ACOUSTICAL CHARACTERISTICS OF VEGETATED ROOFS - CONTRIBUTIONS TO THE ECOLOGICAL PERFORMANCE OF BUILDINGS AND THE URBAN SOUNDSCAPE

by

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Abstract

The multiple benefits of vegetated roofs have been proven to reduce the adverse effects of urban densification on infrastructure, natural systems and health. However, the lack of consideration of the acoustical characteristics and benefits of vegetated roofs has limited the ability of design professionals to implement vegetated roofs as an acoustical design solution for noise mitigation and soundscape enhancement. This research, the first of its kind, addressed this problem by measuring the sound absorption and transmission characteristics of vegetated roofs, and by a case-study comparative analysis of vegetated and non-vegetated roof-top play areas. A sound absorption evaluation of substrates, using an impedance tube method, determined that substrates absorb significant sound, and that porosity, percentage of organic matter, moisture content and compaction are acoustically relevant. A multi-variable regression model, developed to optimize the specification of substrates for sound absorption, indicated that a 12.5% increase in the percentage of organic matter increased sound absorption by 9%. The spherical decoupling method was applied to measure the noise reduction coefficient (NRC) of 25 in-situ roof level test-plots with three plant communities established in viable substrate depths. The NRC of the test-plots ranged from 0.2 to 0.6. Measurements of transmission loss (TL) from an indoor-to-outdoor sound transmission lab commissioned for this research, and field evaluations of vegetated roofs of varied substrate depth, water content and plant species, confirmed that the TL values of vegetated roofs are greater than those of non-vegetated reference roofs by 10 and 20 dB in the low and mid frequencies ranges, respectively. The case-study ambient soundscape analysis of vegetated and non-vegetated rooftop play areas demonstrated that vegetated roofs alter the roof level soundscape by the effect of their sound-absorptive characteristics. Most pronounced was the introduction of sounds of birds supported by the vegetated roof habitats and the sounds generated by people interacting with vegetation on the rooftop. The findings are summarized in design guidelines and application notes for synthesis into the landscape/architectural design process.

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List of Abbreviations

ANSI	American National Standards Institute
ASTM	American Standard Test Method
Avg	Average
AWC	Available water storage capacity
BCIT	British Columbia Institute of Technology
BCLNA	British Columbia Landscape and Nursery Association
B&K	Brüel & Kjær
COMP	Compaction
CHILD	Consortium for Health, Intervention, Learning and Development
dB	Decibel
dB(A)	Decibel (A-weighted)
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau
GRHC	Green Roofs for Healthy Cites
GRRF	Green Roof Research Facility
GR1	Green roof 1
GR2	Green roof 2
GWC	Gravimetric water content
HVAC	Heating, ventilation, and air conditioning
Hz	Hertz
IDP	Integrated design process
Im	Imaginary part
ISO	International Standards Organization
Min	Minimum
Max	Maximum
Mic	Microphone
ML	Mass law
NRC	Noise reduction coefficient

P	Porosity
P1	Sedum plant community
P2	Coastal meadow plant community
P3	Play grass plant community
PSD	Particle size distribution
%OM	Percent organic matter
R	Reflection coefficient
Re	Real part
REF	Reference roof
REM	Roofing evaluation module
RT	Reverberation time
S	Substrate
SBS	Styrene butadiene styrene
SD	Standard deviation
STC	Sound transmission classification
TL	Transmission loss
VWC	Volumetric water content
WHO	World Health Organization
7 C	Seven criteria

List of Symbols

α	Sound absorption coefficient
α_d	Diffuse sound absorption coefficient
α_{av}	Average Sound absorption coefficient
β_0	Beta estimate coefficient
c_0	Speed of sound
°C	Degree Celsius
d	Distance
E_a	Absorbed sound energy
E_i	Incident sound energy
E_r	Reflected sound energy
E_t	Transmitted sound energy
f	Frequency
e	Natural log
h_b	Height of base microphone
H	Transfer function
j	$\sqrt{-1}$
k	Wave number
l	Length form test surface to centre of base microphone
ln	Natural log
L_{p1}	is the average sound pressure level in the source room
L_{In}	is the average normal sound intensity level over the measurement surface
m_s	Mass surface density
η	Damping coefficient
$Ø$	Theta
p_0	Density of air
P_0	Pressure spectrum from source
$P_1(f)$	Pressure spectrum from microphone 1

$P_2(f)$	Pressure spectrum from microphone 2
r_p	Pearson correlation coefficient
$_p$	Spearman correlation coefficient
R^2	Multi-R-squared value
R	Reflection coefficient
S	is the area of the separating partition under test
SM	is the total area of the measurement surface
S_0	Reference area equal to 1 m^2
s	Spacing between two microphones (mm)
V	Volume
Z	Impedance

Glossary

Anisotropic – describes the physical property of a material which is directionally dependent.

Available water storage capacity (AWC) - the difference between the wilting point (plant extraction limit) and field capacity (upper water storage limit of a soil or substrate).

Characteristic particle dimension - the diameter of a sphere which has a volume equivalent to the mean volume of soil particles.

Characteristic impedance - is the ratio of the complex pressure amplitude to the particle velocity of the propagating wave in a medium.

Decibel (dB) - is a logarithmic unit of the ratio of sound energy to a reference level (threshold of hearing). Note: a 1 dB change is usually not recognized by the human ear, an increase of 10 dB is typically perceived as “doubling the loudness” of a signal.

Flow resistivity – is the ratio of pressure gradient to cross-section averaged velocity or velocity of volume displacement.

Gravimetric water content (GWC) – the percentage of water content by mass

Impedance – a frequency dependant parameter which describes the behaviour of sound waves in a medium; expressed as a ratio of the sound pressure to velocity of sound traveling through a material.

Integrated Design Process (IDP) – a process to design, construct and achieve occupancy of a building project through the optimization of all building systems in a manner that is environmentally sustainable.

Materiality - in architecture it is the concept of, or applied use of, various materials or substances in the medium of building.

Particle size distribution - characterizes the whole substrate mix in terms of percent distribution of particle dimensions. The particle size distribution addresses the soil texture component of sand, silt and clay contributions in the complete substrate mix.

Poroelastic material – porous materials of which the solid matrix is an elastic frame; an example is soil.

Soil texture - refers to the relative proportions of sand, silt, and clay in a soil. The course fragment constituents (>2mm) of vegetated roof substrates or natural soil, are not considered to be part of the fine earth fraction.

Transmission loss - measured in decibels, quantifies the reduction of sound energy transmission through single or multi-layered partitions on a logarithmic scale.

Total porosity - the total volume of pore space which can be filled with either water or air.

Tortuosity - a measure of the irregularity of the fluid-filled paths through the solid matrix of soil.

Acknowledgements

Through the course of my journey as I began to enfold myself in the soundscapes of rooftops, I met many people who shared their passion for beautifully vegetated tranquil spaces on the roof planes high above our cities. My gratitude to Cornelia Hahn Oberlander for introducing me to landscape architecture and encouraging my curiosity in the aural precepts of green roofs. And thank you to Kerry Ross and Christine Thuring for guiding me on tours of inspirational rooftops, some of which are reflected in the photo illustrations of as a preface to this thesis.

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Dedication

Veronica Elizabeth (Horne) Connelly
&
Dr. Dennis Eugene Connelly

-to building a city of peace

Foreword

I have taken the liberty of including illustrations of rooftops I have enjoyed over the course of the years, images of vegetated roofs, plants, and people on vegetated roofs – the illustration are a preface to the dissertation, hopefully setting the beauty of the context of vegetated roofs as places, as habitats. These same illustrations represent the inspiration and support I have received for my work.

Illustration 1 Private Residence, Canmore Alberta

Illustration 2 Private Residence, Canmore Alberta

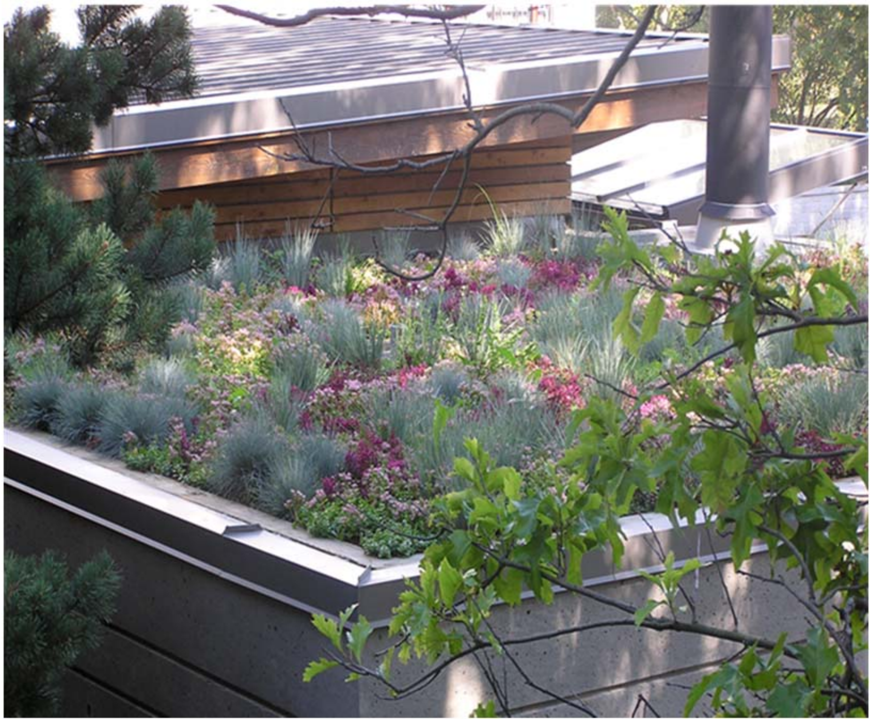

Illustration 3 Marguerite House, multi-family development, Vancouver BC

Illustration 4 Inform Interiors, furniture store, Vancouver BC

Illustration 5 Vancouver Public Library, Vancouver BC

Landscape Architect Cornelia Oberlander

Illustration 6 Multi-family residential, Lattenstrasse, Switzerland

Architect Peter Vetch

Illustration 7 Lizard habitat, Zurich train station, Switzerland

Illustration 8 BCIT Centre for Architectural Ecology, Vancouver BC

CHAPTER 1 Introduction, Methods and Context

1.1 Introduction

This research investigates the contributions of vegetated roofs to architectural spaces and the urban soundscape as determined by the qualitative and quantitative acoustical properties of their material components. The research framework and methods have been developed from the interdisciplinary perspectives of architecture, ecology and physical acoustics. The science of acoustics determines the materiality of the built environment as a critical determinant of how sound is propagated and perceived (Hunt 1978, Ver 2006). The communication approach to soundscape analysis is concerned with the relationships of all species and elements which create acoustical spaces (Shaefer 1977, Truax 1978, 2001).

Vegetated roofs are advancing a fundamental goal of reducing the adverse effects of construction and development on natural systems and global health (Brenneisen 2004, Köhler 2004, Kellert 2005). The benefits and ecological impact of vegetated roofs are recognized within the broad categories of energy and efficiency (Eumorfopoulou 1998, Wong 2003, Takahashi 2004, Connelly 2006), habitat and biodiversity (Gedge 2005), water and waste management (VanWoert 2005, Connelly 2006), materials and resources (Cantor 2008), air pollution (Yang 2008) and carbon sequestration (Getter 2009). Empirical measurements of the sound transmission loss of roofs showed that the addition of the material layers, substrate and plants increased transmission loss (Connelly 2008). Most recently the impact of vegetated roofs on noise propagation at an urban scale has been investigated (Van Renterghem 2008, Yang 2010). The economic value of vegetated roofs has been quantified through life-cycle cost analysis (Porsche 2003, Wong 2003, Banting 2005, Clarke 2008).

The research outcomes reported here will build on and contribute to the growing body of knowledge related to the beneficial impacts of vegetated roofs to the environment, society and the economy. First, this research will quantitatively define vegetated roofs as an acoustical solution for the control of noise and the introduction of natural sounds, ultimately contributing to the quality of the urban soundscape. Secondly, the research will inform the architectural design process about the acoustical characteristics of vegetated roofs and their capacity to increase the sustainable and liveable use of rooftops. Critical environments include urban development below aircraft flight paths, and sites exposed to high levels of community noise including low-frequency industrial noise and elevated road and rail noise.

The World Health Organization regards community noise as a public health problem that is increasing in significance with urban densification (1999). The social health cost of long-term noise exposure includes sleep disturbance, cardiovascular disease, stress and cognitive impairment (World Health Organization 2011). The corollary is also true: reduction of exposure to noise and an increased exposure to natural sounds contribute to reduced stress, increased relaxation, emotional balance, and improved cognitive functioning within the urban environment (Ulrich 1991, Kryter 1994, Cooper-Marcus 1999, Öhrström 2006).

A multi-tiered approach is required to address the ecological contributions of vegetated roofs and their acoustically relevant characteristics at the building and site scale. Sound transmission characteristics of vegetated roofs are most relevant to understanding the contribution of vegetated roofs to the acoustical environments in interior spaces of buildings exposed to high external noise. Investigating the absorption and reflection of sound incident on vegetated roofs is most relevant to understanding the acoustical contribution of the vegetated roofs to those inhabiting the rooftops. Landscape/architectural designers benefit from a deeper understanding of how the natural sounds of birds and insects, whose populations are supported by vegetated roof habitat, enhance the urban soundscape.

As engineered systems, multi-layered vegetated roofs have a high level of design flexibility (Osmundson 1999, Earth Pledge 2005). Vegetated roof systems may be comprised of various material layers: root barrier, water reservoir/drainage layer, filter fabric, substrate and plants (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) 2002, Weiler 2009). The experimental set-ups were devised to measure the relevant acoustical characteristics of vegetated roofs and their components given the variation in the type and depth of substrate, species diversity, biomass and microclimatic conditions. The laboratory and in-situ rooftop experiments were designed to investigate the range of acoustical performance that vegetated roofs were expected to exhibit. The detailed case study of inhabited rooftops allows some generalization of the potential impact of vegetated roofs on the roof-level acoustical environment and provides new knowledge which could ultimately be applied to landscape and architectural design.

Vegetated roof substrates have developed based on the principles of soil science and the discipline of horticulture. The principle functions of the substrate are to provide water, nutrients and anchorage for plants (Dunnett 2004, Snodgrass 2006). Ultimately, the acoustical characteristics of a system are governed by the multiple layers of fluids, solids and poroelastic materials (Biot 1956, Allard 1993). Methods exist to empirically evaluate or model the sound absorption of soils and grounds (Delany 1970, Dickinson 1979, Attenborough 1975, 1981 Allard 2002, De Geetere 2004). However, these have not been empirically validated for the substrates mixed to support plant viability on rooftops. Trees, shrubs, grasses, litter and roots are known to affect the ground propagation by generally increasing sound attenuation (Aylor 1972, van der Heijden 1983, Albert 2004). High absorption and low reflection are the most desirable characteristics of the vegetated roof with regards to outdoor sound propagation. Through surface absorption, vegetated roofs have the potential to reduce noise build-up at the roof level and noise pollution in urban areas. The acoustical characteristics of vegetated roofs affect not only the absorption and reflection of sounds from the roof but also the transmission of sound into and out of the building. Considerable research has been concerned with the transmission of air-borne noise from the urban environment through the building envelope and into the habitable areas of buildings (Sharp 1973, 1996, Cook 1980, Bradley 1998, 2000, 2002, Jean 2004). The vegetated roof materials placed over typically light-weight acoustically reflective roof membranes will significantly modify the sound path, as energy is dissipated by the vegetation and substrate.

Hypotheses

The material attributes of vegetated roofs will determine the degree of sound transmission and absorption over the full range of acoustical frequencies considered in planning and landscape/architecture. The substrate and the vegetation are the two components expected to have the most significant effect on the sound transmission, absorption and reflection. It is expected that the percentage of total porosity and available water content will be the greatest determinants of the absorption coefficient of the vegetated roof substrate samples evaluated. With consideration of the extensive vegetated roofs' limited substrate depths and plant diversity, it is expected that plant foliage and root structure will affect the measured absorption of vegetated roofs.

It is expected that the research will confirm that vegetating rooftops will increase transmission loss, with the most significant impact in the lower frequency range. It is expected that a frequency dependent transmission loss will be a function of the additional mass in both the lower and higher frequency ranges, and the increase in transmission loss will increase with frequency. It is also expected that the absorptive characteristics of vegetated roofs will vary as a function of depth of substrate, plant community, and in-situ conditions and climate.

The case study will document the contributions of vegetated roofs and plants to the urban soundscape as experienced on the rooftop. It is expected that the habitat supported by the vegetated roofs will introduce natural sounds of wind, water and bird song to the soundscape. Additionally, the interaction of people with the vegetated roofs will generate different types of sounds from those generated through activities on non-vegetated roof decks.

Chapter outlines

The remainder of Chapter 1 first outlines the methodological framework used to approach the research question and provides further context for this dissertation. Second, an ecological context for acoustics and the soundscape is presented. This is followed by a discussion of the vegetating of rooftops, as places of habitat and as building systems designed toward a goal of ecological balance within the urban context. The physical properties of the material layers, substrates and plants used to construct a vegetated roof are detailed in Appendix A.

Chapter 2 first presents a literature review on the sound absorption of natural soils and grounds which are relevant to substrates, and then describes the supporting theory and the experimental set-up used to determine the normal incidence absorption coefficients of substrates. This work addresses the current lack of testing protocol in ISO and ASTM evaluation standards. The findings presented provide insight into an understanding of the magnitudes and frequencies of the sound energy that vegetated roofs can potentially absorb; the regression model that was developed from the data provides guidance on the specification of the substrate mix to optimize the sound absorption potential of substrates for noise reduction.

An investigation of the effects of substrate depth and plant communities on the sound absorption of vegetative roofs is discussed in Chapter 3. The development of a measurement method used to measure the sound absorption of vegetated roofs is presented. In addition, the findings of in-situ measurements of vegetated rooftop test plots are presented and analyzed.

The vegetated roof defines a sound separation between the exterior environment and a controlled indoor environment. Chapter 4 first presents a literature review, and an overview of sound transmission theory, which can be applied to vegetated roof systems. Sound transmission loss data from field tests is then presented. The subsequent development of a purpose-built field-laboratory for the measurement of sound transmission is outlined and the transmission loss data of roofs measured at the field-laboratory is analyzed and presented. Finally, the findings are presented in order to draw conclusions about the potential of vegetated roofs to reduce the transmission of intrusive noise. .

Chapter 5 presents a case study. The primary purpose of the case study was to document the differences in the soundscapes of a vegetated roof and a non-vegetated roof, and to acquire an understanding of the relationship between the differences of the soundscapes and the acoustical characteristics of the materials used to construct rooftops designed for programmed use. First, the contextual background sound levels are examined at cross-scale; second, the spatial and material qualities of the spaces are investigated. Third, the method of sound notation and soundscape analysis are presented and, fourth, the findings are used to extend the scope of an existing design evaluation to include consideration of acoustics and the soundscape.

