefits will be most suited to low roofs which are more connected to the rest of the ecosystem. Overall, choosing the most suitable plants depends on a variety of factors and will vary significantly depending on the reason the green roof is being implemented.

3. RESULTS

After constructing buildings using the 2021 LiDAR point cloud, UBC campus contains approximately 3,989,822 sq.ft. of roof surface. Of that value, nearly 2/3 of that was determined suitable for green roof implementation given our criteria. Approximately 379,549 sq.ft. was graded the 'best'; 646,054 sq.ft. was 'mediocre'; and 1,329,091 sq.ft. was 'OK' but still suitable for green roof infrastructure (Figure 1). Of these results, the most suitable buildings for green roof infrastructure include the TRIUMF complex (Figure 1B), University Hill Secondary School (Figure 1C), the Technology Enterprise Facility at the south-east corner of Agronomy and East Mall (Figure 1D), Wesbrook Community center, Mews residence building in Wesbrook Village, the Robert H. Lee Alumni Centre, Focal student residence at 6111 University Blvd., and Central student residence at 6015 University Blvd. Table 3 contains grades ('steps'), building name, building code, local addresses, and approximate square footage of all 3,989,822 sq.ft. of ideal buildings. Our analysis further revealed 363,363 sq.ft. of parkade surfaces to be suitable for green roof space, though a previous SEEDS study has explored this in much more detail and can be further explored at Living Roofs and Low Impact Design (Bankston et al., 2018).

Stormwater runoff was quantified with either intensive or extensive roof surfaces and was only calculated for the most suitable (step 1) buildings from the analysis. Total runoff from all buildings in step one was 41,476 m^3 With surrounding soft landscapes mitigating an average of 18%runoff without any kind of green roof infrastructure (Table 4). By incorporating extensive (50 - 150 mm soil depth) green roofs to all buildings, total runoff reduced would be 784 m^3; whereas incorporating intensive green roofs (150 mm - 300 mm) would reduce runoff by 1437 m^3 (Table 4). A closer look into the theoretical green roof plots can be found in Figures 2 - 7. The impermeability analysis, which essentially examined amount of concrete and asphalt around campus and aides in stormwater mitigation, revealed that incorporating green roof infrastructure would result in over 50% positive change to the overall impermeability of campus (Figure 8).

Extensive research and exploration of suitable plants for green roofs over UBC campus unfortunately revealed very little information that enabled us to formally procure a list of feasible plants to be implemented in green roof infrastructure over UBC campus. In order to fully realize suitable plants to implement over UBC campus, an investigation into biodiversity and ecological connectivity *with respect to* roof surfaces must be conducted, and plants can then be narrowed down based on root depth (which can determine whether extensive or intensive green roofs can be implemented), nativity, and hardiness in the face of both intensive rains and summer drought. From there, a viewshed analysis study could be done from residence buildings to determine which rooftops are most commonly observed, and the most aesthetic plants can be implemented there.

Another study can be conducted in measuring wind speed at various building heights, which can further support decisions in plant selection based upon seed dispersal methods of the plants implemented. One should also consider the seed dispersal mechanisms of plants implemented on very tall buildings and anticipate any crossover into green roof plots on lower buildings. Dispersal of sedum seeds, for example, have commonly found their way into green roof plots that harbour native perennial flowers in Toronto (M. Sifton, personal communication, 2021). Another study can also look into the crop coefficient (Kc) values of plants. Crop coefficient is an estimate of water consumed by an individual plant, taking a ratio of evapotranspiration to potential evapotranspiration - both of which fluctuate following precipitation (Heclman et al., 1982) and growth stages of the crop of interest. In order to understand suitable plants to implement in green roof infrastructure over UBC campus, a series of experiments examining plants of interest and defining their Kc value would be greatly beneficial.

Figure 1 - *(A) The final map of campus building suitability for green roof infrastructure; (B) the TRIUMF complex and location at the southpoint of campus; (C) the University Hill Secondary School; (D) the Technology Enterprise Facility at 6190 Agronomy Rd. Figures 1B-1D captured using Google Earth Pro 2022.*

Table 3 - A final list of buildings determined suitable for green roof infrastructure. 'Step' indicates the first, second, and third stages UBC may take in best to mediocre green roof installation. 'MF' stands for 'Maximum floors'. GREEN_STAT indicates certification achieved for that building: LG = LEED Gold; LS = LEED Silver; RG = REAP Gold; RG+ = REAP Gold Plus

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m^2)
1	TRIUMF - Accelerator	TRF02	2003-01-01	Non-UBC		6	16.55	4004 Wesbrook Mall, Building 7	9634.52
1	TRIUMF - ARIEL	TRF01	2015-08-01	Non-UBC	LG	5	14.21	4004 Wesbrook Mall, Building 4	1202.68
1	TRIUMF - ISAC 1	TRF09	1998-01-01	Non-UBC		5	13.48	4004 Wesbrook Mall, Building 6	2579.73
1	TRIUMF - ISAC 2	TRF10	2003-01-01	Non-UBC		5	12.59	4004 Wesbrook Mall, Building 5	3600.33
1	The Mews	MEWS	2011-01-31	UNA	RG	6	18.24	3333 Wesbrook Mall	2019.64
1	Wesbrook Community Centre	WCOM	2015-09-10	UNA	LG	2	11.94	3335 Webber Lane	2883.45
1	Focal	FOCL	2020-04-17	UNA	RG	6	25.15	6111 University Boulevard	1278.52
1	University Hill Secondary School	UHIL	1995-01-01	Non-UBC		3	14.52	3228 Ross Drive	7339.51
1	Robert H. Lee Alumni Centre	ALUM	2015-04-22	UBC	LG	4	16.30	6163 University Boulevard	1179.73
1	Technology Enterprise Facility 3	TEF3	2003-01-01	Non-UBC	LS	8	30.69	6190 Agronomy Road	1863.82
1	Central	CNTL	2017-05-29	UNA	RG+	7	21.51	6015 University Boulevard	1679.33
2	Orchard Commons - Vantage College, Bartlett/Braeburn House	ORCH	2016-07-15	UBC	LG	20	17.57	6363 Agronomy Road	4109.87