Chapter 6 concludes the thesis, summarizing the new findings from this novel research on the acoustical characteristic of vegetative roofs. The final chapter syntheses the four projects, discussed in Chapter 1 to 4, and proposes a framework to embed the new qualitative and quantitative knowledge of vegetative roofs and the new understandings developed from the case study into the architectural design process. The discussion summarizes how vegetative roofs can provide a shield to noise and can simultaneously embrace and contribute to the contextual soundscape.

Ultimately this will allow designers and users to realize an increase in the aural quality of place, both inside buildings and up on the rooftops.

1.2 Methodological Framework

Research goals and objectives

The materiality of vegetated roofs is unique to every variation of system design and architectural context. Similarly, the qualitative acoustical expressions of vegetated roofs, and their potential contributions to architectural spaces and rooftop soundscapes, are unique to every building, depending on the building envelope and form, the functional and spatial programs, and the site and cultural contexts.

Project based structure

In order to effectively manage the research on the acoustically relevant characteristics of vegetated roofs, the research was organized into three projects and a case study. Project 1 was carried out in acoustics and soils labs, and investigated the sound absorption of a range of substrates used in this region on vegetative roofs and their constituents. The findings not only provide insight into the magnitudes and frequencies of sound energy which a vegetated roof can potentially absorb, but also determine the experimental limits of using a single substrate for the subsequent two projects. The second project, investigating the parameter of substrate depth, and plant community was executed on roof-level test plots over a long-term. The extended schedule was required in order to measure the sound absorption of vegetated roofs as the substrate naturally compacted over time, the plant root system established and the aerial biomass increased. Project 3 was the most arduous of the research investigations and required the construction of a purpose-built indoor-to-outdoor transmission loss field facility in which to execute the acoustical measurements. The critical path for the design, construction and commissioning of the infrastructure and test panel extended over a period of three years before the first measurements were executed.

Case study methodology was used to investigate the acoustical and soundscape phenomena of vegetated roofs within the real-life context of rooftop design and use. Employing an ambient soundscape approach, the case study investigated and contrasted two rooftop areas of comparable use. One area was located on a vegetated roof; the other was located on a non-vegetated roof. Following are further details of the three projects and the case study; these are also outlined in **Table 1**.

Project 1 Sound absorption of vegetated roof substrates

Variations in soil properties will affect the propagation of sound waves through soil, and these effects can be significant across the full range of soil types and conditions (O'Brien 1996, Oelze 2002). Impedance tube methods have been used to deduce the characteristic impedance of soils; impedance characterizes the behaviour of the wave which penetrates into and reflects from a fluid, solid or porous material (Voronina 2003). The method quantifies the reflection of sound waves impinging on the substrate test-sample in the tube. The impedance tube method was applied to investigate substrate blends viable for extensive vegetated roofs and deduce the normal-incidence absorption coefficient of the substrates in different states.

In this parametric study, the samples of substrates and substrate constituents were quantified in terms of the physical properties of particle density, bulk density, total porosity, percentage organic matter, particle size distribution and the characteristics of volumetric water content and compaction which are functions of the micro-climate and roof-level site conditions. The range of moisture content between wilting point and field capacity represents the viable range of moisture for plant survival on a rooftop; thus when practical, the samples were evaluated at three levels of substrate moisture content: oven dried, wilting capacity and field capacity. Likewise, the samples were evaluated in a non-compacted state and in a compacted state representing in-situ rooftop conditions. A frequency dependent multi-variable regression model was derived to predict the normal-incidence absorption coefficient of substrates based on inputs of the physical properties and characteristics.

Table 1 Project framework

	Project 1	Project 2	Project 3	Case Study
Research Focus	Sound absorption of substrates in vegetated roofs	Sound absorption of vegetated roofs	Sound transmission loss of vegetated roofs	Vegetated rooftop contribution to ambient soundscapes
Experimental investigation and parameters (Instances /or intervals of measurement)	Substrate mix Percentage of constituents Moisture content Compaction (87 evaluations)	Substrate depth (25 mm gradients) Plant community (3 communities) Plant coverage (2 seasons) Moisture content (2 conditions)	Substrate depth (50 mm gradients) Plant community (2 communities) Plant coverage (2 seasons) Moisture content (2 conditions)	Background noise Spatial and material qualities Activities Sound types Subjective impression
Research infrastructure required	Acoustic lab Soil lab Sand/Pumice Compost Six substrates	25 - 2.65 m^3 rooftop test plots 7 - non vegetated 18 - planted 3 - plant communities.	Purpose-built indoor-to-outdoor transmission loss facility (89 m^3) Interchangeable roof specimens 2 - 15.9 m^2	Case study Two urban rooftops (one vegetated and one non-vegetated) with comparable architectural program
Primary evaluation method	Impedance tube 2 microphone method Soil property testing	Spherical decoupling method Vegetation coverage evaluation	Transmission loss using intensity measurement	Background noise and noise propagation modeling Design analysis Ambient sound analysis

Project 2 Effects of substrate depth and vegetation on sound absorption

Whereas Project 1 focused on the characteristics and in-situ properties of substrates, the experimental set-up of Project 2 was designed to investigate the impact of the substrate depth, plant species and biomass, and of micro-climatic conditions, on the sound absorption of the substrate and the vegetated roof system. Vegetation directly affects soil porosity in grounds through root mass establishment, offering protection from compaction due to rain, and supplying nutrients through organic decomposition (van der Heijden 1983). The impedance tube method used in Project 1 is ineffective for evaluating soils with live plant material (Dickenson 1979). Alternatively, a spherical decoupling method, based on the similar two-microphone technique utilized in the impedance tube, can be used to measure the acoustical characteristics of grounds. The spherical decoupling method was standardized in an anechoic chamber to measure vegetated roofs. The method was then used to measure the sound absorption of 25 rooftop test plots. Each of the test plots was constructed with material layers representative of typical vegetated roof systems in the Pacific Northwest of North America. The substrate depths in the test plots ranged in 25 mm increments from 50 mm to 200 mm; the plots were planted with three structurally distinct plant species: sedums, a coastal meadows community and grasses. Over a period of two years, as the micro-climatic conditions of the roof-level site changed with the seasons, measurements were made with variations in moisture content, substrate compaction and plant establishment.

Project 3 Transmission loss of vegetated roofs

The objective of Project 3 was to determine by measurement the phenomenological parameters which impact the sound transmission loss of vegetated roofs. A ‘reverse’ testing method developed in the 1970’s was the genesis of the experimental set-up; the test measures the transmitted acoustic intensity radiated by the roof system, while the incident intensity is deduced from the average sound pressure level inside the source room below the roof (Mulholland 1971, Sharp 1996). A series of field tests was first conducted at an existing research centre. The research centre was designed and constructed in 2003 for the purpose of quantifying the contribution of vegetative roofs to cross-scale stormwater management and energy efficiencies; fortunately, the design and layout of the centre effectively allowed the application of the test method to two vegetated roofs and one non-vegetated reference roof. The field test provided transmission loss data, and thus, a preliminary determination of the capacity of vegetated roofs to reduce sound transmission. The field testing provided the inducement to design and construct a purpose-built test facility as the experimental set-up to measure sound transmission loss. The experimental set-up facilitated the installation of roof samples dimensionally constructed as typical structural bays in a mid-span, light-weight roof system which are commonly specified in the industrial, commercial and institutional development sector.

Case study of a vegetated roof and a non-vegetative roof

The analytic case study approach involves a detailed description of the case(s) and the setting of the case(s) within contextual conditions (Creswell 2004). Two rooftop play areas were used to investigate the potential impacts of vegetated roofs on roof-level soundscapes. The layouts and designs of the play areas were different, owing to the building forms and contexts; however, the functional and spatial programs of both play areas are associated with pre-school child-care centres and have been designed to meet the requirements of a single licensing authority.

These roof-level play areas were identified from previously completed research, the CHILD Project – Consortium for Health, Intervention, Learning, and Development (Herrington 2006, 2008). The CHILD reports, documentation, and collected data were made available for this case study. There had been no previous analysis of the acoustical characteristics of the spaces or of the sound recordings which accompanied the original video recordings. Participants in the study survey rated the sound clarity within the play area as part of an overall spatial evaluation. The resulting guidelines, which were generated from the original research, did not include recommendations for acoustical design.

The architectural drawings, photographic images and data collected allowed for identification of the material and acoustical properties of the roof surface and the rooftop appurtenance (mechanical systems, furnishings, hand rails or parapets). The video recordings captured the soundscape of the roof top spaces and the sonic environment beyond the roof edge. The audio component of the video recording facilitated the soundscape analysis.

The sound notation analysis and sound pressure levels predicted from road and traffic noise, and constructed roof level Isobel maps of each roof, were analyzed with respect to the following physical attributes of the rooftop play areas: materiality of the space, amount of vegetation, elevation above grade, and degree of built enclosure. The findings from the roof-level play area with vegetation, and that without vegetation, were first compared to each other and then, to complete the case study, compared to the overall spatial ratings documented in the 7Cs.

1.3 The Ecological Context of Acoustics and Soundscapes

The soundscape as an ecosystem

In the current global context of carbon emissions and global warming, peak oil consumption and depleting resources, escalating waste and the non-equitable distribution of global wealth, one must wonder if the subject of acoustics and the soundscape warrants further discussion. I propose that in an effort to sustain and improve our global condition we need to engage with the aural modality of our perceptions and use all information possible to access key issues affecting ecological balance. Acoustics, in an ecological model, investigates the interrelatedness of sound, human activity and all species within our environments (Schafer 1977).

To study complex systems, the spatial and temporal contexts of energy and information need to be investigated (Kay 1994). Sound itself is energy, with semantic content, spatially propagated over time. However, acoustical performance criteria and value engineering have ubiquitously dissolved the soundscape into the component parts of noise source, path of propagation and receiver. Investigating acoustics in an ecological framework, as demonstrated in the case study, highlights the need for us to reactivate our aural perception and attend to the design of soundscapes. Recognizing vegetated roofs and their contextual soundscapes as an ecosystem allows us to embed the consideration of acoustics and soundscapes into the planning and design process.

The soundscape is an ecosystem, a complex system of concentrated patterns of relationships in which the dynamically balanced network of interactions includes multitudes of sound sources and receivers. The sources and receivers of sounds may switch roles between themselves and have both functions at the same time.

Assigning value to the soundscape

Noise pollution is a leading indicator of ecological imbalance within the complex system of the soundscape. Mitigating the impact of noise is critical to sustaining our health and wellness. Sound isolation and noise control are value-engineered within the matrix of economics. In the context of development and construction, an increase in noise control leads to an increase in cost. In the context of health and wellness, reduced noise leads to reduced costs (European Commission 1996).

With the adoption of an economic matrix which deals with the externalities of noise pollution levels it is possible to assign cost to excessive sound (Smith 1998). Sound attenuation, based on 5 dB increase in transmission loss attributed to a vegetated roof, is calculated to have a one-time increase in property value to the owner of 3.5%. (Tomalty 2009). However, these economic matrices cannot yet value the quantified ecological contribution of vegetation on rooftops.

Aesthetics, as a key element in the improvement of our quality of life, can be used as a framework to forward the discussion of the soundscape into the sustainability debate (Hedfors 2003). "Improvement in quality of life," as a very general statement, embraces the social and ethical dimensions of human welfare, and provides the value-based support for most of the proceedings and conclusions from the World Urban Health Organization, the United Nations and the European Commission.

One of the greatest capacities of the science of acoustics is its potential to advance ecological practices in the design of the soundscape. Planners, landscape/architects and engineers have the managing responsibility to engage the full breadth of sensory perception and experiences in order to address ecological balance and work towards reducing the rate at which we are degrading urban soundscapes.

1.4 Vegetating Rooftops and Places for People

Many of the important aspects of vegetated roof technology can be summarized in three discussions. The first discussion is of the technology's design flexibility; the technology can be implemented in such a manner as to provide an optimal solution for a specific need and/or specific climatic or cultural context. The second discussion is of the multi-faceted benefits of the technology and its contribution to low-impact environmental design, which can be realized at all environmental scales: the building site, the urban scale and global scale. The third discussion is of the capacity of vegetated roof technology to stimulate and engage human affinity for nature, arguably a pre-requisite for advancing ecologically based design for the increasing populations in urban communities.

Historical overview of roof habitation and vegetation

Throughout history, the use of the rooftop responded to fundamentally basic needs, in which the social and cultural contexts were embedded. The flexibility in the design of vegetating roofs allows for an optimal response to varying programs, climates and cultural contexts. This discourse is focused on the typologies and precepts which illustrate the historical movement towards the current programs of use for roofs and towards vegetating roofs for cross-scale ecological benefits. The archaeological history of the northern regions of Scandinavia and North America demonstrates that the First Peoples, Vikings and pioneering cultures made use of natural materials and vegetated roofs to provide temporary and permanent shelter (Mackin 2004, Ross 2009). The history of the southern global regions of Central and South America, the Mediterranean, Middle East and India, illustrates a treaty of rooftops designed for dwelling (Martinez 2005). In the origins of inhabiting roof tops, the vernacular roof design was responsive to climate, geographical zone, altitude and orientation, and to its location within a community.

The vernacular use of roofs originated at the scale of the household unit. Its uses were to dry food, condition textiles, cook safely with open fires, and to provide security to sleep. At the community scale, the boundary between private and public use of the roof above a dwelling became blurred. This is exemplified by Algiers, a city which could be crossed via the rooftops without going down to street level, where the routes were allocated to armies, workers and animals (Martinez 2005).

Archaeologists illustrate majestic programs for rooftop use in Antiquity, as uncovered at the Villas of Pompeii, with programs of ceremonies, recreation and relaxation, all facilitated by large scaled podiums. Complex building programs were developed for the grandly scaled podiums of the large urban villas in the Baroque period (Osmundson 1999). By the beginning of the 18th century, European cities advocated the use of flat roofs for hygienic purposes. The hygienist precept included both the concept of isolation of the ill, and perhaps more pivotal, the recognition of the rooftop's contextual characteristics of daylight, clean air, and views of naturally vegetated environments to aid in the healing process.

With the inclusion of the elevator in the apartment typology in the mid-19th century, the vertical hierarchy of building forms was reorganized and the advantages to inhabiting the roof level - namely sunlight, clean air, extended views - were rediscovered by the upper class, and the rooftop was no longer a residual place of solitude above the servant quarters. Programming and the designs of rooftops were redefined through technological advancements and the ideological expansions of the hygienist precepts to quell the stresses of urban densification. The hygienist precept extended to the programming of dedicated classroom spaces and children's recreational spaces on rooftops; a current program thereof provides the case study within this dissertation work.

Once new waterproofing roofing materials were advanced, along with the structurally reinforced concrete roof decks of the 20th century, the inclusion of a vegetated layer was reconciled as a viable engineering solution (Schunck 2003). The development of the garden city concept expanded the use of rooftop gardens. Le Corbusier's theory of garden roofs (Le Corbusier/ Pierre Jeanneret 1926) advocated the use of vegetated roofs in modern architecture and urban planning.

However, wide scale adoption of theory and practice was not prioritized with the development of building envelopes and mechanical systems in the latter half of the 21st century. The roof top became, for the most part, a residual space to accommodate mechanical equipment and vent indoor air exhaust. The expansion of programming of spaces at the roof level is escalating, after more than half a century delay, in our effort to sustain and improve our global condition, and to address ecological imbalance.

Ecological benefits

Today, our most pressing need is to arrest the decline of urban ecosystems. Vegetated roofs can be optimally designed as a response to pressing ecological needs at the site level and in the cross-scale context. The ecology benefits were summarized in the introduction of this chapter. A vegetated roof system can be designed with specific material layers, substrate depth and suitable planting to address a primary site level or multi-scale environmental priority. When vegetated roofs are designed to respond to multiple environmental needs, the benefits of the vegetated roofs to the urban infrastructure collectively increase and provide overall positive impact at the global scale. Following is a brief discussion to exemplify how some of the multi-faceted benefits of vegetated roofs can be quantified at cross-scale.

Several properties of vegetated roofs contribute to their thermal characteristics: direct shading of the roof, evaporative cooling from the plants and substrate, and the additional thermal mass effects of the substrate. Research has determined that vegetated roofs can lower a building's energy demand for cooling/heating through improved thermal performance in diverse climate conditions (Eumorfopoulou 1998, Liu 2004, Wong 2003). The insulating effects increase thermal comfort and reduce heating and air-conditioning use. Vegetated roofs reduce the diurnal temperature variation of the roof membrane up to 94%, eliminating thermal stress in the membrane and extending the membrane service life (Connelly 2006). The energy cost savings and increased material durability represent direct economic benefit to the building owner (Banting 2005). Covering the roof with a vegetated system eliminates the exposed membrane's absorption of solar radiation during the day and the reradiating of heat at night. Strategic coverage of rooftops with vegetation in urban areas can reduce urban heat island effects, and improve air quality (Yang 2008). At aggregate scales this addresses community and global targets for reduction of green–house gas emissions (Takahashi 2004, Getter 2009).

Vegetated roofs are viable tools for integrated stormwater management (VanWoert 2005, Bennett 2008). At the site level, vegetated roofs are considered roof level source controls; the benefit is programmatically and financially realized in the reduction of required grade-level retention strategies (Carothers 2005). Strategic coverage of rooftops with vegetation in urban areas further reduces the impact of buildings by contributing to the region’s stormwater and a watershed management plan, and enhances the environment through improved water quality management (Mentens 2006).

Programs for conserving and restoring biodiversity and providing territory for endangered habitat are realized on vegetated roofs (Mann 1999). Plant species, invertebrates and birds have all found refuge on rooftops as urban development has displaced their original grade-level habitat (Brenneisen 2006). The vegetated roof can be designed for habitat and biodiversity benefits at a specific site; again the aggregate benefit is greater at the community scale, as the vegetated roofs function as stepping stones creating links between larger habitat patches, parks and green belts through the city to the rural edge, facilitating the movement of energies, nutrients, and biotic elements across landscapes (Gedge 2002, Calkins 2005).

Biophilic capacities

The therapeutic benefits and the value of the aesthetic of vegetative roofs are summarized here, for the sake of brevity, with the biophilic capacities of vegetated rooftops. The biophilia hypothesis proposes that there is an instinctive bond between human beings and all natural living systems (Wilson 1993). Ultimately, the most intriguing aspect of vegetated roof technologies is their ability to stimulate and engage our inherent affinity for the natural world and nurture our nature-based values. Experiencing natural processes, diversity and contact with natural systems greatly affects our physical and mental wellbeing (Day 2010, Kryter 1994). Natural environments have restorative effects (Evans 2004, Gidlöf-Gunnarsson 2007).

People's physical and mental health depends on regular contact with attractive natural scenery (Ulrich 1991, Kaplan 1993).

Vegetated roof technologies facilitate experiences of nature through observation of and interaction with, the life cycles of plants, through the seasonal variation of the plant colour and structure, and through habitat, such as patterns of nesting and paths of bird migration. Natural materials in vegetated roofs facilitate stimulation of sensory experiences. The wind moves through the foliage and across our skin and the plants transpire around us providing a cooling environment relative to that of the concrete decks or black radiating furnace of the exposed membrane. The aroma and taste of lemon thymes and sweet tomatoes from the roof top garden captivate our senses of smell and taste. The aesthetic stimulation of nature through our senses produces refined capacities for observational discovery and creation, critical to human physical and mental maturation (Kellert 2005).

Vegetated roofs as a harmonization of the natural and built environments can advance the fundamental goals of reducing the adverse effects of high density development on infrastructure, natural systems and human health, and promote more positive contact between people and nature in the built environment.

The investigations within the scope of this dissertation will qualify and quantify the multiple acoustical benefits of vegetated roofs and contribute to the growing body of research on urban soundscapes. Vegetated roofs have the potential to provide excellent external/internal sound isolation due to their high mass and low stiffness. Through surface absorption, vegetated roofs have the potential to reduce noise pollution in the community from aircraft, elevated transit systems, industrial sites and noise build-up in urban areas. This research will reveal that, as urban densification escalates human use of rooftops, vegetated roofs have the capacity to stimulate and engage human affinity for nature through aural perception.

CHAPTER 2 Sound Absorption of Substrates

2.1 Introduction and Literature Review

This chapter presents research on the relationship of the physical characteristics of vegetated roof substrates and two in-situ conditions, moisture content and compaction, to sound absorption. The first section of this chapter presents the background and a literature review on the acoustical energy balance and the acoustical characteristics of natural soils, grounds and manufactured porous materials. The second section describes the physical characteristics of the six test substrates and constituents, and the experimental set-up. The third section presents the results and findings, as well as the development of a regression model to predict the absorption of vegetated roof substrates.

The findings provide insight into the magnitudes and frequencies of sound energy which vegetated roofs can potentially absorb, and can provide guidance for the specification of the substrate mix to optimize the sound absorption potential of substrates for noise reduction.

Vegetated roofs as engineered systems vary widely in terms of design and implementation. As natural systems, vegetated roofs vary distinctively in terms of the in-situ ecological succession of the plant species (Köhler 2006). Vegetated roofs can be comprised of various material layers: root barrier, water reservoir/drainage layer, filter fabric, substrates and plants (Schunck 2003). The vegetative substrate is complex to characterize, varying in terms of the substrate constituents and mix, the depth of the substrate, the vegetation's aerial biomass and root structure, and the in-situ microclimate. In order to understand the sound absorption characteristics of an established vegetated roof system, it is of interest to first examine the absorption characteristics of the substrate before the vegetative substrate layer is investigated.

Vegetated roof substrates have a granular structure; the aggregates are separated from each other in a loosely packed arrangement. The substrate must be sufficiently porous to provide internal aeration, and be structurally capable of resisting excessive compaction beyond the mechanical compaction of the substrate on the roof during installation. There is a percentage of sand in most substrates; the void between the sand particles promotes free drainage of water, and entry of air into the soil. The percentage of organic matter provides a balance of drainage and water retention. The proportion of minerals to organics varies depending on plant requirements, depth and the projected maintenance regime. Clay has good moisture-holding capacity and also provides surfaces that attract and bind nutrients. However, clay and silts tend to clog up drainage layers and fabric, and subsequently are not as predominant in substrates as in natural soils (Craul 1999, Dunnet 2004).

Acoustic energy balance

To investigate the reflection and absorption of sound at the surface of the vegetated roof, first consider the condition of a sound wave incident on an ideal boundary - a mass-less plane - between the incident fluid medium of air and the non-vegetative porous medium of the vegetated roof substrate. When a sound wave impinges on the surface of a material, the sound energy is either reflected, absorbed or transmitted. The statement of the acoustic energy balance is simply:

$$\boldsymbol{E_i = E_r + E_\alpha + E_t} \qquad \textbf{Equation 1}$$

The sound energy reflected from a plane wave on the incident side of the surface is equal to the total wave energy less the wave energy which is absorbed or transmitted by the material. The total sound energy on the incident side of the surface is the combination of that of both the wave incident on the surface and the wave reflected from the surface. The intensities and pressure amplitudes of the reflected, transmitted and absorbed waves to those of the incident wave depend on the acoustical impedances of the air and the material. In air, the characteristic impedance is a real number independent of frequency. In a material such as the substrates under investigation, additional physical and mechanical properties are involved and the characteristic impedance is a complex quantity. Assuming a single refracted wave propagating into the boundary, and using Snell's law of refraction, it can be shown that, at a boundary surface, the complex reflection coefficient, expressed as the ratio of the complex pressure amplitudes of the reflected and incident plane waves, is an adequate representation of the total sound field in front of the reflecting surface (Long 2004).

With a suitable experimental set-up, a complex reflection coefficient can be deduced from data measured by two pressure microphones located in front of the reflecting surface. The experimental set-up is described in Section 2.2.

Sound attenuation in soils

Soil can be defined in acoustical terms as an unconsolidated granular sound absorbing material. When an acoustic wave propagates in any medium, there is a dissipation of acoustic energy; this loss of energy from the propagating sound wave is referred to as attenuation. Energy attenuation in soil is due to viscous losses and heat conduction losses; both of these mechanisms cause the acoustic energy to convert slowly into heat. The air molecules in the soil pores oscillate when excited by an incident sound wave. Frictional losses occur owing to the oscillation of the air against the surrounding soil constituent, the frame which defines the pore. Attenuation is due to the two mechanisms of absorption and diffusion. Making the assumption that substrates are relatively homogenous, absorption will be examined, whereas diffusion, the scattering of acoustic energy, which occurs only in inhomogeneous media, will not (Janse 1969, Metah 2008).

The relative volume of pore space (porosity) of a medium is a parameter which affects how all porous materials absorb sound; the effectiveness of a porous material to attenuate sound energy depends on its flow resistance, quantifying the degree of difficulty with which the air flows through the material. The flow resistance is dependent on the density of the material; in general the greater the density, the greater the flow resistance. Tortuosity and pore structure cause changes in the flow direction; the expansion and contraction of the air flow through the irregular pores results in a loss of momentum of the directional wave propagation of a medium. This is more significant at high frequencies (Delany 1970).

Soil has been modeled theoretically as both a rigid porous material and as an elastic porous material. Biot theory provides the bases for the development of several theories which account for sound propagation within the idealized porous material (isotrophic, quasi-homogenous with uniform porosity), consisting of an elastically-framed matrix in which the relative motion of the fluid and the soil framework is examined. Biot produced constitutive relationships for fluid-saturated granular media and followed these with an analysis of elastic wave propagation by means of a Lagrangian formulation (Biot 1956).

Several theories of sound propagation within idealized porous material have been applied to soils (Brutsaert 1964, Attenborough 1981, 1982). The formulations take into account both viscosity and heat conductivity, but consider the losses from forced mechanical oscillation of the skeleton of a porous material to be so low that it is reasonable to neglect losses due to molecular exchange of energy (Attenborough 1982).

Acoustical measurements of soils and grounds

There is no published literature which reports the relationship between the properties of vegetated roof substrates and their acoustical characteristics, or the impact of microclimatic and site conditions on the sound absorption of substrates. The following is a summary of the findings of published measurements on and modeling of sand, natural soils, bare grounds and manufactured porous materials most relevant to this study.

Laboratory measurement, executed with an impedance tube with one end of the tube submerged in the sand, has shown that the absorption coefficient of sand increases with frequency from 250 to 1000 Hz. Moreover, the absorption coefficient increases incrementally with the increase in the percentage of moisture content up to 6% and then decreases with a greater percentage of moisture content (Dickenson 1979).

Absorption coefficients of grounds, measured by the in-situ use of an impedance tube, have shown that absorption decreases immediately after rainfall relative to pre-rainfall conditions, and that absorption increases as the ground drains over the next few days and then decreases as the ground dries (van der Heijden 1983).

Acoustical attenuation and propagation speed have been determined to be a function of soil moisture and levels of compaction. In non-saturated soils, sound attenuation has been shown to positively correlate with water-filled porosity and volumetric water content, whereas, in saturated soils, there was no significant correlation between attenuation and any one soil parameter. In compacted soils, attenuation positively correlated with increased water content, yet no significant correlation was found with either soil texture or organic matter content. Although measurements have been made over a wide range of soil textures, none of the soils evaluated would provide viability for plants on vegetated roofs (O'Brien, 1996).

The magnitude and phase of the plane wave reflection from a ground are strongly dependent on the real and imaginary parts of the normal acoustical impedance of the ground. Reported measurements and outcomes of acoustical prediction models are most often in terms of the specific or characteristic impedance, from which the reflection and absorption coefficients are deduced. The characteristic impedance and the propagation coefficient of manufactured fibrous absorbent material have been modeled as a function of frequency and specific flow-resistance (per unit thickness- i.e. flow resistivity). The flow-resistance is predominately a function of the bulk density and the anisotropic fibre size (Delany 1970). The models assume the material is a homogenous, unbounded, infinitely extended medium. The application of this model to vegetated roof substrates may not be assumed valid, as the physical characteristics of substrates are not anisotropic.

The characteristic impedances and propagation constants of single constituent manufactured granular materials have been successfully predicted from porosity, tortuosity, specific density of grain base and the descriptive parameter, characteristic particle dimension. The characteristic particle dimension has been shown to be a valid characteristic of a single manufactured constituent (Voronina 2003). Again, this is not necessarily applicable to a vegetated roof substrate, which has multiple natural constituent components with widely varying particle size distribution and pore characteristics.

Hypothesis

The volume of pore space in the substrate and the water content within the pores will affect the degree of attenuation sound due to absorption. The percentage of each constituent type (pumice, sand, organic matter) used in the substrate determines the particle size distribution and, as such, the volume of pore space between the particles and the intercellular pore space. It is expected that the relative percentage of constituents will determine the absorption capacity of the substrate.

2.2 Methodology - Experimental Study

Physical, chemical and biological properties of substrates are all critical parameters to investigate for plant viability on rooftops. The physical properties of substrates and the range of in-situ conditions are of the greatest interest in the investigation of the vegetated roof substrate's capacity for sound absorption.

An experimental study was developed to determine which physical properties and characteristics of vegetated roof substrates contribute most significantly to the absorption of sound energy. The substrate characteristics of interest include: particle density, bulk density, total porosity, percentage organic matter, particle size distribution. The properties which are a function of the micro-climate and site conditions of interest include volumetric water content and compaction.

The normal incidence absorption coefficients of six vegetated roof substrates and their three primary constituents - sand, compost and pumice - were measured in an impedance tube at three levels of volumetric water content - oven-dry (0%), wilting capacity and field capacity - and at two states of compaction. The sample depths were 98 mm as this was the maximum depth allowable in the impedance tube sample holder. This is a reasonable range of depths for extensive vegetated roofs. The permanent wilting capacity and the field capacity define the minimum and maximum available water content required for plant viability and hence defined the limits of volumetric water content. The substrates were evaluated as either non-compacted or compacted at a level which approximates in-situ conditions. The relationship between the absorption coefficient and the properties of the substrate and constituents were examined using multiple linear-regression modeling.

Physical properties and characteristics of the test samples

Five of the six substrate samples were randomly selected from products on-site at the BCIT Green Roof Research Facility. The samples represent a range of vegetated roof substrates comprised of natural materials and currently used for extensive and semi-extensive vegetated roofs in the Pacific Northwest. The sixth substrate had previously been evaluated for conformance to both British Columbia Landscape and Nursery Association (BCLNA) and Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) recommendations and had been selected for the subsequent 25 experimental rooftop test plots (see Chapter 3) and the subsequent transmission loss research (see Chapter 4). The sand, compost and pumice, common to most of the substrates, were provided by the suppliers of the selected substrates.

Vegetated roof substrates for extensive and semi-intensive applications have specified ranges of percentage of organic matter and particle size distribution of all constituents. The range of volumetric moisture content between wilting point and field capacity represents the viable range of moisture for plant viability and survival. Compaction is a site condition which may occur at the time of substrate installation and will occur over time due to loading and rain compaction.

The physical characteristics were measured in a commercial lab according to standard soil test methods. Particle density (Klute 1982, Carter 1993), available water storage capacity (Klute 1982 ASTM D2325-2004), particle size distribution (FLL 2002 McKeague 1978) and total porosity are independent of micro-climate conditions. The percentage of organic matter (McKeague 1978) changes over time but not within the time duration of the study and was measured before acoustic testing. The bulk density and percent moisture content were measured within 24-36 hours of acoustical testing using an oven-dry method (McKeague 1978).

Table 2 Test sample characteristics

Samples	% OM [1]	Particle Density kg/m^3	Total Porosity % vol.	Field Capacity % vol.	Wilting Capacity % vol.	PSD[3]	
Sand	< 1	2704.3	36.6	7.5	3.6	0.43	91.48
Compost	32	1755.9	72.6	46.7	36.7	0.28	31.05
Pumice	< 1	1996.5	74.7	31.3	27.1	0.28	13.27
Substrate 1	15	1980.9	72.4	33.0	23.7	1.00	59.84
Substrate 2	14	1909.9	74.9	30.6	29.4	0.70	74.24
Substrate 3	15	2196.0	63.0	31.1	25.0	1.00	68.47
Substrate 4	14	2447.2	57.6	18.7	12.5	0.57	21.89
Substrate 5	2	2361.6	61.5	30.5	23.3	1.00	53.70
Substrate 6	25	2205.0	57.7	17.9	15.5	0.86	30.90

[1] Percentage of organic matter

[2] Field capacity measured at 33 J/kg, Wilting Capacity at 1500 J/kg

[3] Particle size distribution (See **Figure 1**)

Table 2 shows the characteristic of the test samples. The percentage of organic matter (%OM) in the six substrates ranged from 2 to 25%OM. The mean value of 14%OM is greater than the 8%OM recommended by the FLL. The maximum water storage capacity measured at 10 J/kg ranged from 24 to 42% by volume and, with one exception, meets the FLL recommendation of 35 to 45%. Aeration Porosity at 10 J/kg ranged from 23 to 34% by volume and, with one exception, met the FLL recommendations of aeration porosity greater than 25%. The particle size distribution curves correlate the particle size distribution of the substrate mix to a recommended percentage of three grades each of silt, sand and aggregate. The particle size distribution curves of three of the substrates fit within the recommended maximum and minimum curves; two had minor deficiencies with either slightly more or less coarse and/or fine aggregate. Two substrates contained a higher than recommended percentage of aggregate particles >2 mm. The constituent as a single component cannot comply with distribution recommendations (**Figure 1**).

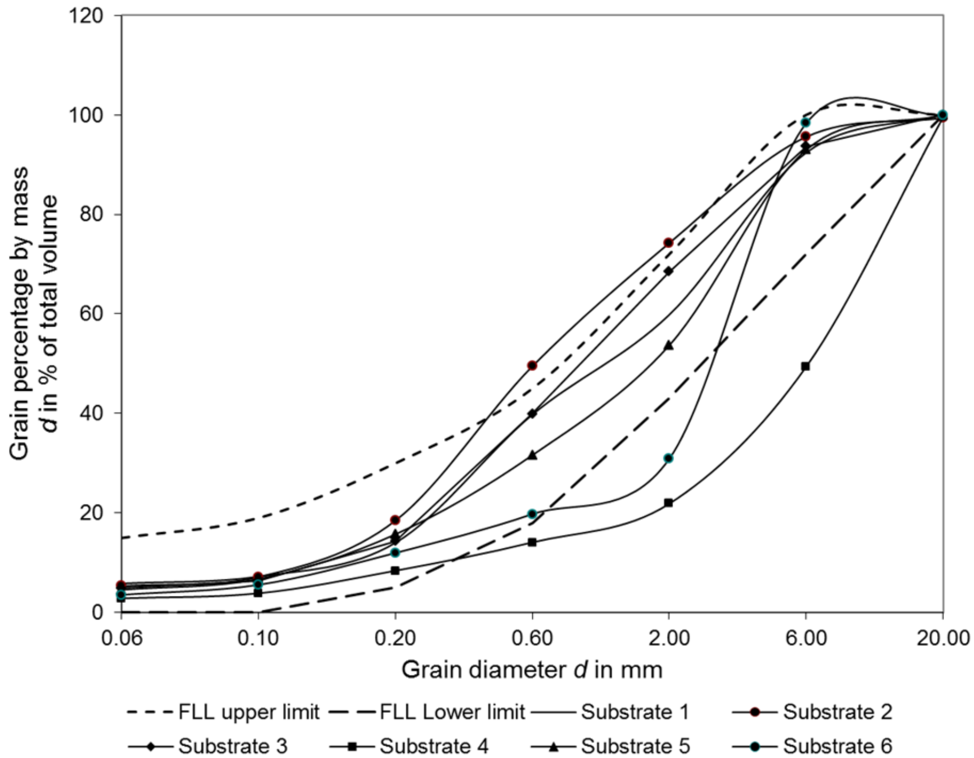

Figure 1 Particle size distribution of the sample substrates

The most direct method for evaluating the absorption potential of vegetated roof substrates is to measure the complex reflection coefficient in an idealized incident sound field using an impedance tube (Allard 1988). This method, which has been standardized in ASTM E1050_98 2006, is a current standard for parametric studies and for industry to assign performance values to materials, as well as to validate predictive models.

Using broadband white noise, plane waves are generated from one end of the impedance tube normal to the surface of a sample located in a holder at the opposite end of the tube (**Figure 2**). Two microphones (B&K ¼" type-4135 microphone with B&K 1/" type 2669 preamplifiers) are set within the face of the tube at a known distance from the sample and from each other. When the wave reflection from the surface of the sample is not equal to zero, a standing wave pattern is created within the tube.

Figure 2 Impedance tube experimental set-up

A frequency analyser (Soundbook by SINUS GmbH) calculates a frequency response function (transfer function) from the sound pressures which is measured simultaneously at the two microphone locations in the impedance tube. From this, the complex reflection coefficient is calculated. From the complex reflection coefficient, the normal incidence sound absorption coefficients and normal specific acoustic impedance ratios are calculated. It can be shown that the complex reflection coefficient (R) is derived from the measured transfer function (H) and the geometry of the impedance tube:

$$R = |R|e^{j\emptyset_R} = R_r + jR_i = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l-s)}$$ **Equation 2**

The complex reflection coefficient defines both the magnitude and the phase. In that we are only interested in the total amount of energy removed by the sample from the incident sound field at the surface boundary, the magnitude rather than the phase is examined and the normal incidence sound absorption coefficient is:

$$\boldsymbol{\alpha = 1 - |R|^2}$$ **Equation 3**

The theory assumes that the substrate is semi-infinite, locally reactive and that the surface normal impedance is equal to the characteristic impedance. A surface may be considered to be locally reactive if the reaction to a wave at any one point is independent of the reaction at any other point on the surface. The surface impedance is then independent of the angle of incidence. Moreover, the diffuse field value of the absorption co-efficient can be calculated from the impedance, and a NRC value determined.