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m^2)
2	Totem Park Residence - q̓ələχən House	TPR4	2011-08-23	UBC	RG	8	20.19	2525 West Mall, Building 4	1042.95
2	David Strangway Building	STRG	2005-12-23	UBC		6	28.06	5950 University Boulevard	3553.86
2	Institute for Computing Information and Cognitive Systems	ICCS	1993-01-01	UBC		8	19.58	2366 Main Mall	2926.94
2	Thunderbird Residence - Cassiar	THR1	1995-01-01	UBC		4	13.31	6335 Thunderbird Crescent, Building 5	1226.29
2	Biomedical Research Centre	BRC	2005-05-25	UBC		4	21.85	2222 Health Sciences Mall	1232.84
2	Fred Kaiser Building	KAIS	2004-10-12	UBC		5	20.70	2332 Main Mall	2997.72
2	Student Recreation Centre	SRC	1995-01-01	UBC		2	19.24	6000 Student Union Boulevard	2527.88
2	Totem Park Residence - həm̓ləsəm̓ House	TPR5	2011-01-01	UBC	RG	8	21.62	2525 West Mall, Building 5	1567.20
2	Chan Gunn Pavilion	GUNN	2017-10-27	UBC	LG	2	9.21	2553 Wesbrook Mall	1229.01
2	Leon and Thea Koerner University Centre	UCEN	2008-08-29	UBC		3	12.13	6331 Crescent Road	2351.00
2	Thunderbird Residence - Monashee	THR2	1995-01-01	UBC		4	11.69	6335 Thunderbird Crescent, Building 4	1285.11
2	Allard Hall	ALRD	2011-08-29	UBC	LG	5	25.52	1822 East Mall	3540.53
2	Totem Park Residence - c̓əsnaʔəm House	TPR7	2017-07-20	UBC	LG	8	19.26	2525 West Mall, Building 7	1384.07

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m²)
2	University Services Building	USB	1992-01-01	UBC		2	9.27	2329 West Mall	7813.99
2	Life Sciences Centre	LSC	2004-08-20	UBC	LG	8	11.96	2350 Health Sciences Mall	2395.94
2	Thunderbird Residence - Selkirk	THR3	1995-01-01	UBC		4	13.55	6335 Thunderbird Crescent	1279.16
2	Museum of Anthropology	MOA	2009-03-20	UBC		2	13.64	6393 NW Marine Drive	8666.02
2	Chan Centre for the Performing Arts	CHAN	1997-01-01	UBC		6	29.76	6265 Crescent Road	3331.35
2	Campus Energy Centre	CEC	2016-01-01	UBC	LG	2	17.66	6130 Agronomy Road	1578.84
2	Library PARC@UBC	PARC	2015-08-28	UBC	LG	2	12.17	6049 Nurseries Road	2185.04
2	Brock Commons South	BRCS		UBC		13	10.08	6180 Walter Gage Road	1794.80
3	FERIC	FERC	1990-01-01	Non-UBC		3	12.36	2601 East Mall	1255.51
3	FPInnovations	FPIN	1990-01-01	Non-UBC		2	13.34	2665 East Mall	6927.76
3	Power House	POWR	1925-01-01	UBC		4	15.89	2040 West Mall	1532.74
3	Frederic Lasserre Building	LASR	1962-01-01	UBC		5	17.88	6333 Memorial Road	1092.37
3	Frank Forward Building	FORW	1968-01-01	UBC		6	29.64	6350 Stores Road	1295.29
3	Pulp and Paper Centre	PAPC	1985-01-01	UBC		4	18.82	2385 East Mall	1566.78
3	HR MacMillan Building	MCML	1967-01-01	UBC		4	19.56	2357 Main Mall	3570.43
3	Irving K. Barber Learning Centre	IBLC	1927-01-01	UBC		5	26.87	1961 East Mall	6581.41