Experimental limits of validity

Two impedance-tube diameters were available - a 98 mm diameter for frequencies from 177 to 2050 Hz, and a 29 mm diameter for frequencies higher than 2050 Hz. This investigation was limited to the lower frequency range, as the 29 mm tube diameter is too small to accommodate a homogenous sample of the test substrates due to the granular size of the aggregated components. The upper frequency limit is inversely proportional to the diameter of the tube and equates to 2050 Hz for the 98 mm impedance tube. The lower frequency limit is related to the spacing of the microphones and the accuracy of the sound analyzer (ASTM E1050-90). The lower frequency cut-off of the apparatus was estimated to be the lower limit of the 250 Hz one-third octave band (177 Hz). In this investigation, the impedance tube was used in a vertical orientation (**Figure 2**) so that loose granules and water could be retained in the sample holder. The orientation of the impedance tube does not affect the measurement results.

The substrate granules did not fit smoothly and continuously against the impedance tube sample holder (**Figure 3**); this is a possible limitation of the experimental set-up as the theory assumes a complete surface boundary between the sample and the sample holder.

Measurement procedure

Large samples of the six substrates and the constituents - sand, pumice, and compost - were oven dried to 0% volumetric water content (%VWC). From a large container, the first random sample was ladled into the impedance tube sample holder and levelled to the rim (**Figure 3**). In order to maintain a representational and random granular distribution of the mix, the substrate was ladled into the sample holder rather than poured. After the first impedance tube measurement was completed, the sample was weighed; then two repeat measurements were done with equal masses of substrate measured from the large container and placed into the sample holder.

The same process was followed to measure three samples of substrate or constituent at wilting and/or field capacity (see **Table 3** for summary of sample test conditions). The substrate was mixed using a mass approximation of water volume to a predetermined %VWC representing the substrate's specific wilting or field capacity. The air, water and substrate were maintained at the same temperature ($\pm 1^{o}$C). After the sample was tested in the non-compacted condition, the sample was tested in a compacted state. At wilting and field capacities, a compaction rate of 18% was feasible within the impedance tube sample holder. This compaction rate is

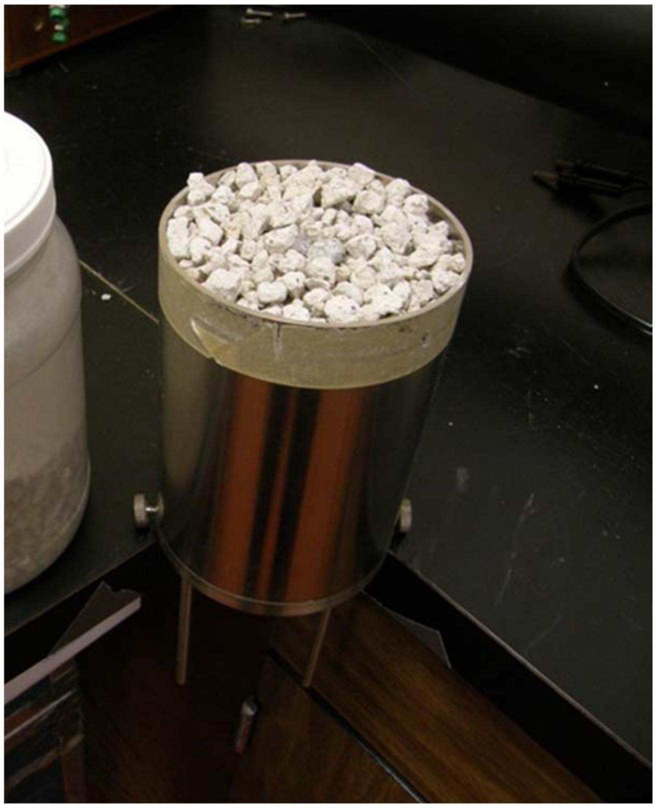

Figure 3 Pumice in impedance tube sample holder

comparable to on-site compaction specifications and general practices. The sample was compacted in layers while being placed in the sample holder in order to avoid a exaggerated surface compaction. If the percentage difference between wilting and field capacities was less than the resolution of 5%, then only the oven dried substrate was tested, at wilting capacity. The bulk density, volumetric water content, air porosity and total compaction are parameters which are a function of the volumetric water content, and were determined within 24-36 hours of the acoustical measurement using an oven–drying method.

Table 3 Number of samples and test conditions

Sample	Test condition				
	Oven Dried	Wilting Capacity	Wilting-compacted	Field Capacity	Field-compacted
Sand	3	-	-	-	-
Pumice	3	-	-	-	-
Compost	3	-	-	-	-
Substrate 1	3	3	3	3	3
Substrate 2	3	3	3	-	-
Substrate 3	3	3	3	3	3
Substrate 4	3	3	3	3	3
Substrate 5	3	3	3	3	3
Substrate 6	3	3	3	-	-

2.3 Results - Absorption Coefficient of Constituents and Substrates

The normal incidence absorption coefficients of the substrate are presented in **Table 4** for each octave band from 250 to 2000 Hz, and for each of the test conditions; the ranges and variability of the octave band values and the values averaged over all frequencies are also given. There was a high level of consistency in the test repetitions of each substrate in each of the five states of evaluation: oven dried, wilting capacity, wilting capacity - compacted, field capacity, field capacity - compacted. The significant range in the characteristics of the substrates resulted in a wide range in the values of the absorption coefficients. In the oven dried state the range from the minimum to maximum absorption coefficient was 0.21 to 0.49 across the frequency bands. The ranges for wilting capacity, wilting capacity - compacted, field capacity, field capacity - compacted were 0.37 – 0.51, 0.35 - 0.48, 0.09 - 0.77, 0.27 – 0.54 respectively. These results indicate that, in the octave bands 250 to 2000 Hz, the percentage of organic matter and volumetric water content have the most significant effect on the sound absorption of the substrates. The absorption coefficient of the evaluated substrates correlated positively with percentage organic matter and negatively with moisture content and increased compaction, with the exception of the state of compaction having negligible impact on sound absorption in the lowest (250 Hz) octave band.

Table 4 Average normal incidence absorption coefficients of test substrates

		Octave Band (Hz)				
Oven Dried		250	500	1000	2000	AVG.
	Mean	0.62	0.76	0.68	0.79	0.71
	Min	0.28	0.63	0.53	0.70	
	Max	0.77	0.91	0.80	0.91	
Wilting Capacity						
	Mean	0.28	0.71	0.58	0.75	0.58
	Min	0.15	0.36	0.41	0.52	
	Max	0.52	0.87	0.81	0.89	
Wilting Capacity - Compacted						
	Mean	0.35	0.50	0.49	0.58	0.48
	Min	0.18	0.22	0.32	0.39	
	Max	0.53	0.70	0.68	0.79	
Field Capacity						
	Mean	0.17	0.28	0.42	0.54	0.35
	Min	0.13	0.09	0.07	0.08	
	Max	0.22	0.70	0.71	0.85	
Field Capacity - Compacted						
	Mean	0.12	0.13	0.23	0.40	0.22
	Min	0.03	0.04	0.04	0.06	
	Max	0.30	0.34	0.58	0.49	

Figure 4 shows the absorption coefficient of the compost, sand and pumice, and the average of all test substrates, at 0% moisture content and in a non-compacted state. With the conditions of moisture and compaction removed, the sand, with less than measureable organic content and low pore volume, had the lowest absorption coefficient (0.26 to 0.40). Absorption increased with frequency in the range of 200 to 2050 Hz. The pumice, with less than measureable organic content but with a high pore volume, had a higher absorption coefficient range. The compost, with a high

percent of organic matter, had the highest absorption range. The constituents of sand, pumice and organic matter (compost) formed the majority of the substrate mix. The average of the absorption coefficients of the substrate mixes is between that of sand and compost.

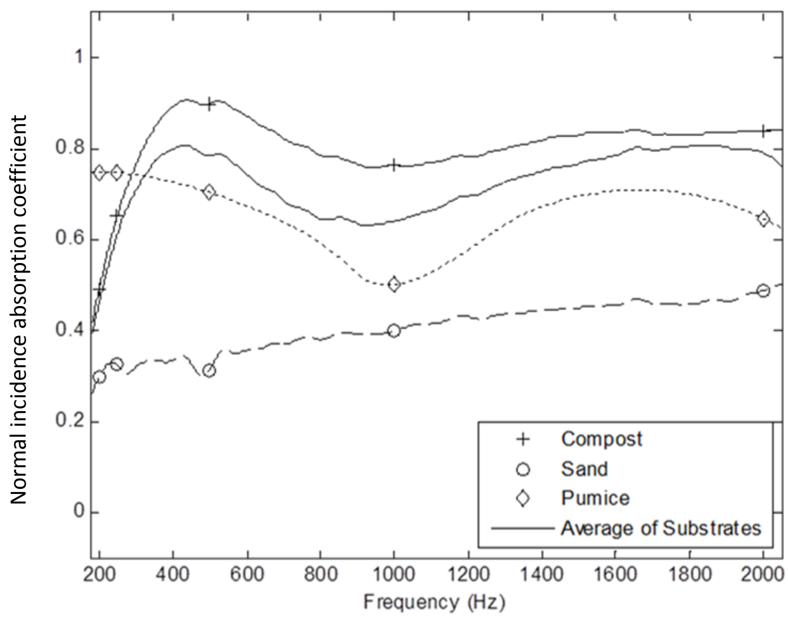

Figure 4 Absorption coefficients of substrate and constituents at 0% moisture content at wilting capacity

The sharp decrease in the absorption at low frequencies - below 500 Hz - of the compost and the substrates with compost constituent may be explained by the decrease in inter-granular pore space associated with an increase of finer particle sizes. **Figure 5** shows the relationship of the percentage of organic matter to the absorption coefficient of the substrate. One substrate had only 2% organic matter, and the absorption coefficient is closer to that of sand than any other substrate. Four of the substrates had 14 or 15% organic matter, which increased the absorption coefficient by 0.15 (1000 Hz) at wilting capacity; the absorption of the substrate with the highest organic content (25%) was an additional 0.15 higher (1000 Hz).

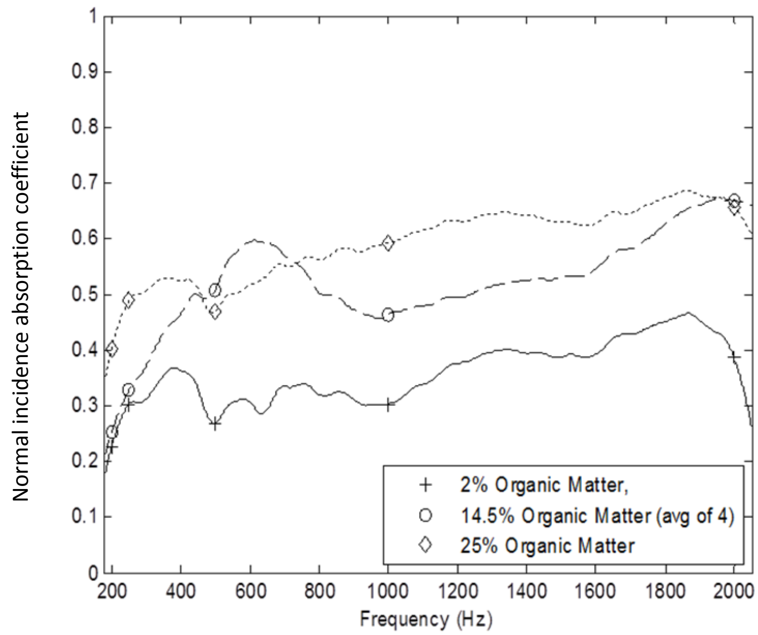

Figure 5 Variation of measured absorption coefficients with percentage organic matter

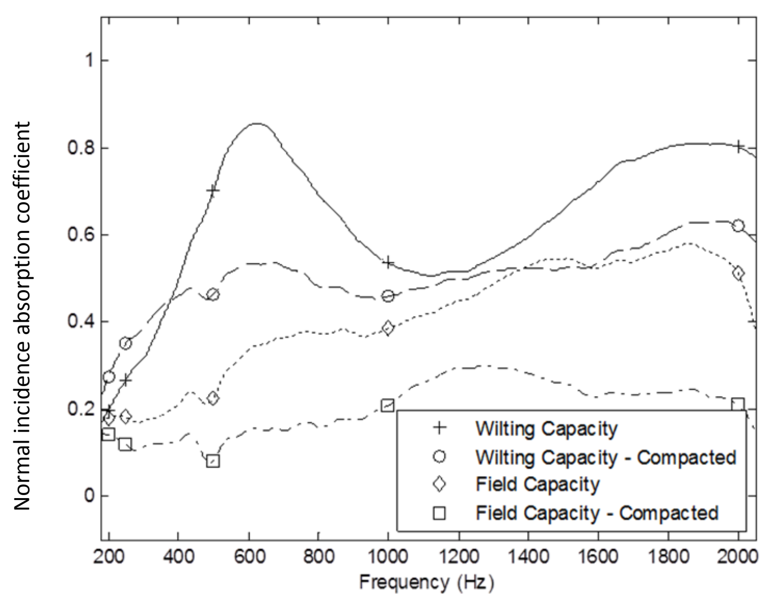

Figure 6 Variation of measured absorption coefficients with percentage moisture content

Figure 6 shows the impact of increased volumetric water content and of compaction on the absorption of the six substrates. In general, absorption decreased with both factors. The moisture content required for plant viability of the substrates evaluated has a range of 2 to 10% volumetric water content. This range of water content translates to a range of the absorption coefficient 0.26 averaged over all the evaluated substrates.

2.4 Multi-variable Regression Models

The relationship between the absorption and the properties (**Table 2**) of the test substrates and constituents was examined using multiple linear regression modeling. The measured absorption coefficients of the substrates - the dependent variable - were normally distributed and did not require transformation prior to analysis. The parameters of soil properties and characteristics - the independent variables - included: percentage of organic matter, bulk density, particle density, porosity, available water content, air-filled porosity, volumetric water content, compaction, particle size distribution, and percentage of particles greater than 2 mm. On bivariate analysis, independent variables that were statistically significant ($p < 0.05$) were considered for inclusion in multiple linear regression models. Co-linearity of the independent variables was evaluated using the Pearson correlation for continuous variable pairs, the Spearman correlation for categorical pairs, and a Chi-squared test for the association of the categorical pair. Highly correlated independent variables ($r_p > 0.4$, $r_s > 0.4$, $p < 0.05$ significance) were evaluated and the variable with the stronger association with the dependent variable on bi-variant analysis was retained in the model. Frequency dependent models were developed separately to predict the absorption coefficients in octave bands from 250 to 2000 Hz. The final frequency dependent models to predict the absorption coefficients were regressed against the determinants by a backward stepwise linear regression process, retaining only statistically significant variables ($p < 0.05$).

There were 87 observations for each model. The R^2 values indicate that the models explain 66 to 78 % of the variability in the absorption coefficient. **Table 5** reports the coefficients and R^2 for the final regression models. The models for prediction of the absorption coefficient are:

$$\alpha = \beta o + \beta(1)(\%OM) + \beta 2\,(P) + \beta(3)(VWC = Wilting) + \beta(4)(VWC = Field) + \beta 5\,(COMP)$$

Equation 4

Table 5 Coefficients for multi-variable octave band regression models

				Coefficients				n= 87
Frequency Band Models	Intercept β_0	% OM β_1	Porosity β_2	VWC= Wilting β_3	VWC= Field β_4	Compaction β_5	Multiple R-Squared	p-value
250 Hz	0.0609	0.7000	0.6259	-0.3388	-0.4218	0.0000	0.7837	0.0000
500 Hz	-0.0423	0.3800	1.0129	-0.1365	-0.4208	-0.1489	0.7887	0.0000
1000 Hz	-0.0503	0.8500	0.8151	-0.1331	-0.2357	-0.0970	0.7471	0.0000
2000 Hz	0.1396	0.7000	0.7195	-0.0439	-0.2263	-0.2016	0.6627	0.0000

The multi-variable analysis supports the observations made during measurement. The normal incidence absorption coefficient is positively associated with the % organic matter and negatively associated with compaction and water content. An increase in water content from wilting capacity to field capacity decreased the absorption coefficient by 0.16. Progressing from a state of non-compacted to compacted decreases absorption by 0.10 in the frequencies above 250 Hz. The effect of these changes in state is of the same magnitude for substrates with 2 to 25% organic matter.

Although the unit increase in sound absorption is similar for % organic matter and % porosity the value of % organic matter can vary from as low as 2 to as high as 25, whereas porosity varies within a smaller range (57 to 72 % in the sample evaluated). Therefore, the greater range of the variability of % organic matter can affect absorption to a greater extent than porosity. The trends of the four frequency dependent models are similar with the exception of the $ß_1$ for the % organic matter and porosity. This cannot be physically explained. The multi-variable model indicates that there is no effect of compaction in the lowest frequency range of 250 Hz.

2.5 Discussion

The objective of this research project was to identify the substrate characteristics and properties which most significantly affect sound absorption. A review of literature supported the feasibility of using the standing wave impedance tube method to measure the normal incident absorption coefficient. Six substrates and their three major constituent components - sand, compost and pumice - were evaluated. This investigation focused on the substrate blends commonly used for extensive, semi-intensive and intensive vegetated roofs and the in-situ conditions of moisture content and compaction. The working hypothesis, based on the known relationship between porosity and the sound absorption characteristics of soils and grounds, was that the percentage of organic matter, sand and pumice used in the substrate will affect the particle sizes, the volume and geometry of pore space between the particles and the amount of intercellular pore space and thus sound absorption.

The findings confirm the working hypothesis and have shown that the soil parameters affecting the physical mechanism of sound absorption include porosity, % organic matter and moisture content. The measures of the percentage of organic matter can predict the absorption capacity of the substrate, whereas the percentage of large aggregate over 2 mm did not predict the absorptive capacity.

The findings of the effects of porosity and moisture content align vegetated roof substrates with previous research findings on soils and in-situ grounds. However, more significant to the design and acoustical optimization of substrates, the empirical values of substrate characteristics and properties which predict the absorption coefficient are percentage of organic matter, moisture content and state of compaction. The multi-variable regression model which was developed predicts that increasing the amount of organic material by 12.5% has a proportional increase in the absorption coefficient by 9%. As the moisture content of the substrate increases within the range for plant viability, from wilting capacity to field capacity, the percentage of sound attenuated by absorption decreases by up to 26%. In-situ compaction reduces sound absorption by 10%.

One limit of the experimental set-up was the selection of pre-engineered industry products as the test samples; a fabrication of substrate samples, with an incremental gradient of the percentages of constituents, would have benefited the analysis. Second, the samples evaluated were prepared in the lab to represent in-situ conditions of water content and compaction. The samples extracted from in-situ test plot, represent the vertical redistribution of particle size which occurs over time. Project 2 however, addresses these experimental limits.

The substrates evaluated represented the range and diversity of mixes used on extensive vegetated roofs. The lab preparation was consistent and measurements of properties were executed with accuracy. The findings on the absorption coefficient fill a knowledge gap on the acoustical characteristics of substrates, a material which is now used, in some form, on an increasing number of rooftops. The findings were also instrumental in structuring the experimental set-up of the second project which investigated the absorption capacity of vegetative roof plots with substrates of varying depth.

2.6 Chapter Summary

The research project presented in this chapter focused on the identification of the characteristics and properties of the vegetated roof substrates which have the greatest potential to affect sound absorption of vegetated roofs. The chapter presented literature on the acoustical properties of soils and ground which were relevant to the uniquely engineered substrate blends and identified an ASTM method, using a standing wave impedance tube, which is appropriate to evaluate the substrates. Six substrates, which represented the range of blends commonly used in the Pacific-Northwest for vegetated roofs, were evaluated. The substrates were evaluated at moisture content and compaction levels which represent realistic in-situ conditions for rooftop plant viability.

From the measured data on the physical properties and the normal incident absorption coefficients of substrates, a multi-variable regression model was developed. The model can be used to assess the impact of the design of blends on sound absorption. The amount of organic matter used in regional substrates can affect the absorption by as much as 9%, and likewise the range of water availability, determined by substrate composition, impacts the sound absorption by as much as 26%. In addition, the level of site compaction can affect sound absorption by as much as 10%.

The standing wave impedance tube method used for the acoustical evaluation of substrates could not be utilized for the evaluation of an established vegetated roof system. The sample size for the impedance tube would be too small in cross-area to represent the diversity of foliage and root structure. In addition to providing data on the absorption coefficient of substrates, the analysis of the physical properties and the acoustical characteristics of the substrate blend allowed for a knowledgeable selection of substrate blend for use in the research presented in the following chapter. The substrate blend selected for the research on the absorption coefficient of vegetated roofs of varying depth of substrate and diverse plant communities represents the mean absorption coefficient of all substrates evaluated.

CHAPTER 3 Absorption Coefficients of Vegetated Roofs

3.1 Introduction

The research on the investigation of the absorption potential of vegetated roof plots by the measurement of their absorption coefficients is presented in two parts in this chapter. The first part investigates the implementation and application of the spherical decoupling method, for in-situ measurement of the absorption coefficient of vegetated roofs. The second part presents the use of the standardized method to perform in-situ measurements and deduce the absorption coefficients of 25 vegetated and non-vegetated test plots representing a range of substrate depths and plant communities commonly used for extensive vegetated roofs. The goal is to understand the impact of substrate depth and plant species type and coverage on the absorption potential of vegetated roofs, in order to design and construct vegetated roofs for optimal sound absorption.

The spherical decoupling method has been used to measure sound reflection properties and deduce the sound absorption of locally reactive surfaces and grounds, such as playing fields and forest floors (Allard 1985, Kruse 2007). However, the substrate surface particles and the plants of the vegetated roof do not provide a homogeneous and specularly reflecting surface (i.e. with no diffusion), surface properties which are inherent assumptions in the theory supporting the spherical decoupling method. Less than ideal surface conditions have previously been accommodated in measurement methods through the determination of an appropriate geometric configuration of the sound source, the microphones and the surface plane, and through repeated measurements at multiple surface locations.

The first investigation on one test plot was completed using the spherical decoupling method inside the controlled environment of an anechoic chamber. An anechoic chamber is a room in which the floor, ceiling and walls are covered with sound absorbing material to effectively eliminate all reflections, approximating a free-field condition. Within the chamber, a dimensionally representative test plot was built on a plywood floor, creating a hemi-anechoic condition to approximate a rooftop context.

The in-situ measurements of 24 of the 25 rooftop test plots were completed on a 1400 m^2 roof top. These test plots were constructed with material layers representative of the common vegetated roof systems of the Pacific Northwest of North America. The test plots ranged in substrate depth in 25 mm increments from 50 to 200 mm; seven test plots contained the substrate only. Previous work on various grounds suggests that only the first 90 mm depth of ground affects absorption (van der Heijden 1983). Eighteen test plots were planted with three structurally distinct plant species: sedums, a coastal meadows community and grasses. Vegetation foliage and root structure are known to affect the impedance, and thus the absorption, of grounds (Aylor 1972). Examined plant communities have shown differences in sound absorption due to differences in height, foliage and mass (Linskens 1976). Vegetation is known to impact the physical characteristics of soil (Glinski 1990); the vegetation affects porosity and water content through the mechanisms of soil temperature, organic and inorganic composition and animal life in soil (van der Heijden 1983). The mechanism of accessing water from the soil is a function of the root structure and soil interface. Additionally, the aerial foliage affects the micro-climate of the soil properties. It has been determined that leaf dimension and mass are important properties of plants affecting sound reflection and hence sound energy incident on soils (Martens 1981, 1985). It is not known if the variability of vegetation foliage and root structure, within the limit of the plant species suitable for vegetated roofs, will affect the absorption of the vegetated roof.

Acoustic theory

The spherical decoupling method is a two-microphone technique which measures the reflection coefficient at any incident angle from which the diffuse-field absorption coefficient can be derived (Allard 1983). The experimental set-up and the geometry of the measurement set-up are illustrated in **Figure 7**. The acoustic field is approximated as the superposition of the incident wave and a reflected wave from the point source in a free-field condition. A spherical wave propagates from a real source to the microphones. The two microphones, on a normal axis, are close to each other and to the ground plane relative to the height of the sound source above the plane. Assuming spherical wave propagation in a free-field, the complex sound pressure spectra at each of the microphones are:

$$P_1(f) = P_0(f) * \left[\frac{e^{ikr_{11}}}{r_{11}} + R(f, \theta_1) * \frac{e^{ikr_{21}}}{r_{21}} \right]$$ **Equation 5**

$$P_2(f) = P_0(f) * \left[\frac{e^{ikr_{12}}}{r_{12}} + R(f, \theta_2) * \frac{e^{ikr_{21}}}{r_{21}} \right]$$ **Equation 6**

where $P_1(f)$ is the pressure spectrum from microphone 1, $P_2(f)$ is the pressure spectrum from microphone 2, and $P_o(f)$ is the pressure spectrum of the source. θ_1, θ_2, r_{11}, r_{12}, r_{21} and r_{22} are defined in **Figure 7**.

It can be shown that the reflection coefficient can be deduced from the measured frequency response function (transfer function, H). The frequency response in the acoustic field at the location of two microphones is the ratio $P_2(f)/P_1(f)$ and is expressed as:

$$H = \frac{\dfrac{e^{ikr_{12}}}{r_{12}} + R(f, \theta_2) * \dfrac{e^{ikr_{22}}}{r_{22}}}{\dfrac{e^{ikr_{11}}}{r_{11}} + R(f, \theta_1) * \dfrac{e^{ikr^{21}}}{r^{21}}}$$ **Equation 7**

Reflection from a surface is a function of the angle of sound incidence. The angle of incidence from the source to each of the two microphones is approximated by a single angle of incidence from the source to the ground point of the normal axis of the microphones; that is, when $h_s >> h_2$ and $h_s >> h_1$, θ_1 and θ_2, approach θ. From the measured value of the frequency response, the reflection coefficient is expressed as:

$$R(f,\theta) = \frac{\dfrac{e^{ikr_{12}}}{r_{12}} - H(f,\theta_2) * \dfrac{e^{ikr_{11}}}{r_{11}}}{\dfrac{e^{ikr_{21}}}{r_{21}} * H(f,\theta_1) - \dfrac{e^{ikr_{22}}}{r_{22}}}$$

Equation 8

The normal incidence absorption coefficient of the ground plane is calculated from the magnitude of the reflection coefficient:

$$\alpha(f,\theta) = 1 - |R(f,\theta)|^2$$

Equation 9

For locally reacting surfaces, as we assume ground and vegetated roofs to be, the impedance will not change with the angle of incidence.

$$z(f) = \frac{1 + R(f,\theta)}{1 - R(f,\theta)} * \frac{1}{\cos(\theta) * (1 + 1/ikr_0)}$$

Equation 10

The diffuse-field absorption coefficient is calculated from the impedance (Morse, 1936):

$$\propto_d = 8\kappa\{1 + \left(\frac{\kappa^2 - \sigma^2}{\sigma}\right) \; tan^{-1} \; \left[\frac{\sigma}{\sigma^2 + \kappa^2 + \kappa}\right] \; - \; \kappa \; ln \left[\frac{(\kappa + 1)^2 + \; \sigma^2}{\kappa^2 + \sigma^2}\right]$$

where $\boldsymbol{\kappa} = \mathbf{Re}(\mathbf{1}/\boldsymbol{z})$ and $\boldsymbol{\sigma} = \mathbf{Im}(\mathbf{1}/\boldsymbol{z})$ **Equation 11**

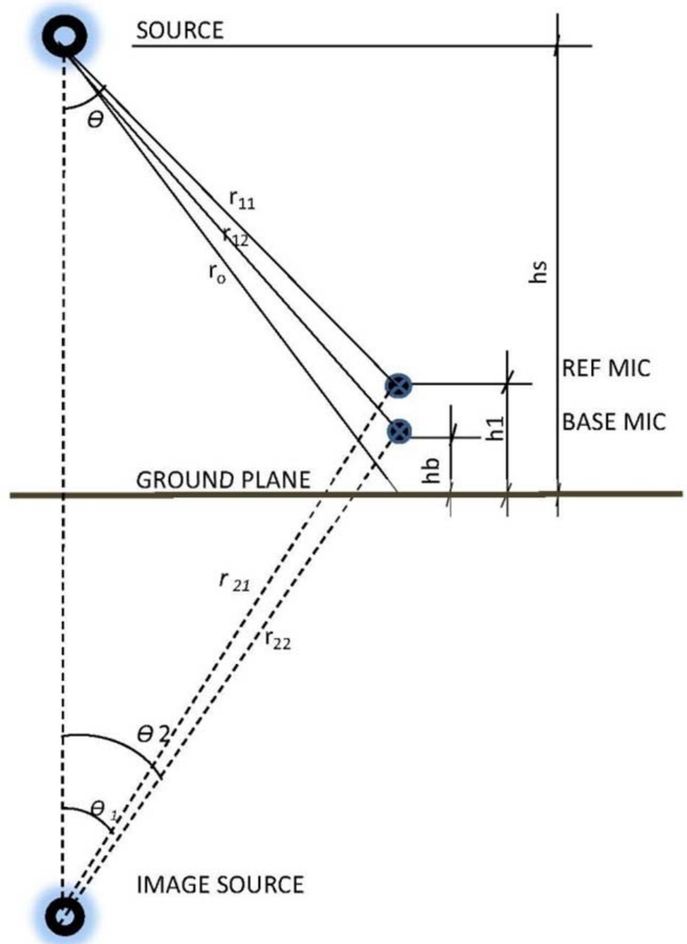

Figure 7 Geometric configuration of spherical decoupling method experimental setup (from De Geetere 2004)

Considerable work has been completed to define the optimal geometry to use in the measurement of the frequency response to calculate the impedance of grounds (Kruse 2008). The lower (f_{min}) and upper frequency (f_{max}) limits of validity of the spherical decoupling method are a function of the distance between the two microphones and the angle of incidence (θ) of the sound source. Frequency limits are derived by the following formulas and are numerated in **Table 6**.

$f_{min} = 0.1*c/(2*s*cos(\Theta))$ **Equation 12**

$f_{max} = 0.8*c/(2*s*cos(\Theta))$ **Equation 13**

Table 6 Frequency limits of spherical decoupling method

	$\theta = 0°$		$\theta = 45°$		$\theta = 75°$	
s(mm)	f_{min}(Hz)	f_{max}(Hz)	f_{min}(Hz)	f_{max}(Hz)	f_{min}(Hz)	f_{max}(Hz)
25	686	5489	970	7762	2667	21332
50	343	2744	485	3881	1333	10667
100	171	1372	243	1941	667	5333

At air temperature of 19.7°C

3.2 Methodologies of Measurements

Part 1 – Spherical decoupling method standardization

The objectives of Part 1 were: first, determine the geometric configuration of the sound source and microphones relative to the surface; second, investigate potential compromises on a roof-top to the theoretical free-field condition; and third, determine the impact of the surface properties on the repeatability of the measurements.

The test chamber is fully anechoic. A plywood subfloor was floated on the wire walking mesh to create a hemi-anechoic condition which approximates a rooftop context, and to provide support for the vegetated roof test plot. The loudspeaker was hung from the wire mesh ceiling; the two microphones were supported with a GRAS sound intensity probe allowing microphone spacings of 25, 50 and 100 mm. The probe was supported by a tripod stand with the base of the microphone situated 1 m behind the microphones. The microphone pre-amps were connected to a signal analyzer (Soundbook by SINUS GmbH). The analyser was located in the lab outside of the anechoic chamber.

Three primary set-ups were used: the plywood subfloor covered with 50 mm cotton fibre baffles; a non-vegetated vegetated roof test plot; and a vegetated roof test plot (**Table 7**). To determine the optimal geometric configurations, and investigate disruptions to the theoretical free-field condition, variations were made to the first two primary set-ups.

The 1.68 m x 1.68 m test plot was constructed in the anechoic chamber, and with two exceptions, constructed of the same materials and details as the rooftop plots. In the anechoic chamber the perimeter frame was wood and the subsurface was plywood on a suspended wire mesh (**Figure 8**).

Table 7 Experimental set-ups in anechoic chamber

Configuration set-up	Objective of investigation
Cotton fibre baffle	Investigate potential compromises to the theoretical free-field condition of the perimeter frame surrounding the test plots and sky lights, parapets, and equipment stands
Non-vegetated plot	Determine the required geometric configuration
Vegetated plot	Determine the impact of the surface properties on the repeatability of the measurements.

The substrate used in the anechoic chamber was from the same batch mix as used in the rooftop test plots. The substrate is a blend of white pumice, sand, 15 % organic matter and a non-significant percentage of proprietary amendments. The substrate was evaluated in previous lab tests; the percent organic matter, percent porosity, particle size distribution, and available water content meet the regional guidelines (BCLNA 2007) and standards and the international guidelines (FLL 2002) for extensive vegetated roof substrates.

Figure 8 Set-up of vegetative vegetated roof test plot with surrounding baffles

In the final of the three primary set-ups in the anechoic chamber, the vegetated roof test plot was planted with *Sedum album* ("Coral Carpet") with aerial biomass coverage of 70%. The sedums were planted for the duration of the measurements only; as such, the root growth was not established (**Figure 8**). The water content approximated at wilting capacity.

Part 2 – Vegetated and non-vegetated test plots

The site for the in-situ measurement is on a 1400 m^2 rooftop. The roof is 14 m above grade and has full sun exposure. The annual precipitation measured at the nearest Environment Canada Station[1] is 1885 mm and the average daily temperature is

[1] Canada Climate Normal Data, Burnaby Mountain Terminal

10.5^{0}C. Allowable load capacity determined the locations and limits of the test areas on the rooftop. The roof slope is 2% and the test areas are free-draining without any residual rainwater pond below the test plots. The rooftop has a weather station which provides temperature, relative humidity, wind direction and speed, rainfall and solar radiation data.

Two 25 m^2 test areas have nine 1.68 m x 1.68 m plots (**Figure 9**). One 25 m^2 test area has seven 1.68 m x 1.68 m plots with substrate only. **Figure 10** illustrates the material layers. **Figures 11** and **12** illustrate the construction. The range of substrate depth in the Pacific Northwest region is most typically from 75 to 150 mm depth. The wider range of 25 to 200 mm depth was selected to confirm the minimum limit of substrate depth for plant viability and to acoustically evaluate the extended range of depths. Each plant species has a minimum substrate depth required for viability, hence the matrix of the substrate depth to plant species is triangulated (**Table 8**). It was not known if the plants would in fact thrive in the shallowest depth allocated, as viability is a function of the site-specific context and seasonal climatic conditions. The goal was to measure the vegetated plots at two levels of coverage, in the fall and the spring. The seven substrate plots were installed for a limited time period (**Figure 13**). See **Table 9** for detailed description of plant communities.