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m²)
3	Douglas T. Kenny Building	KENN	1983-01-01	UBC		4	23.22	2136 West Mall	2688.70
3	Neville Scarfe Building	SCRF	1962-01-01	UBC		6	21.13	2125 Main Mall	4410.18
3	Hector J. MacLeod Building	MCLD	1963-01-01	UBC		4	16.58	2356 Main Mall	1795.44
3	Lower Mall Research Station	LMRS	1960-01-01	UBC		3	14.84	2259 Lower Mall	2017.09
3	Music Building	MUSC	1967-01-01	UBC		4	22.74	6361 Memorial Road	1446.64
3	P. A. Woodward Instructional Resources Centre	IRC	1972-01-01	UBC		6	26.98	2194 Health Sciences Mall	3972.97
3	School of Population & Public Health	SPPH	1979-01-01	UBC		5	17.46	2206 East Mall	1682.53
3	Place Vanier Residence - Commonsblock	VNR03	1960-01-01	UBC		3	13.98	1935 Lower Mall, Building 1	1922.11
3	War Memorial Gymnasium	MGYM	1950-01-01	UBC		5	21.55	6081 University Boulevard	4007.08
3	Anthropology and Sociology Building	ANSO	1975-01-01	UBC		4	11.89	6303 NW Marine Drive	2946.53
3	Totem Park Residence - Commonsblock	TPR1	1964-01-01	UBC		3	9.58	2525 West Mall	2544.27
3	3800 Wesbrook Mall	3800	1985-01-01	Non-UBC		5	20.69	3800 Wesbrook Mall	3808.13
3	UBC Life Building	LIFE	1968-01-01	UBC		3	18.70	6138 Student Union Boulevard	7045.14
3	Thea Koerner House	THEA	1961-01-01	UBC		4	18.66	6371 Crescent Road	1368.91
3	The Leonard S. Klinck Building	LSK	1947-01-01	UBC		5	21.87	6356 Agricultural Road	2450.69

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m^2)
3	Woodward Library	WLIB	1964-01-01	UBC		4	21.12	2198 Health Sciences Mall	2195.57
3	Walter H. Gage Residence - Commonsblock	WGR1	1972-01-01	UBC	LG	2	13.24	5959 Student Union Boulevard, Building 1	2190.04
3	Robert F. Osborne Centre - Unit 2	OSB2	1972-01-01	UBC		2	7.54	6108 Thunderbird Boulevard, Building 2	2593.08
3	Walter H. Gage Residence - Gage Apartments	WGR2	1984-01-01	UBC	LG	5	13.68	5959 Student Union Boulevard, Building 5	1760.51
3	UBC Hospital - Koerner Pavilion	KPAV	1980-01-01	Non-UBC		5	30.97	2211 Wesbrook Mall	8006.77
3	Buchanan Building	BUCH	1958-01-01	UBC	LG	5	15.26	1866 Main Mall	3876.97
3	Buchanan Building	BUCH	1958-01-01	UBC	LG	5	14.25	1860 East Mall	2192.47
3	Chemistry A Physics	CHPH	1989-01-01	UBC		5	24.48	6221 University Boulevard	1674.54
3	Civil and Mechanical Engineering Building	CEME	1976-01-01	UBC		3	17.40	6250 Applied Science Lane	4936.98
3	Civil and Mechanical Engineering Laboratories	CEML	1969-01-01	UBC		2	11.51	2275 East Mall	4239.15
3	Brock Hall	BRCK	1940-01-01	UBC		3	16.75	1874 East Mall	3601.68
3	UBC Hospital - Detwiller Pavilion	DPAV	1968-01-01	Non-UBC		7	28.93	2255 Wesbrook Mall	3554.34
3	Hennings Building	HENN	1945-01-01	UBC		4	17.31	6224 Agricultural Road	3684.22

Step	NAME	BLDG_CODE	OCCU_DATE	JURISDICTI	GREEN_STAT	MF	BLDG_HEIGHT	FULL ADDRESS	Shape_Area (m^2)
3	JB Macdonald Building	MCDN	1967-01-01	UBC		4	16.42	2199 Wesbrook Mall	2495.30
3	UBC Hospital - Purdy Pavilion	PPAV	1977-01-01	Non-UBC		6	27.51	2221 Wesbrook Mall	2739.90
3	Walter H. Gage Residence - West Coast Suites (Gage Court)	WGR3	1972-01-01	UBC	LG	4	11.80	5961 Student Union Boulevard	1136.10
3	Frederic Wood Theatre	FRWO	1963-01-01	UBC		3	19.44	6354 Crescent Road	1596.80
3	Robert F. Osborne Centre - Unit 1	OSB1	1970-01-01	UBC		2	10.35	6108 Thunderbird Boulevard	3073.53

3.1 CLOSER LOOKS

TRIUMF Complex

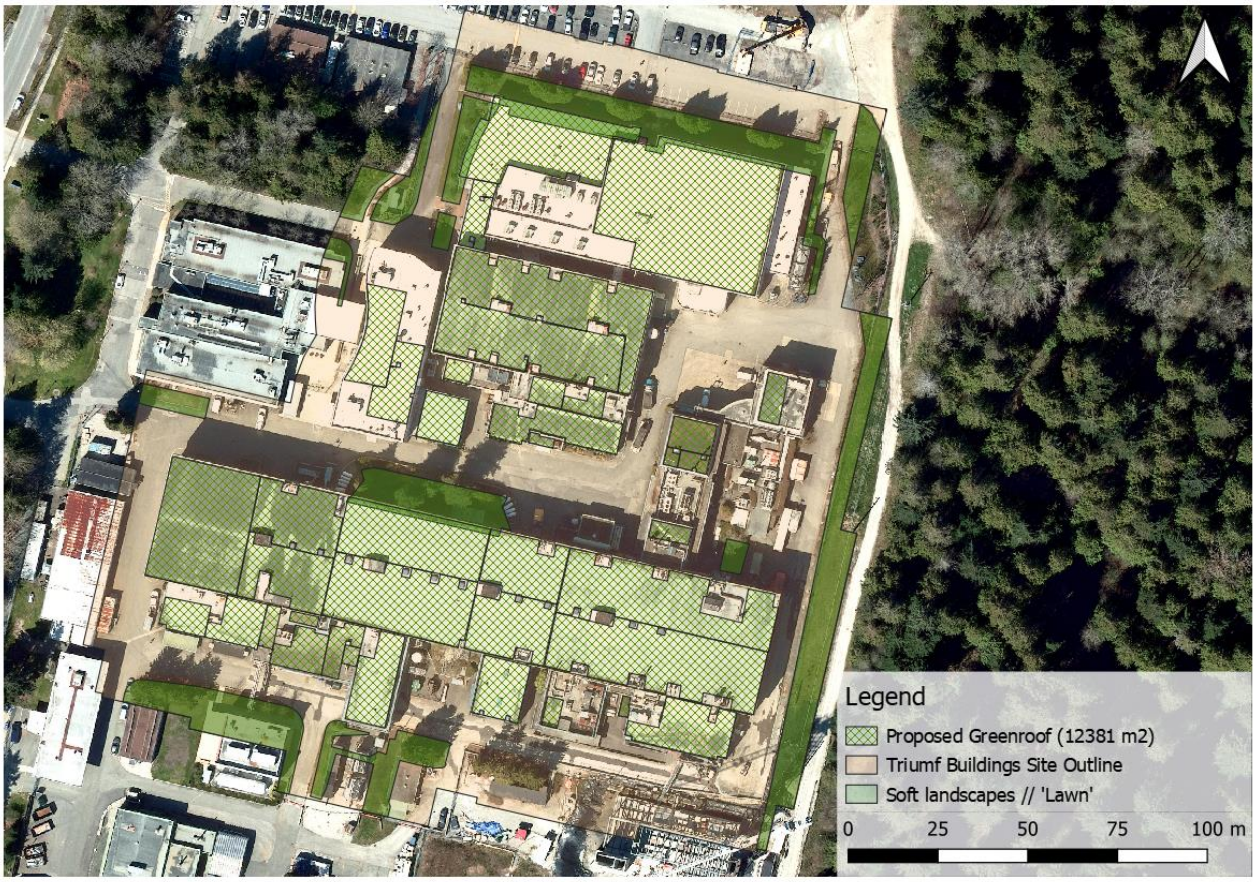

Figure 2 - A close-up of the TRIUMF complex, which was the largest cluster of buildings our analysis graded as 'best' for green roof infrastructure. The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

The TRIUMF Complex at 4004 Wesbrook Mall is composed of several buildings, but our suitability analysis determined buildings 4-7 as being most suitable for green roof infrastructure. In total, the building and roof surface occupies 17,140 m² and amounts to 17,423 m³ of surface runoff annually, mitigating 12% of runoff with the current soft landscapes shown (Table 4; green shapes, Figure 2). With an extensive green roof occupying 12,381 m² of roof surface (green cross-hatched shapes, Figure 2), runoff is reduced by 358 m³ and is capable of 14% mitigation, whereas an intensive roof occupying the roof surface results in a 657 m³ reduction and 16% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by 50% when incorporating intensive green roofs, and 20% with extensive green roofs (Table 4).