Table 8 Matrix of depths and plant communities

Substrate depth (mm)	Rooftop Test Plots			
25	-	P1	-	-
50	S	P1	-	-
75	S	P1	P2	-
100	S	P1	P2	-
125	S	P1	P2	P3
150	S	P1	P2	P3
175	S	P1	P2	P3
200	S	P1	P2	P3

Experimental plots layout and details

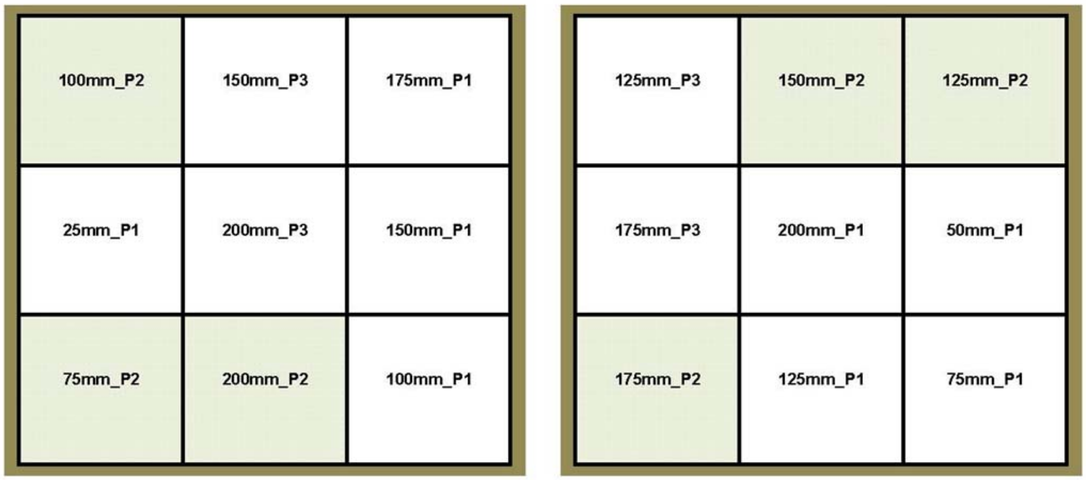

Figure 9 In-situ plot layout

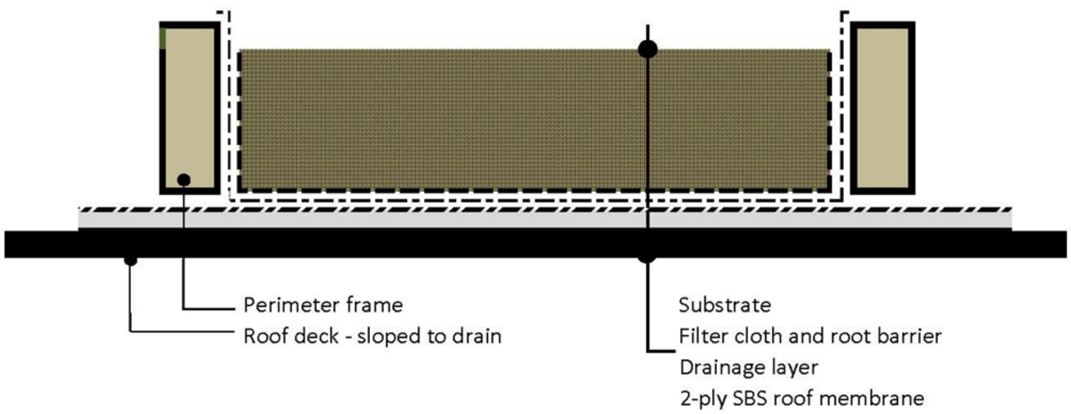

Figure 10 Section detail and material layers

Figure 11 In-situ plots under construction – drainage layer and frame

Figure 12 In-situ plots under construction – filter cloth / root barrier

Figure 13 In-situ plots-substrates measurements, September 2010

Figure 14 In-situ plots – P1 community in foreground, P3 community in mid-ground, September 2010

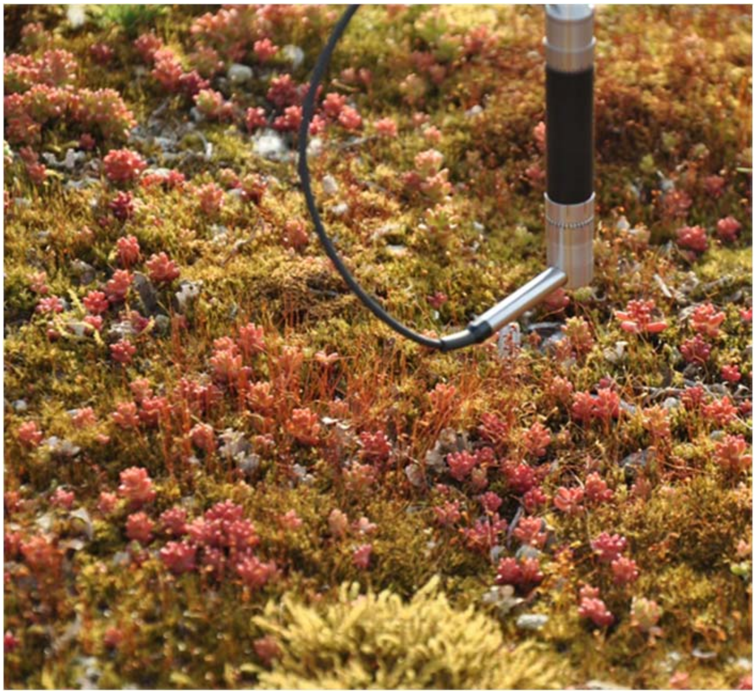

Figure 15 Close-up of microphone probe suspended over P1 community, June 2011

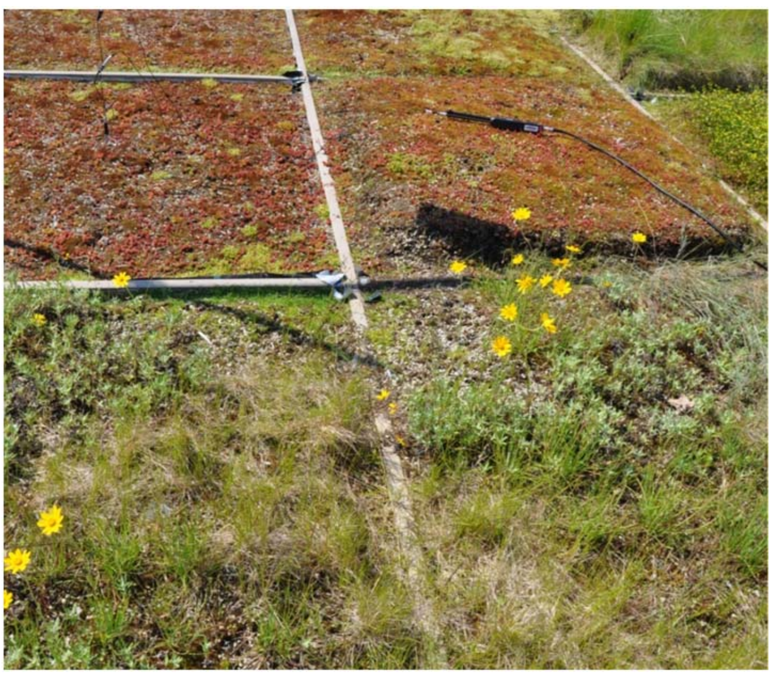

Figure 16 In-situ plots P3 community in foreground, P1 community in mid-ground, June 2011

Plant selection

The plant species were selected based on the diversity of the structural characteristics of aerial biomass (foliage above substrate) and root systems. Three communities have been selected: 1) *Sedum album* 'Coral Carpet'; which has a dense and evenly distributed foliage with an extremely shallow root structure of only a few millimetres depth; 2) a coastal community of plants with structural foliage and deep or massive root systems, including *Eriophyllum lanatum, Allium cernuum, Armeria maritima and Festuca Ruba;* and 3) a mix of cultivated grasses sowed and maintained as required for a playing field. Within the second community, the foliage above and the root system below the substrate surface will not be homogenous across the test plots. The plants were grown in 100 mm (4") pots in the nursery with the same substrate as the test plots rather than in a typical peat-based potting soil, so as to ensure consistency through the substrate parameter (**Table 9**). The test plots were planted in May 2009 with an average of 150 mm spacing on centre plants (**Figures 14-16**).

Plant coverage

The method to determine plant coverage was determined by visual assessment using a 25 square matrix array over each 1.65 m x 1.65 m plot. The percent coverage of total plants, the percent coverage of original planted species and the spontaneous plant coverage were determined. For each matrix, values were assigned on a scale of 1 to 10 where 1 indicates 0 to 10% coverage, 2 indicates 11 to 20% and to 10 indicating 100% coverage. The values assigned are averaged over the 25 square arrays to determine the percent coverage. The total plant coverage is a value which describes the surface of the plots in terms of vegetation relative to exposed substrate inclusive of the original species planted and the spontaneous growth. The spontaneous coverage is a value which describes the surface of the plots in terms of spontaneous plant establishment relative to exposed substrate (Rousseau 2010). The three plant communities selected have significant structural differences in terms of the aerial biomass and root development.

Moisture content of substrate

The plant root structure of the test plots is sufficiently developed such that removal of substrate in order to evaluate the volumetric water content would be destructive to the plots. Nominally, all plots were evaluated at field capacity. The plots were irrigated to full saturation in order to approximate field capacity 36 - 48 hours after water saturation.

Table 9 Description of plant communities in test plots

Code_Short name	Description
P1_Sedums 	Sedum species are favourites for extensive vegetated roofs. *Sedum album* (Common name: Coral Carpet) - groundcover plant, clustered rounded leaves, shallow root structure. This community established as a sedum/moss community. The moss established as 1- 5 mm depth surface coverage and has no root structure.
P2_Coastal Meadow 	This community represents typical plants on shallow coastal vegetation stands in this region. *Eriophyllum lanatum* (Wooly Sunflower) - a perennial herb, grows in branched clumps with yellow flowers. *Allium cernuum* (Nodding Onion) – a perennial herb, stemmed white dropping flower with bulb. *Armeria maritima* (Sea Thrift) – a herbaceous perennial blooms with small pink flowers. *Festuca Ruba* (Red Fescue) leaves are narrow and needle shaped.
P3_Grasses 	Turf grassed roofs are typically mowed short and irrigated in order to develop walking and playing surfaces. Grasses may otherwise be left to develop high aerial biomass and to dry naturally at the end of the vegetation period. *Poa pratensis* (Kentucky Bluegrass) – herbaceous perennial plan, broad blunt leaves at base to create mat, rhizomes roots are *Lolium multiflorum Lam* (Annual Ryegrass) rolled leaves *Lolium perenne L.*(Perennial Ryegrass) flat leaves, bunch-type growth.

3.3 Results from Lab and Field Measurements

Part 1 - Standardizing the spherical decoupling method

Geometric configuration

To investigate the configuration of the equipment set-up, measurements were repeated with dimensional variations to the geometric configuration, specifically: the distance between the two microphones; the distance from the test surface to the closest microphone; and the location of the sound source with respect to angle and distance to the microphone probe. Measurements were completed on baffles on plywood, substrate only, a vegetated roof test plot and a sedum planted vegetated roof test plot. The angle of incidence of the sound source to the microphone probe was normal to the plot surface ($\theta = 0°$).

It was determined that the measurements made with the 25 mm spacer are the least erratic, in terms of the variability of the phase and magnitude of the reflection and the absorption coefficients over the frequency range of interest (250 – 4000 Hz). The geometric configuration using the smallest spacer is less susceptible to the non-physical artefacts of the measurement method (See **Figure B1, Appendix B**).

On the sedum-planted test plot, comparisons of the microphone spacers were repeated at three heights of the reference microphone above the surface (hb): at each height above the surface, the smaller spacer, 25 mm, produced the most consistent results. This is consistent with the results of the measurements on the substrate plot (see **Figure B2, Appendix B**). The use of the 25 mm microphone spacer and the 50 mm microphone spacer provided results for the reflection and absorption coefficients which are in reasonable agreement in the lower frequency range. The agreement suggests that the lower frequency limit is too conservative (at $\theta = 0°$).

The second dimension of the geometric configuration investigated was the height of the reference microphone above the surface (*hb*). The use of the 25 mm microphone spacer and the location of the reference microphone closest to the sedum planted ground surface have produced results that suggest that the smaller height is moderately less susceptible to interference than the larger height.

Perturbation of the free field

To investigate the significance of sound-field perturbations by rooftop architectural apertures, measurements were made in the approximate free-field condition of the anechoic chamber and then repeated with representative perturbations. On the rooftop, known perturbations of the free-field condition included: a perimeter edge constructed of 38 mm x 98 mm plastic wood composite framing the 1.65 m x 1.65 m vegetated roof test; a non-continuous surface with variable conditions outside the frame (absorptive and/or non-absorptive surface); and the possible perturbation of the free-field due to the posts which support the loudspeaker and architectural apertures.

Perimeter frame

In the anechoic chamber the perimeter edge could only be removed and replaced for measurement with the baffle surface (the frame was required to maintain the substrate when the substrate was in the chamber). Measurements were repeated with and without the perimeter edge. A total of 28 measurements were made, $\theta = 0°, 45°$ and $75°$. At $\theta = 0°$ a combination of three base microphone heights and distances between microphones was used. The perimeter frame does not interfere with the planar wave reflecting from the sound source at $\theta = 0°$.

Surrounding surface conditions

The conditions of the surface surrounding each roof test plot are different. Depending on the location of the plot in the test area, the surrounding surface conditions are different and there may be 2, 3, or 4 adjacent plots, and/or the highly reflective roof membrane. In the anechoic chamber the baffles were laid on the plywood subfloor to simulate the various surface conditions beyond the perimeter frame. A total of 16 measurements were made over $\theta = 0°, 15°, 30°, 45°, 60°$ and $75°$ with the baffles surrounding the plot, surrounding half the plot, and without baffles on the surrounding plywood subfloor. Findings indicated that there was no interference by the highly reflective surfaces surrounding the test plot when the sound energy from the source loudspeaker is incident at normal incidence to the surface, on axis with the two microphones, i.e. $\theta = 0°$. As the angle of incidence increases, the agreement in the measurements between the three surface conditions decreases (See **Figure B3, Appendix B)**.

Architectural apertures

On the rooftop, architectural apertures exist in the form of skylight upstands, (sheathed with roofing membrane) within 1.5 m of the constructed vegetated roof test plots. Additionally, the suspension of the sound source directly above the vegetated roof test plots requires base supported posts. The anechoic chamber represents an ideal free-field environment; introducing randomly placed blocks and panels approximating the potential perturbations of the free field on the rooftop site. Measurements were taken with and without the blocks and panels.

A total of 12 measurements were made over $\theta = 0°, 15°, 30°, 45°, 60°$ and $75°$ with the geometry constant and the free field non-perturbed or perturbed. At the same location ($\theta = 0°$), the results show the impact of the perturbed field. This is especially evident at frequencies below 1000 Hz (See **Figure B4, Appendix B**). This has a potentially significant impact on the in-situ rooftop measurements. In the field, it will not be possible to remove the apertures; however, it may be possible to diminish the impact by facing the upstands and the loudspeaker stand with highly sound-absorptive materials.

Repeatability of the measurements

Standards recommend averaging four repeated measurements to accommodate the variations in natural ground (ANSIS1.18 1999). At the location of wave reflection for each measurement the vegetated roof may have diverse surface properties, variations in foliage (biomass and root structure) and substrate condition (exposed constituents). Measurements were taken at ten different locations on the substrate test plot at a fixed geometric configuration to determine the minimum number of repetitions required.

Standardization of method of measurement

The geometric configuration which was derived from the investigation in the anechoic chamber involved the following: placing the loudspeaker 175 cm above and normal to the surface, placing the probe directly below the loudspeaker, setting the height of the closest microphone above the surface (*hb*) equal to 55 mm, and using the 25 mm microphones spacing (see **Figure 17**). In order to meet recommended standards the minimum number of measurement repetitions of four has been adopted.

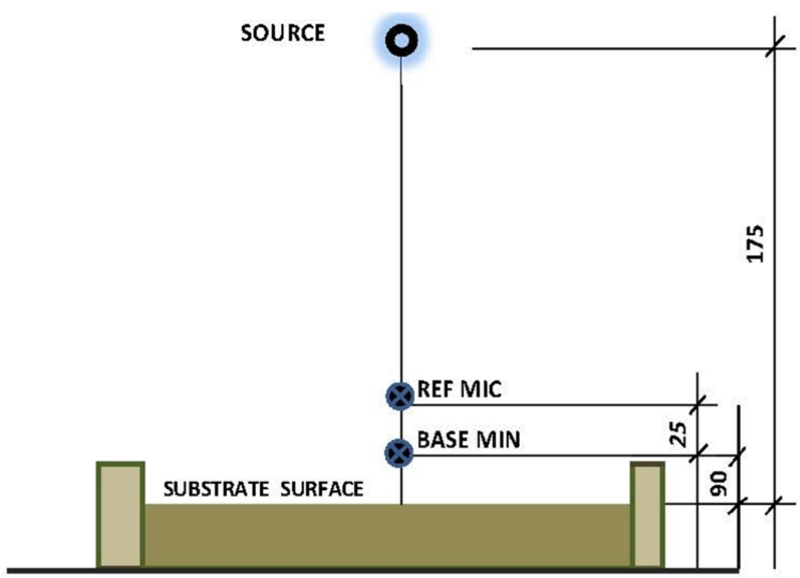

Figure 17 Standardized geometric configuration of spherical decoupling method for rooftop test plots

Part 2 - Measurment of experimental test plots

Measurements were completed on seven substrate plots and 17 of the 18 planted rooftop test plots over the course of two seasons. Measurements were completed within a time span of 36 to 48 hours after complete saturation to represent field capacity. Air temperature at time of testing ranged between 15°C and 23°C. A minimum of four measurements were made on each plot using the geometric configuration developed in Part 1 investigation. A necessary deviation from the geometric configuration was the height of the base microphone over the substrate surface, which was typically more than 90 mm owing to the high plant foliage.

The diffuse field absorption coefficient of the substrates increased with frequency from 200 to 1250 Hz and remained stable to 5000 Hz. The diffuse-field absorption coefficient of the substrates tended to increase with depth (**Figure 18**). The noise reduction coefficient (NRC) is used to describe the average of the octave-band diffuse-field absorption coefficients from 250 to 2000 Hz. The mean NRC was 0.62 for depths from 50 to 200 mm (**Table 10**). The highest absorption in these measures was not associated with the greatest depth. There was no association between the gravimetric water content and the NRC of the substrates.

The absorption of the substrate plots, without planting, is significantly greater than that of the exposed roof membrane. At 1000 Hz, the mean absorption coefficient of the substrates was 0.58 higher than that of the roof membrane. The mean NRCs of the substrate plots and the roof are 0.62 and 0.06, respectively.

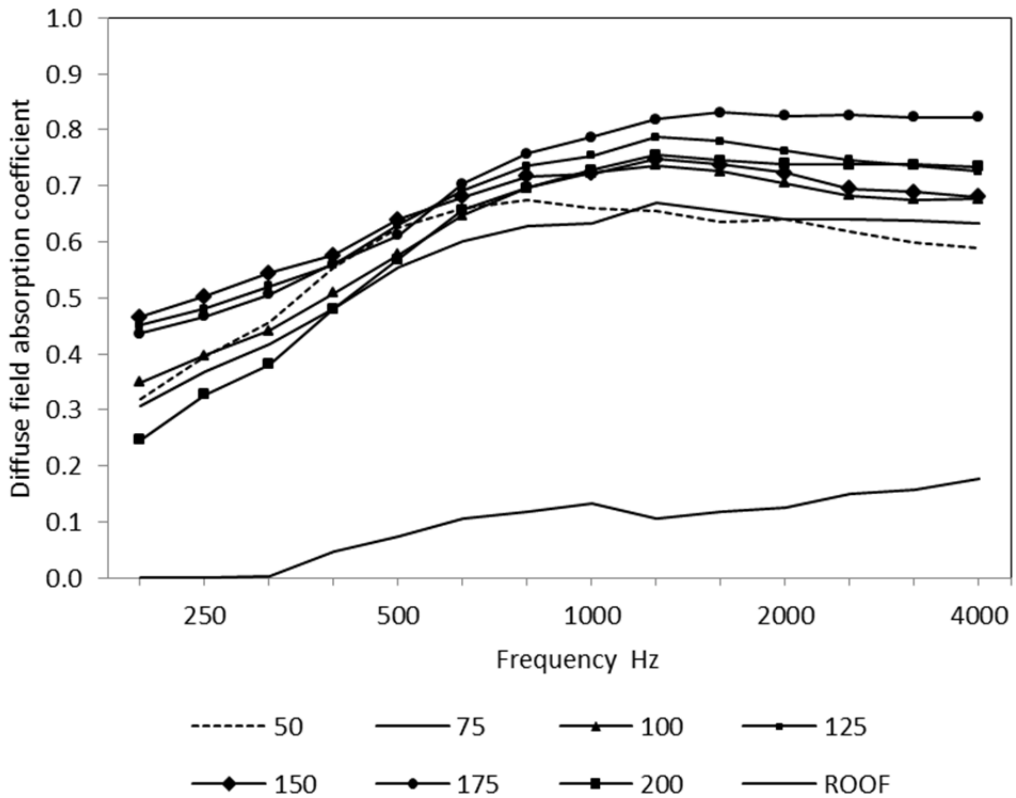

Figure 18 Absorption of substrates – 50 to 200 mm depths

Table 10 NRC of substrates – 50 to 200 mm depths

Date	Depth (mm)	GWC	NRC
5-Sep	50	48	0.57
	75	53	0.56
	100	46	0.61
	125	50	0.67
	150	49	0.65
	175	49	0.70
	200	52	0.61

The P1 plots, planted with *Sedum album,* were colonized with mosses over the time frame of the plant establishment period. The total plant coverage in the plots was distributed between the planted species of sedums and the spontaneous establishment of mosses. The plot with a 25 mm depth of substrate was not considered sufficiently viable in terms of plant coverage to evaluate. The mosses accounted for 37 to 80% of total coverage (**Table 11**). The trend of increased absorption relative to depth, which was observed in the non-planted plots, was not observed in the plots with the established P1 community (**Figure 19**). A bivariate analysis shows no association between depth and NRC. However, there was a negative trend between the percentage of spontaneous coverage and the NRC with the range of plots from 50 to 200 mm.