University Hill Secondary School & Wesbrook Community Center

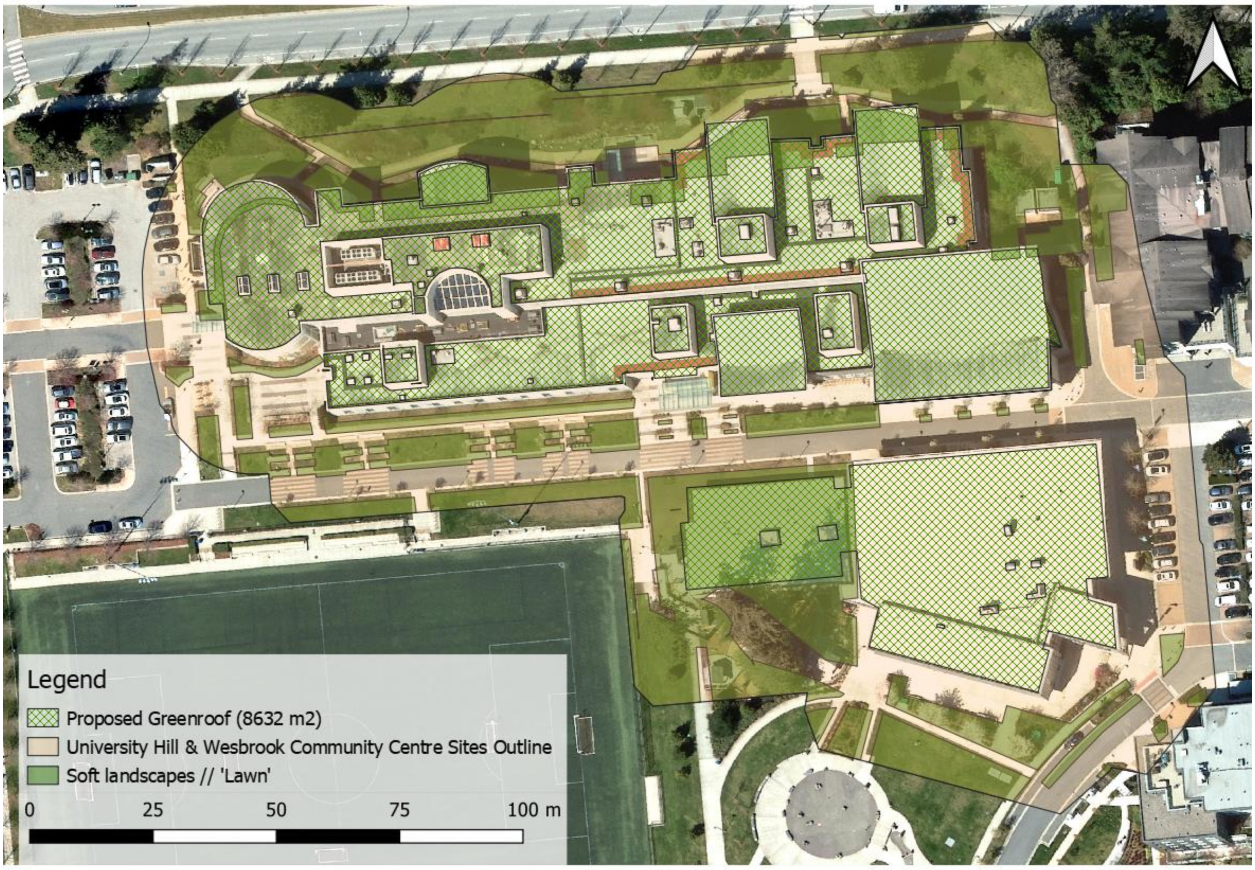

Figure 3 - A close-up of University Hill Secondary School and Wesbrook Community Centre, the second largest area our analysis deemed suitable. The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

Due to their proximity and shared soft landscapes, University Hill Secondary and Wesbrook Community Center were also combined to realize stormwater runoff reductions. In total, the building and roof surface occupies 10,233 m^2 and amounts to 9,171 m^3 of surface runoff annually, mitigating 28% of runoff with the current soft landscapes shown (Table 4; green shapes, Figure 3). With an extensive green roof occupying 8,632 m^2 of roof surface (green cross-hatched shapes, Figure 3), runoff is reduced by 246 m^3 and is capable of 30% mitigation, whereas an intensive roof occupying the roof surface results in a 450 m^3 reduction and 32% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by nearly 50% when incorporating intensive green roofs, and less than 10% with extensive green roofs (Table 4). There was significantly more 'lawn' coverage in the buffered site of these two buildings, which heavily contributed to the initial amount of stormwater mitigation.

The Mews

Figure 4 - A close-up of The Mews, in close proximity to University Hill Secondary School and Westbrook Community Centre (just to the hypothetical left of the image above). The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

In total, the Mews building and roof surface occupies 2,021 m^2 and amounts to 3,905 m^3 of surface runoff annually, mitigating just 3% of runoff with the current soft landscapes shown (Table 4; green shapes, Figure 4). With an extensive green roof occupying 1,878 m^2 of roof surface (green cross-hatched shapes, Figure 4), runoff is reduced by 53 m^3 and is capable of 4% mitigation, whereas an intensive roof occupying the roof surface results in a 97 m^3 reduction and 5% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by 29% when incorporating intensive green roofs, and roughly 13% with extensive green roofs (Table 4).

Technology Enterprise Facility 3

Figure 5 - A close-up of Technology Enterprise Facility 3, located at 6190 Agronomy Rd. The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

Technology Enterprise Facility 3 has a building and roof footprint of 1905 m² and amounts to 2950 m³ of surface runoff annually, mitigating 24% of runoff with the current soft landscapes shown (Table 4; green shapes, Figure 2). With an extensive green roof occupying 1021 m² of roof surface (green cross-hatched shapes, Figure 2), runoff is reduced by just 30 m³ and so retains the same mitigation amount (24%). An intensive roof occupying the same surface results in 56 m³ reduction and 25% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by over 30% when incorporating intensive green roofs, and around 10% with extensive green roofs (Table 4).