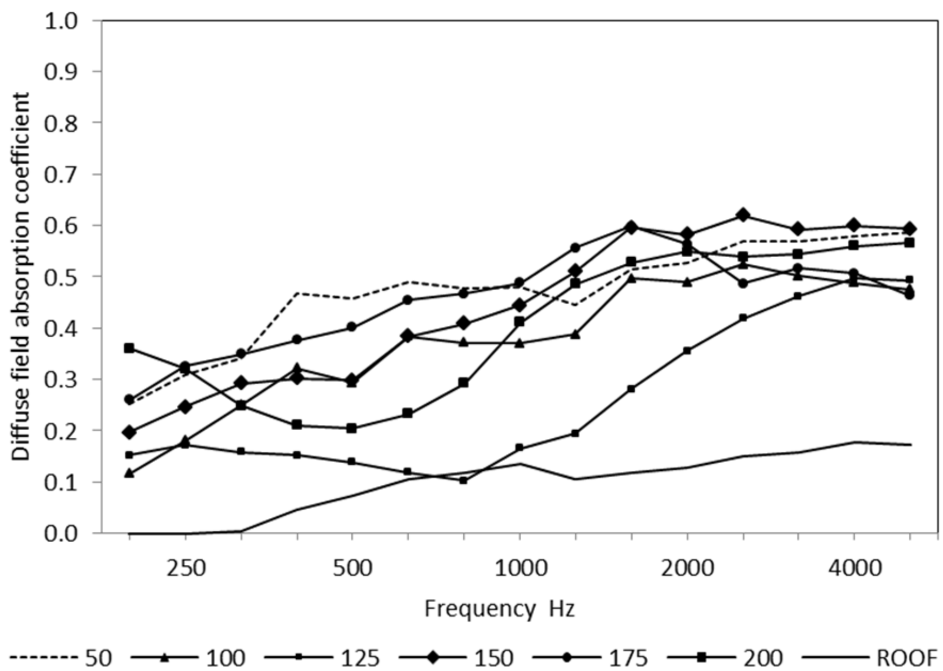

Figure 19 Absorption of test plots planted with sedums (P1)

Table 11 NRC of test plots planted with sedums (P1)

Date	Plant Species	Depth (mm)	Coverage (%) Total	Coverage (%) Spontaneous[1]	NRC
29-Sep	P1	50	52.6	25.4	0.46
		75	54.2	25.4	-
		100	72.6	27	0.37
		125	56.6	45.4	0.24
		150	82.6	31.8	0.44
		175	75.4	35.4	0.43
		200	43	13.4	0.39

Overall, the absorption of the plots planted with community P1 was lower relative to the absorption of the substrate plots. The trend over the frequency range was similar for both; however, the mean difference in the absorption coefficient ranged from 0.14 at 200 Hz to 0.35 at 800 Hz in the 1/3 octave band analysis. The mean NRC decreased by 0.24 (**Figure 20, Table 12**).

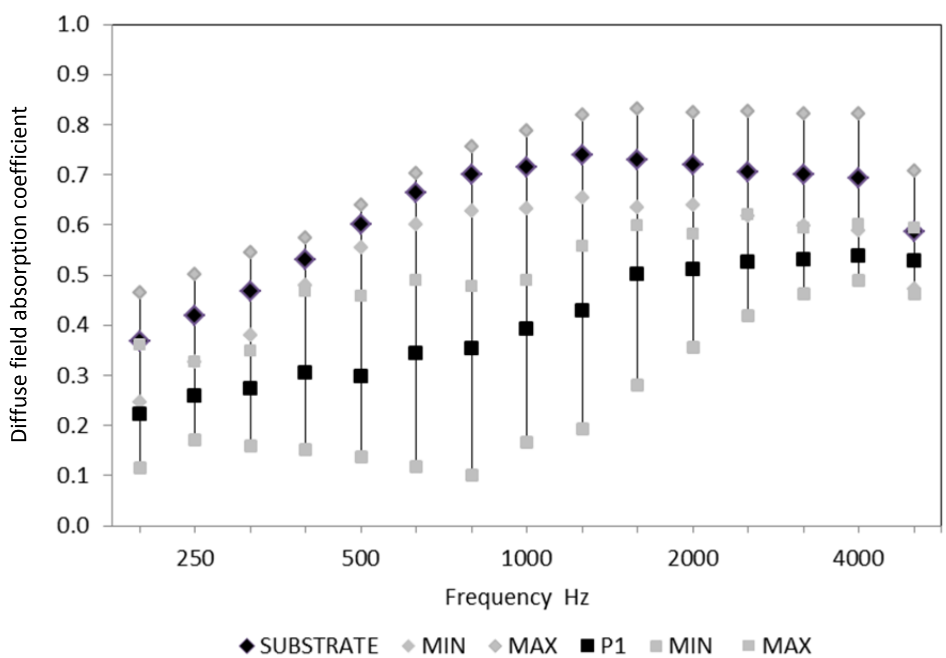

Figure 20 NRC of substrate and sedums (P1)

Table 12 Difference in mean value between substrate and sedums (P1)

Frequency (Hz)	Mean Difference	Frequency (Hz)	Mean Difference
200	0.14		
250	0.16	1250	0.31
315	0.19	1600	0.23
400	0.23	2000	0.21
500	0.3	2500	0.18
630	0.32	3150	0.17
800	0.35	4000	0.16
1000	0.32	5000	0.16

The P3 plots were investigated in a comparison between two seasons (**Figure 21**). In November 2010, the plants were established with a total coverage of 95%, spontaneous coverage of 4%, and in substrate depths from 125 to 200 mm. By July 2011, the biodiversity had altered considerably. The total coverage had decreased non-significantly and the grasses were predominately dormant; however, the spontaneous plant growth had increased to 42%. The plots were saturated 36-48 hours before evaluation; however, it is reasonable to assume that there was greater evapotranspiration in July when the maximum daily temperature before acoustical evaluation was 27 °C, versus 16° C in November. The variability in plant coverage and the climatic difference affected the absorption in all lower frequency ranges; above 500 Hz a greater impact on absorption is observed.

After two years of plant establishment, the measurements of the absorption coefficients of the plant communities suggest a relationship between the plant community and sound absorption. However, because these absorption coefficients were averaged from measurements of plots ranging in depth (125 to 200 mm), and the absorption coefficients overlapped between communities, this does not allow for a conclusive differentiation in the sound absorption effect of the three communities (**Figure 22**). The total plant coverage, initial species plant coverage and spontaneous plant coverage are detailed in Appendix E.

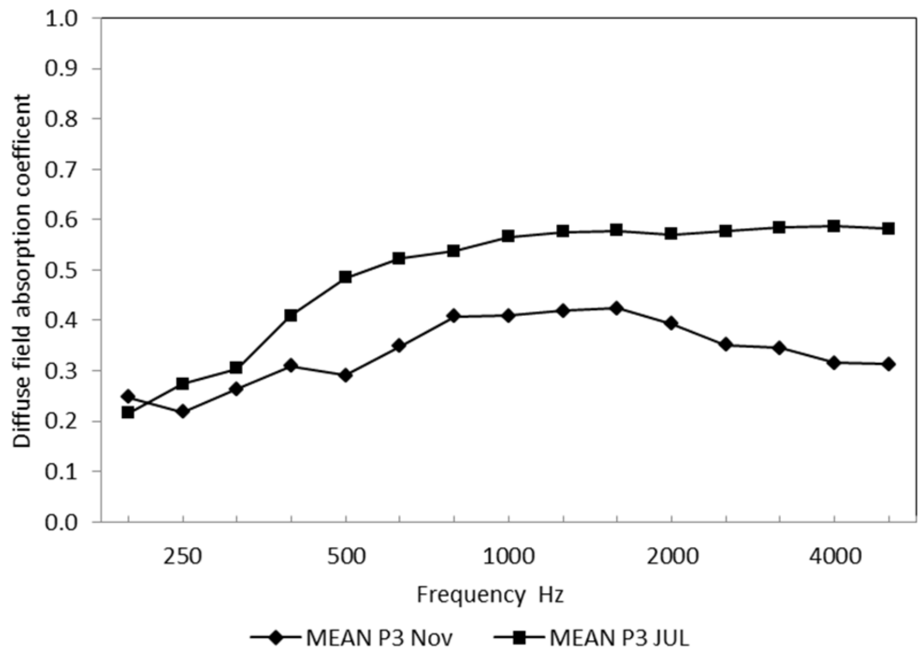

Figure 21 Absorption of P3 community (depth 125 to 200 mm) in fall and summer seasons.

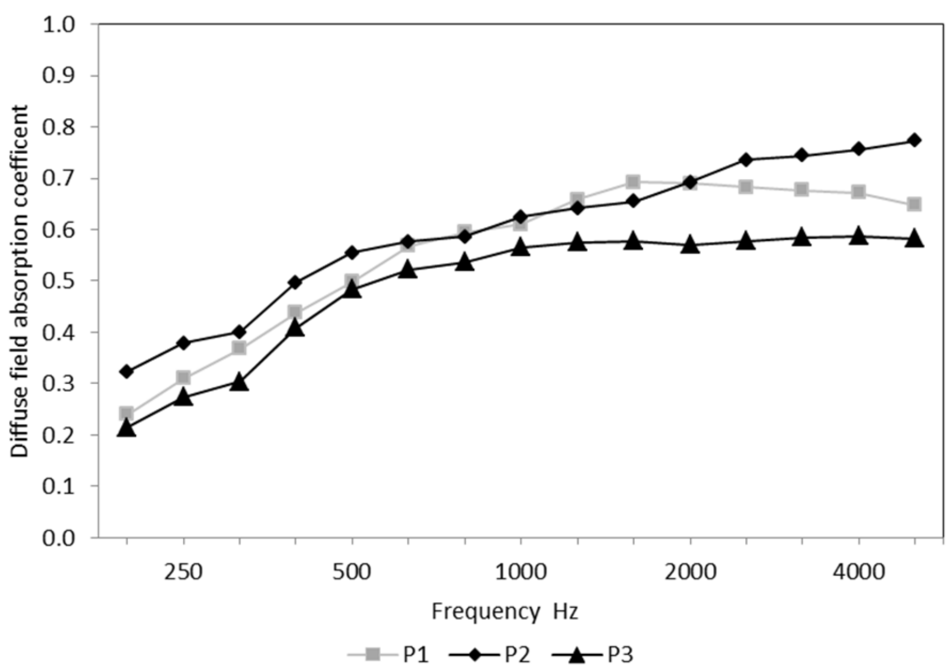

Figure 22 NRC of three plant communities (depth 125 to 200 mm) after two seasons of establishment

3.4 Discussion

The spherical decoupling technique is viable to evaluate the absorption capacity of vegetated roofs in the architectural range from 200 to 5000 Hz. In the controlled environment of an anechoic chamber, the most optimal geometric configuration of the spherical decoupling set-up for the measurement of vegetated roofs was determined to be achieved when the distances of the base microphone above the surface plane and between the two microphones were minimized.

Absorption of the sedum-planted test plot in the anechoic chamber, as quantified by the NRC, was 0.63. The in-situ plot, of the same depth, planted with the P1 community, was 0.37. The results are not directly comparable as the surface properties of the test plots varied considerably. In addition to variation in plant species coverage and establishment, the significant differences between the two plots included the level of compaction, the level of moisture content, and the surface level particle size distribution. In the anechoic chamber, the plot was planted with an even distribution of 4 inch pots. On the rooftop, the coverage was not evenly distributed; the plant viability and mortality varied as the plot established over time. These findings suggest that short-term experimental set-ups and controlled lab conditions, which do not accurately represent in-situ rooftop properties of a vegetated roof, may exaggerate the absorption potential of the vegetated plots. The method developed for this dissertation addresses the lack of the generalizability of experimental set-ups with simulated plantings in controlled environments.

In the sedum/moss community, the range of the NRC was 0.21 across the substrate depths from 50 to 200 mm. In the coastal meadow community, the range of the NRC across substrate depths of 125 to 200 mm was 0.60, as measured in the fall, and 0.13 as measured in the summer. In the grass community, the range of the NRC was 0.12 across the depths from 125 to 200 mm in both seasons. The lowest absorption (NRC 0.20), was measured on the coastal meadow community planted in a 200 mm substrate depth. This measurement took place in the late fall in conditions of cool temperatures and high levels of moisture in the plants and substrate. The same community in 100 mm substrate depth had the highest absorption measured (NRC 0.62), and was measured in summer climatic conditions.

The trend of increasing absorption with increasing depth was observed in the measurements of non-vegetated substrates; however, there is not sufficient evidence to suggest that absorption is a function of the depth of substrate in vegetated substrates. The results aligns with previous findings on grounds which indicate that depth up to 90 mm affects absorption, after which additional depth can be neglected.

The trend of absorption values, across the substrate depth and plant communities, illustrates that the addition of vegetation decreases absorption as compared to the substrate-only plots. The structure of the mosses, such as in community P1, provides a high retention of water at the surface and maintains moisture content in the substrate (Rixen 2005). The coastal meadow community is composed of high plants which have significant root mass for water uptake from the substrate and store the water content within the aerial foliage. Additionally, the aerial foliage provides shading to the substrate and modifies the temperature and moisture content. The measurement results support findings which indicate that plant density, leaf area of canopy and root structure affect the porosity and sound absorption of grounds. The measurements of the in-situ plots indicate that absorption is a function of plant coverage and establishment and also of moisture content in the plants and substrate.

In this study, the two-dimensional method of determining plant coverage neglected plant foliage superposition and the health and height of the plants, and was not included in the data collection. Additional modification for future testing should include additional plant evaluations and embedded soil moisture probes to precisely identify the volumetric water content. It must also be noted that the compromise on the rooftop to the theoretical free-field condition due to architectural apertures, and the post required to support the loudspeakers were not mitigated and caused non-physical measurement results at low frequencies. Although the unperturbed and perturbed data from measurement in the anechoic chamber were compared in 1/3-octave band analysis and showed good agreement, it is not possible to confirm the actual effect of the apertures on the rooftop measurements.

The in-situ rooftop plots were identically constructed with materials in a manner common to this region, thus providing the opportunity to evaluate representative substrate and roof top plant communities as they establish naturally over time in the harsh rooftop field environment. The evaluation over a gradient of substrate depths and plant establishment with diverse communities provided an opportunity to identify the interfacing acoustically relevant sound absorption characteristics of vegetated roofs.

The measurements compiled in this research validate vegetated roofs as a building envelope system with highly absorptive characteristics and qualify the conditions which optimize the absorption potential of vegetated roofs. The acoustical properties of all architectural surfaces on a rooftop will affect the acoustical quality of the spaces designed for occupancy. The use of vegetated roofs as absorptive surfaces to reduce noise build up and reverberation in rooftop spaces formally defined with wall enclosures can now be investigated with accurate absorption data. Absorption and reflection are significant acoustical properties of building surfaces affecting outdoor sound propagation. As Eco-density initiatives are increasing, so will the utilization of the rooftop for amenity spaces. These findings will contribute to current research on excess attenuation of sound propagation attributed to vegetated roofs in urban communities and support an initiation of research on the use of vegetated roofs as a noise source control for rooftop mechanical equipment.

3.5 Chapter Summary

The research presented in this chapter consisted of two consecutive research programs. The first part investigated a known method of evaluating the acoustical characteristics of grounds. The objective was to adopt and standardize the method, the spherical decoupling technique, to evaluate the sound absorption of vegetated roofs. The second part utilized the standardized method and evaluated the diffuse absorption coefficient of vegetated roofs. 25 rooftop test plots were constructed, and three plant communities selected for their structural differences; aerial biomass and root systems, were established in the test plots with a range of substrate depths from 25 to 200 mm.

In an anechoic chamber, the spherical decoupling technique was determined to be a viable method to evaluate the absorption capacity of vegetated roofs in the architectural range from 200 to 5000 Hz; an optimized geometric configuration of the experimental set-up was determined for use on rooftops. The measurement of the diffuse absorption coefficient of seven plots (substrate only, without plants) determined that the absorption increased with increased gradient of substrate depth. However, measurements also confirmed that with the addition of vegetation, and with an increase in plant establishment, the absorption decreased. The absorption of sound energy of seventeen established vegetated roofs plots, planted with three distinct plant communities in a gradient of substrate depth, varied from 20% to 63% when evaluated in different climatic conditions. It was confirmed that the absorption of vegetated roofs is not a function of a single variable of substrate depth or plant community. Through measurement and trend analysis, the complexities of vegetation structure and the mechanics of plant foliage and roots affecting the moisture content of the substrate were identified.

Previously unmeasured, the reported data on the sound absorption of vegetated roofs can now be utilized to investigate the propagation of sound over rooftops and the noise build-up and reverberation effects of installing vegetated roofs in rooftop spaces designed with wall enclosures for wind protection and safety. The same vegetated roof material layers (including substrate blend), gradient of substrate depth and plant communities were utilized in the research infrastructure presented in the following chapter, commissioned to investigate sound transmission through vegetated roofs.

CHAPTER 4 Sound Transmission of Vegetated Roofs

4.1 Introduction

As a building envelope, a vegetated roof is a constructed boundary between the natural exterior and indoor environments. The focus of sound transmission research on building envelopes most commonly emphasizes the transmission of air-borne noise from the urban environment through building envelopes into the habitable areas of buildings. The benefits of vegetated roofs may be the most significant to habitable spaces in urban development below aircraft flight paths, and in the geographical context of urban slopes where the roof planes are at elevations below transit corridors. Concerns regarding noise generated in industrial or infrastructure facilities transmitting sound to the outside are less frequently considered. When excessive noise is generated within a building, for example, from a district water pumping station, a vegetated roof may provide a community benefit through the reduction of excessive noise. The greatest benefits will likely be recognized in the case of lightweight roof assemblies, and/or open plenum ceilings used in multi-family residential, industrial, commercial and institutional development.

The first section of this chapter presents the aspects of sound transmission theory that apply to vegetated roof systems, and identifies through a literature review, the existing knowledge base to support the research direction. The following section reviews existing empirical data and experimental approaches used to evaluate transmission loss. Next, the development of a method for controlled indoor-to-outdoor evaluation of the sound transmission loss through vegetated roofs is presented. The final sections present results from measurements of field and field-lab roofs, vegetated and non-vegetated reference roofs, and conclude with discussion.

4.2 Theory of Sound Transmission

Single-material panels and complex building envelopes, such as vegetated roofs, introduce large changes of acoustic impedance into the transmission path of propagating sound. Transmission is defined as the acoustical energy passing through a material and is dependent on the surface reflection and the dissipating process of absorption. The vegetated roof, as a series of finite planes, impedes sound energy as it transmits through each layer of the system. The various layers of a partition are either solid media, such as the vegetated roof structure, deck, protection board, membrane, or porous media - for example, the insulation, water retention mat and vegetated substrate. The air outside and the air inside the building are fluid media. The sources of dissipation of acoustical energy through a vegetated roof may be due to losses in the layers at the boundaries of each medium. It has been a hypothesis of this research that losses in the layer of the vegetated substrate will have a significant impact on transmission.

The transmission loss of vegetated roofs may be modeled as a single-layer panel or a multi-layer partition. The roof deck and materials can be, as a first approximation, considered a single massive element; in acoustical terms, multi-layer components which are bonded together permanently across their entire surface form one solid layer. Assuming a non-vegetative roof is a single-layer panel, the addition of the vegetated roof material layers and the vegetated substrate is considered an increase in mass.

Mass law

The fundamental principle of single panel transmission loss theory is that sound energy incident on a solid panel imparts movement to the panel and precipitates the transmission of wave motion, of decreased intensity, into the fluid medium of air on the opposite side of the panel. The relationship between the incident intensity and the transmitted intensity is expressed as the transmission coefficient, a measure of how much sound energy is reduced in transmission through materials. In decibel terms transmission loss is expressed as a function of the characteristic impedance of air, panel mass and frequency. At any given frequency, in the practical range of architectural acoustics, the characteristic impedance of material panels is large relative to air and the transmission loss depends mainly on mass per unit area (Long 2006).

$$TL = 20\log\frac{\pi}{\rho_0 c_0} + 20\log m_s f$$

Equation 14

Equation 14 defines the fundamental mass law at normal incidence. Mass law predicts that transmission loss increases by 6 dB with each octave increase in frequency and 6 dB with each doubling of the mass. The idealised diffuse field model is assumed when plane waves are incident from all directions with equal probability and with random phase, for example, in a room. A field-incidence transmission loss is equated as 5 dB less than at normal incidence (Equation 15):

$$\Delta L_{TL} = 20\log(m_s f) - K_{TL}$$ **Equation 15**

where, K_{TL} = 47 dB in metric calculations.

A roof acting as a single panel is large in size compared to acoustic wave-lengths in the frequency range of interest. The relative size facilitates the panel’s reaction to an applied pressure not only as a limp mass, but also as a plate, which can bend or shear. Thin panels are easier to bend than shear and, as such, bending stiffness is the predominant impedance at high frequencies above the coincidence frequency. Defining the roof plane as a plate permits the thin panel theory to be investigated.

Transmission loss is frequency-dependent; the frequency ranges in which the mechanisms of inertial mass, bending stiffness, or shear impedance predominate are defined around a critical frequency attributed to a phenomenon called the coincidence effect. Coincidence occurs when the velocity of airborne sound waves is equal to the velocity of the bending wave in the plate, resulting in a reduction in transmission loss at and above the corresponding wave frequency. Theoretically, the transmission loss is null; however in reality, due to internal damping the transmission loss is not null, but is significantly reduced.

Mass impedance predominates at frequencies below the coincidence frequency and the fundamental mass law relationship applies (Equation 16). Above the coincidence frequency, the diffuse field transmission loss can be written as an inertial term of mass law with a damping coefficient. The damping term is 20logη, where η is a damping coefficient < 1.0 (Long 2006).

$$\Delta L_{TL} \cong 20\log\left(\frac{\omega_c m_s}{2\rho_0 c_o}\right) + 10\log\left\{\frac{2\eta}{\pi}\left(\frac{f}{f_c}-1\right)\right\}$$ **Equation 16**

Thin panels are easier to bend than shear, and as such, bending stiffness is the predominant impedance at high frequencies above the region of coincidence. The slope of the transmission loss curve relative to frequency above the coincidence frequency is 9 dB per octave increase, in principle.

In thin panels, the resulting plate impedance is a combination of the mass impedance and the bending impedance. In thicker panels, high frequency wavelengths can develop as propagating shear waves. If the panel is thicker than the bending wavelength, then the shear wave dominates as the composite impedance. The relative value of the shear frequency to the critical frequency determines the predominant impedance (Long 2006).

Literature review - empirical findings

A general trend of increased transmission loss with frequency, and the elimination of the coincidence effect, have been found with the addition of materials in built-up roofing. A literature review of transmission loss values measured on roofing (up to 32.6 kg/m^2 mass per unit area) indicates that mass law may predict higher values and a frequency slope less than measured (Alexander 1980). In the context of overhead aircraft noise, adding ceiling treatments (mass, resilient channels and absorptive insulation) to current light-weight roof systems eliminates the coincidence effect and increases transmission loss significantly at mid and high frequencies (Long 2006, Bradley 2002). With respect to slope, nominally flat roofs have a higher transmission loss than a 27° sloped roof constructed of the same materials (Cook 1979). In terms of natural materials, two findings of relevance were identified. The first is a comparative finding on transmission loss of insulation materials applied as additional surface layers on steel deck roofs. Cork overburden provides significant additional sound isolation in the low frequency range and eliminates the coincidence effect. The overburden and other insulation materials exhibited a similar trend - a generally flat curve from 125 to 315 or 400 Hz, and material dependent transmission loss curves with slopes varying from 18 to 30 dB per octave band (Friberg 1973). The second finding illustrates an increase in transmission loss at low and mid frequencies with a pebble overburden (Bradley 2002). The latter configuration is not unlike a low-organic extensive vegetated roof substrate without plant establishment. Two limited studies of pre-cultivated sedum mats suggest, but do not quantify, that the moisture content of the water retention layer, in the vegetated roof system, is the most significant physical property that affects the acoustical characteristics of the pre-cultivated mats. The studies found the sedum mat provided approximately 10 dB increase in sound isolation at low frequency, with the sound isolation increasing with frequency (Gerhart 1992, Ouis 2004).

With the goal of increasing the transmission loss of building envelopes, novel experimental approaches to the problem of designing roof/ceiling assemblies were undertaken in the 1970's because of the global increase in aircraft noise. The acoustic design objective was to increase mass through the addition of discrete masses to flexible panels in such a way that the stiffness of the panel was not substantially increased. Although the addition of any material, in any form, would increase the stiffness of the panel at some frequencies, the objective was to arrange for the increase in stiffness to occur at frequencies greater than the critical frequency.

The concept of a massive flexible ceiling in the floor/ceiling system was presented, "sand is an almost perfect material for sound-attenuating structures, embodying all the most desirable features—high mass, low stiffness and high damping" (Sharp 1973). However, the acoustical solution was limited without an architectural solution to hold the sand in place. This concept is an inversion of the material layers of vegetated roofs. As an alternative, the installation of a flexible base panel attached to the underside of the ceiling joist, and the addition of ¼ to ½ inch of sand plugging were investigated. The transmission loss prediction model was composed of the fundamental mass law term with an additional term for frequencies above 125 Hz, which generated a transmission loss slope of 18 dB/octave. This work occurred at the same time as the emergence of new European technologies for vegetative roof systems; however, the use of vegetated roofs as a design resolution to the acoustical proposal did not transpire.

Findings indicate that soil texture affects the attenuation of sound propagating through ground soils (O'Brien 1996). Through the investigation of outdoor sound propagation over ground, the plant root soil interface has been identified as affecting the normal specific impedance (van der Heijeden 1983). Chapters II and III of this thesis reviewed literature on the relationship between the physical properties and acoustical characteristics of soils, including particle size distribution, bulk density and porosity, flow resistivity and characteristic particle-dimension. The soil conditions of moisture and compaction are variables affecting the acoustic characteristics of impedance, sound absorption and propagation speed (Delany 1970, Attenborough 1982, Vasina 2006).

The literature review of empirical findings on the transmission loss of roofs highlights three key concepts supporting the use of vegetated roofs as acoustical barriers. First, the use of additional materials to mass-load and add damping to the roof can virtually eliminate the coincidence effect and increase transmission loss at low frequencies. Second, in the absence of vegetated roof technology, increased transmission loss was achieved by the addition of a ceiling. However, this addition to the roof assembly increased transmission loss only in the mid and high frequency ranges, not in the low frequency range of potentially disturbing noise from aircraft and where transmission loss is lowest. Third, the pre-cultivated mats provided evidence that moisture content is a physical property that affects the acoustical characteristics of pre-cultivated vegetated roof systems.

The empirical findings identified in the literature review lend support to the investigation of how added mass and low stiffness resulting from the addition of the material components of extensive vegetated roof systems above the membrane can improve the low and high frequency transmission loss of lightweight roof systems.

4.3 Methodologies

The vast majority of both laboratory testing methods and in-situ field testing methods of transmission loss are focused on interior walls and floors, exterior building facades and facade elements. There are no standardized test methods which have been developed specifically for the measurement of sound transmission through roofs. ATSM and ISO standards define several measurement procedures for evaluating the transmission loss using sound suites - a pair of reverberation rooms separated by a partition with an opening in which the test sample is mounted. The testing methods standardize a diffuse sound field generated in one reverberation room and the measurement of sound transmission through the test panel into the second reverberation room. Sound transmission suites provide a high level of control for evaluating the transmission loss of single-layer and multi-layer partition wall and floor/ceiling systems under laboratory conditions.

Existing research infrastructure at the Green Roof Research Facility (GRRF) provided an opportunity to evaluate a non-vegetated reference roof and established vegetated roofs with known system variables. A reverse testing method incorporating an indoor to outdoor procedure of propagating sound from an interior diffuse field to an exterior free field was adopted (Mulholland 1978, ISO 15186-2). The method uses an intensity approach to evaluate the transmitted acoustic intensity radiated by the element under test while the incident intensity is deduced from the average sound pressure level in the source room. Sound transmission loss is calculated as:

$$TL = \left[L_{p1} - 6 + 10\log\left(\frac{S}{S_0}\right)\right] - \left[\overline{L}_{In} + 10\log\left(\frac{S_M}{S_0}\right)\right] \qquad \textbf{Equation 17}$$

The estimated precision of the intensity method (ISO 15186-2) is derived as an average overestimation with respect to the ISO 140-3 sound pressure level test method. The precision varies with frequency. For the frequency ranges 125-400 Hz, 500-1600 Hz and 2000-3150 Hz, the average over estimation is 1.0, 0.5, 1.0 dB and the standard deviation is 1.5, 1.5 and 2, respectively.

The sound transmission losses of vegetated roofs and non-vegetated reference roofs were measured at two sites. At an existing field research facility, there are two established vegetated roofs and an associated non-vegetated reference roof (33 m^2). At the same site, nine roofing evaluation modules - eight were vegetated and one was an associated non-vegetated reference - were measured. At a second site, in an indoor-to-outdoor sound transmission suite, which was designed and commissioned for this dissertation, measurements were made over a gradient of substrate depth, and on two plant communities.

Field testing (GRRF)

An existing research facility has three research roofs originally commissioned in 2003 for the evaluation of storm water runoff characteristics and the thermal performance of vegetated roofs (Connelly 2005) (**Figure 23**). Each 4.8 m x 6.8 m roof is structurally independent of the adjacent roofs and constructed in dimensional lumber (38 x 286 mm joist on 400 mm spacing, nominal 2 x12" joist on 16" spacing). The structure was overdesigned for the existing load to allow for future increase in substrate depth. The roof deck is a composite of two layers of plywood and furring in order to construct the deck slope with the consistent thickness of insulation for thermal performance research. One roof is a conventional two-ply SBS roof system which acts as a reference roof, the other two roofs (GR1 and GR2) have the same roof system to the top of the membrane as the reference roof, plus identical vegetated roof components, differing only by the depth of substrate. GR1 has 75 mm and GR2 has 150 mm of substrate (**Figure 24**). At the time of measurements, the coverage provided by the sedum plant community was 55% and 63% for GR1 and GR2, respectively. Potential sound flanking paths through roof drains, which lead to internal meters, and the roof jack conduits, containing the thermal performance and weather station wiring, were eliminated with sand filled bags and 12 mm steel plates. There is no additional ceiling in the research facility.

An array of five loudspeakers was used in the GRRF interior to create a diffuse sound field (**Figure 25**). The average sound pressure level was 93 dB generated in each 1/3 octave band. For calculation of the transmission loss, the space-averaged sound pressure was measured below each of the three roofs. The radiating intensity was measured at twelve discrete points on each of the three roofs.

A number of challenges existed in the execution of the testing. Rainfall, wind turbulence and background levels of urban noise were disruptive to the acoustical evaluation; therefore, measurements could only occur when climatic conditions were favourable, and after 11:00 PM when traffic noise had abated. The virtual measurement surface, where the closest microphone of the intensity probe is located to the surface being measured, is required to be within a specified distance of the radiating surface; however, the plant heights were not consistent with this for all test specimens. The plant foliage was often higher than the virtual surface preventing a continuous sweeping of the probe; therefore, an averaged discrete point method was use for the positioning of the probe.

Figure 23 Field test facility (GRRF)

Figure 24 Field test facility, non-vegetated roof and two vegetated roofs

Figure 25 Interior of field test facility

Figure 26 Roofing evaluation modules (REM)

Roofing evaluation modules (REM)

The REMs were originally commissioned in 2006 to obtain stormwater and thermal performance data on specific vegetated roof systems (**Figure 26**). The REMs provided opportunities to evaluate eight different vegetated roof systems compared to a reference and to investigate trends which may relate to the variability of material layers, substrate depths and plant species. The REMs also provide an opportunity to investigate small sample testing. The 4 m^2 roof deck is supported on 38 x 184 mm joist, 400 mm spacing (nominal 2” x 8”, 16” spacing). The interior volumes (3.5 m^3) of the REMs are small compared to the low frequency wavelengths generated. One of the REMs had a vegetated roof system with material layers comparable to GR2.

The structural design and construction details of the short spans of the GRRF and REMs roofs were designed specifically to accommodate substantially greater depths of substrates, and the roof decks were detailed with additional framing to accommodate specification for research on the storm water and thermal performance of vegetated roofs. The resulting roof panel is assumed to be atypically stiff for wood frame construction.

Purpose-built field-laboratory

A purpose-built indoor-to-outdoor sound transmission field laboratory was designed and commissioned for the measurement of the transmission loss of vegetated roofs with a gradient of substrate depths and different plant communities. In order to represent standard light-weight roof construction, the interchangeable roof test panels (3.56 m x 4.46 m) were designed to the practical dimensions and spans of roofing materials, decking and steel joists (**Figure 27**). The interior dimension ratio of 1:1.26:1.59 was adopted for an ideal diffuse sound field above 125 Hz (ASTM E90-2004) (**Figure 28**). The lowest frequency band in which standing waves will not compromise the diffuse field was predicted based on the Schroeder equation to be 315 Hz (Schroeder 1969) and based on the Slingerland equation to be 125 Hz (Ramakrishnan 2008).

In order to meet the goal of generating an idealized diffuse sound field and testing dimensionally representative roof test panels, a number of realistic determinants needed to be addressed; the maximum size and site location were determined by financial restraints and logistical restraints associated with BCIT and City of Burnaby approvals and permits. Additionally, the operation of the crane lifting the roof test panels into place had to be accounted for within the layout of the experimental set-up.

The concrete floor and wall construction creates a highly reverberant interior volume of 88.8 m^3. The reverberation chamber contains a single omni-directional loudspeaker, support cables for locating microphones as required for measurement of the spatial variation of the diffuse sound field, and a temperature/RH sensor. The chamber is conditioned at a constant temperature of 21°C (ASTM E90-2004). The conduits for power cables and the air handling unit were blocked during testing.

Two roof test panels were constructed as identically as possible (inclusive of all bolts, welds, and roofing material patterns and overlays) in order to cross-validate results. The roof test panel is supported on resilient pads in the concrete wall perimeter frame; additional sandbag blocks are utilized to reduce flanking paths. Perimeter rails for fall safety and for the attaching the sound barrier enclosure to reduce ambient noise were attached to the wood framed parapet of each test roof (**Figures 29-32**).

Measurements of transmission loss were first made of test roofs A and B in the non-vegetated reference condition. Gradients of substrate (on drainage boards and filter cloth/root barrier) were evaluated on test roof A only. At the maximum substrate depth of 150 mm, the sedum community, P1, was planted on test roof A. Test roof B was evaluated with 150 mm substrate depth and the coastal meadow plant community, P2. The drainage board and filter cloth/root barrier, substrate and plant communities P1 and P2 were the same as in the test plots for the absorption studies (see **Chapter 2**). The sequence of measurements is listed in **Table 13** (**Figures 33-35**).

Table 13 Sequence of measurements

Test Roof	Substrate Depth (mm) Plant community[1]
Roof A	Reference
	50
	75
	100
	125
	150
	P1
Roof B	Reference
	150
	P2

[1] See Chapter 3 for detailed description of plant communities

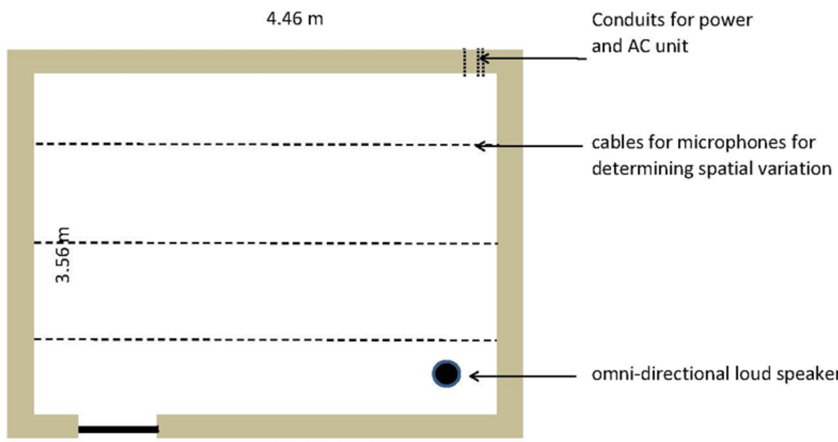

Figure 27 Plan diagram of sound transmission suite