Robert H. Lee Alumni Centre

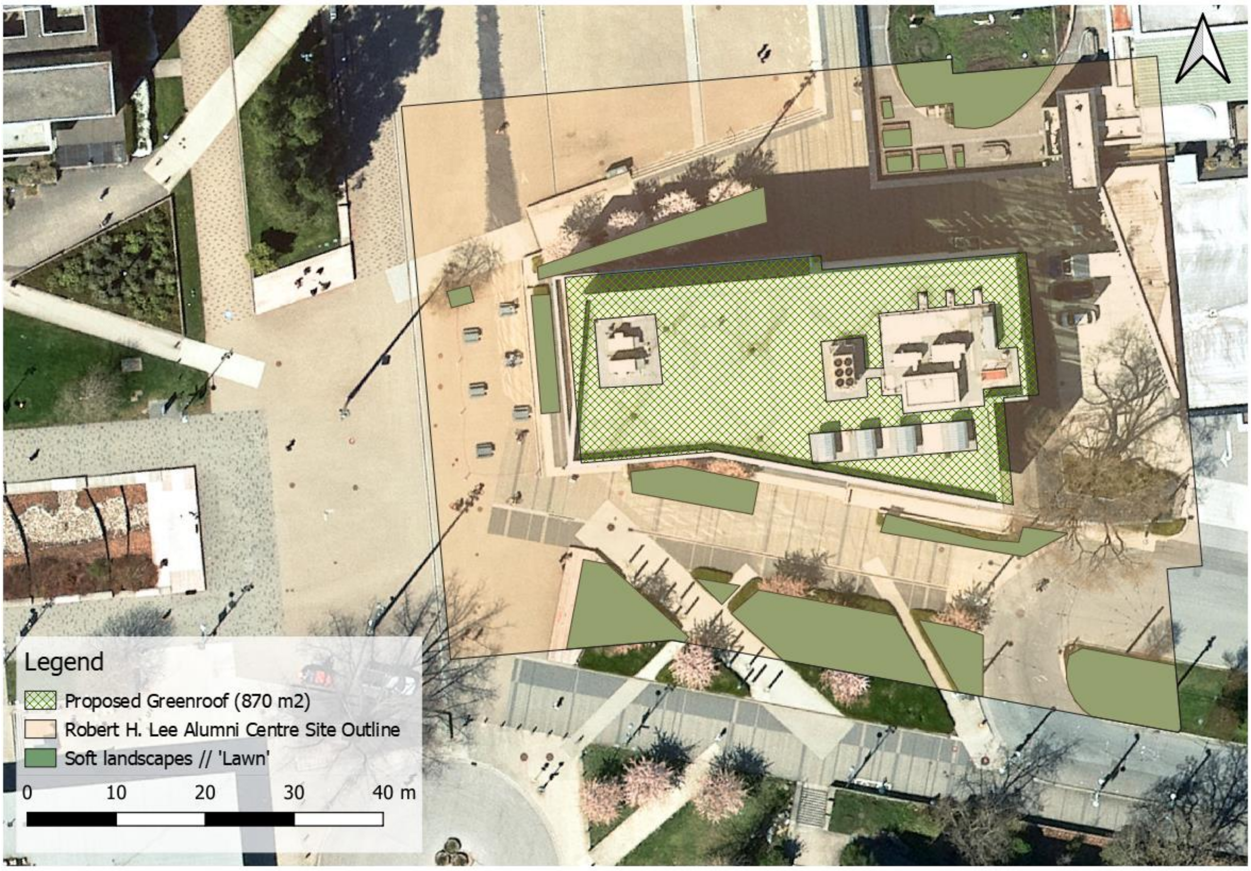

Figure 6 - A close-up of the Robert H. Lee Alumni Centre at 6163 University Blvd. The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

After the 20 m buffer, the total site around the Robert H. Lee Alumni Centre is 5695 m², though the northeast corner also encompasses a portion of The Nest at 6133 University Blvd. The building rooftop footprint is 1181 m² and has 2557 m³ of surface runoff annually, with the current soft landscapes mitigating 18% of stormwater runoff (Table 4; green shapes, Figure 6). With extensive green roof occupying 870 m² of roof surface (green cross-hatched shapes, Figure 6), runoff is reduced by 25 m³ and 19%, whereas an intensive roof occupying the same space results in a 46 m³ reduction and 20% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by 25% when incorporating intensive green roofs, and around 10% with extensive green roofs (Table 4).

Focal & Central (Student Residency)

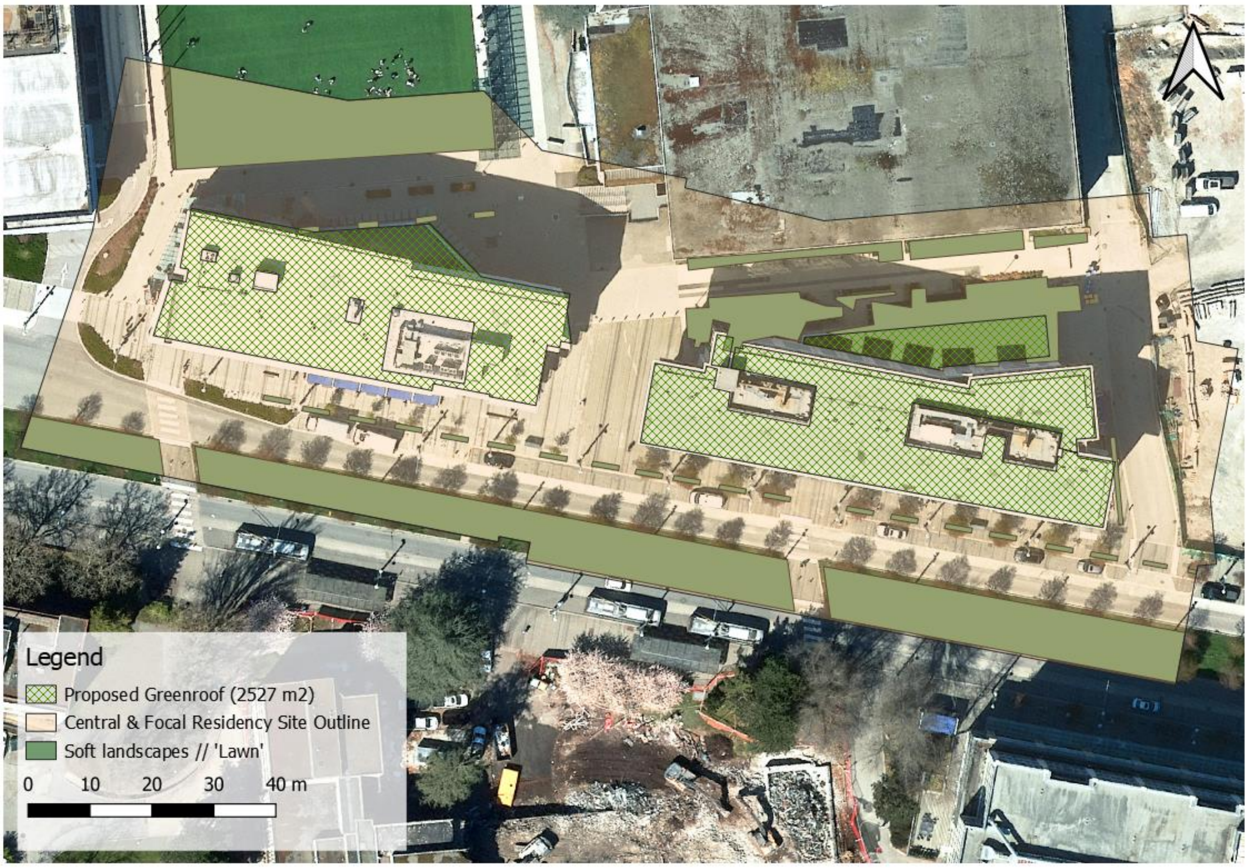

Figure 7 - A close-up of Central and Focal student residencies on University Blvd, just East of the Robert H. Lee Alumni Centre. The map above displays the theoretical plots that could cover the roof surface whilst avoiding machinery, as well as shapes from the Softlandscape analysis by Nicholas Mantegna.

Due to their proximity and shared soft landscapes, Focal and Central student residency buildings were also combined to realize stormwater runoff reductions. In total, the building and roof surface occupies 3033 m^2 and amounts to 5398 m^3 of surface runoff annually, mitigating 21% of runoff with the current soft landscapes shown (Table 4; green shapes, Figure 7). With an extensive green roof occupying 2527 m^2 of roof surface (green cross-hatched shapes, Figure 7), runoff is reduced by 72 m^3 and is capable of 21% mitigation, whereas an intensive roof occupying the roof surface results in a 131 m^3 reduction and 22% mitigation (Table 4). Major rainfall events' (2 year at 60.33 mm; 5 year at 76.30 mm; 10 year at 86.8 mm) runoff volumes can be reduced by 30% when incorporating intensive green roofs, and around 13% with extensive green roofs (Table 4).

Table 4 - Stormwater runoff values for annual runoff, percent mitigated, and volume of runoff mitigation over 24 hours of extreme precipitation events for grey roof (G - no greenroof infrastructure; to be understood as the present state of campus); intensive green roof (I); and extensive green roof (E). All calculations were done using the application developed by Wu et al. (2021).

							Runoff Volume in 24h of major storm event								
Building(s) from Step 1 & theoretical Green roof area	Annual Runoff (m^3)			Runoff Mitigated (%)			2 year (60.33 mm)			5 year (76.30 mm)			10 year (86.8 mm)		
	G	I	E	G	I	E	G (m^3)	I (m^3)	E (m^3)	G (m^3)	I (m^3)	E (m^3)	G (m^3)	I (m^3)	E (m^3)
TRIUMF Complex (12381 m^2)	17423	16766	17065	12	16	14	1743.2	809.2	1353.2	2270.6	1063.7	1880.6	2621.0	1234.8	2231
University Hill & Wesbrook Comm. Centre (8632 m^2)	9171	8721	8925	28	32	30	715.7	379.0	664.7	1019.3	519.7	968.4	1225.3	618.6	1174.3
The Mews (1878 m^2)	3905	3808	3852	3	5	4	387.4	277.3	328.3	501.1	358.8	442.0	576.0	412.5	516.8
Technological Enterprise Facility 3 (1021 m^2)	2950	2894	2920	24	25	24	296.8	193.0	264.7	388.4	254.2	356.2	449.6	308.7	417.4
Robert H. Lee Alumni Centre (870 m^2)	2557	2511	2532	18	20	19	255.8	191.4	228.4	333.1	250.0	305.7	384.5	357.1	289.0
Central & Focal Student Residency (2527 m^2)	5470	5339	5398	20	22	21	551.6	386.3	472.0	723.0	509.5	643.4	837.9	592.6	758.3
TOTAL	41476	40039	40692				3950.5	2236.2	3311.3	5235.5	2955.9	4596.3	6094.3	3524.3	5386.8
Total Mitigation		*1437*	*784*					*1714.3*	*639.2*		*2279.6*	*639.2*		*2570*	*707.5*

3.2 IMPERMEABILITY COMPARISON

Figure 8 *- Final results of the impermeability analysis before green roof consideration (left) and after (right). Incorporating all green roof infrastructure (Steps 1-3) results in a 50% positive change over UBC campus.*

4. FUTURE IDEAS

The objective of this study was to assess UBC buildings on campus for green roof infrastructure potential. We examined structural integrity to the best of our knowledge - using construction material type to realize suitable buildings. We also accounted for slope, building management, and 'accessibility' byway of using roof surfaces that had machinery present, assuming that the machinery requires maintenance and therefore some means of accessing the roof surface. The secondary objective was to quantify stormwater run-off reductions from the green roof infrastructure. This step was done with only the most suitable buildings for green roof infrastructure, and found a reduction of 784 m^3 annually for the most suitable buildings. Lastly, we attempted to craft a list of suitable plants to implement in green roof infrastructure, but realized this objective requires further experimentation. Therefore, some next steps include:

1. Reviewing our list of suitable buildings for green roof infrastructure and examine the true structural integrity of these buildings from the blueprint. Our suitability is only a proxy based on construction type - we did not use any building load weights in our analysis. One can also incorporate data regarding retrofits of buildings across campus and argue for the incorporation of green roof alongside any renewal plans.
2. Investigate the list of suitable buildings and confirm that those rooftops *would* be accessible to a green roof maintenance technician (ground-truthing our results). Furthermore, calculating costs of implantation and maintenance and comparing that to a quantified list of benefits that green roofs provide. A risk assessment of green roofs can also be performed, as there are concerns about maintenance costs, safety, and potential leaking.
3. Continue the process of sketching & calculating stormwater run-off values for the remaining buildings across campus (secondary and tertiary suitable buildings). Further this study by using elevation and drainage points around campus, looking into the total run-off that would be reduced from each drainage point.
4. Conduct a viewshed analysis from residential buildings and categorize the visible roofs separate from non-visible, as this can inform what kind of plants may be implemented for aesthetic purposes.
5. Repeat the experiment but incorporate shading and building height as factors that determine suitability - this can also inform plant selection and prevent planting of full-sun perennials into shady areas.
6. Further experiments and studies into suitable plants for green roof infrastructure including:
    a. Gathering wind data for building roof tops for seed dispersal information
    b. Measuring Kc values for individual plants to optimize evapotranspiration
    c. Examine the biodiversity of campus and follow the ecological chain to determine which plants are needed to optimize biodiversity

d. Investigate current types of landscapes surrounding buildings and create theoretical green roof plots that improve ecological connectivity and create green corridors for those landscapes.

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APPENDIX A - NATIVE PLANT LIST FOR GREEN ROOF

List of green roof plants provided by Holly Horne at Gingko Sustainability Inc, reduced to include native plants suitable for green roof only.

LATIN NAME	COMMON NAME	SUN	LATIN NAME	COMMON NAME	SUN
Achillea millefolium	Yarrow	S/PSH	Gaillardia aristata	Brown-eyed Susan	S
Allium acuminatum	Hooker's Onion	S	Galium boreale	Northern Bedstraw	S/PSH
Allium cernuum	Nodding Onion	S/PSH	Geum macrophyllum	Large-leaved Avens	S/SH
Allium schoenoprasm	Chives	S/PSH	Heuchera cylindrica	Round-leaved Alumroot	PSH/S
Anaphalis margaritaceae	Pearly Everlasting	S/PSH	Olsynium douglasii (Sisyrinchium)	Douglas Blue-eyed Grass	S/PSH
Anemone multifida	Cut-Leaved Anemone	S/PSH	Penstemon confertus	Yellow Penstemon	S
Antennaria microphylla	White Pussytoes	S	Penstemon davidsonii	Davidson's Penstemon	S/PSH
Antennaria rosea	Rosy Pussytoes	S	Penstemon fruticosus	Bush Penstemon	S-PSH
Aquilegia formosa	Red Columbine	S/PSH	Potentilla nivea	Showy Cinquefoil	S
Armeria maritima	Common Thrift	S	Prunella vulgaris	Self Heal	S/SH
Arnica lonchophylla	Longleaf Arnica	SH	Saxifraga tricuspidata	Three-toothed Saxifrage	S
Artemisia frigida	Pasture Sage	S	Sisyrinchium californicum	California Yellow-eyed Grass	S
Aster subspicatus	Douglas Aster	S	Sisyrinchium idahoense	Idaho Blue-eyed Grass	S/PSH

Brodiaea coronaria	Harvest Brodiaea	S	Solidago canadensis	Goldenrod	S/PSH
Brodiaea (Triteleia) hyacinthina	Fool’s Onion	S	Solidago multiradiata	Northern Goldenrod	S
Camassia leichtlinii	Great Camas	S/PSH	Tellima grandiflora	Fringecup	PSH/SH
Camassia quamash	Common Camas	S	Arctostaphylos uva-ursi	Kinnikinnick	S/PSH
Campanula rotundifolia	Harebell	S/PSH	Dryas drummondii	Yellow Mountain Avens	S/PSH
Castilleja hispida	Harsh Indian Paintbrush	S	Dryas octopetala	White Mountain Avens	S
Castilleja miniata	Indian Paintbrush	S	Fragaria chiloensis	Coastal Strawberry	S
Chrysopsis (Heterotheca) villosa	Hairy Golden Aster	S	Fragaria vesca	Woodland Strawberry	PSH
Erigeron compositus	Cut-Leaved Daisy	S	Fragaria virginiana	Wild Strawberry	S/PSH
Erigeron peregrinus	Subalpine Fleabane Daisy	S	Rhodiola rosea	Roseroot	S/PSH
Erigeron philadelphicus	Philadelphia Fleabane Daisy	S	Sedum divergens	Spreading Stonecrop	S
Eriophyllum lanatum	Wooly Sunflower	S	Sedum oreganum	Oregon Stonecrop	S
Eschscholzia californica	California Poppy	S/PSH	Sedum spathulifolium	Broad-leaved Stonecrop	S
			Carex densa	Dense sedge	S/PSH

APPENDIX B – SUITABLE BUILDINGS AND UBC CAMPUS HEAT MAP

Another project undertaken by our colleague examined urban heat spots across UBC campus (Yujie Chen – ‘‘How do shading and cooling of urban forests across the University of British Columbia Vancouver Campus affect building temperatures” 2022). When we overlay our proposed green roof-suitable buildings (yellow shapes) with Chen’s (2022) final heat map (red zones), there is a coincidental perfect fit for our proposed areas: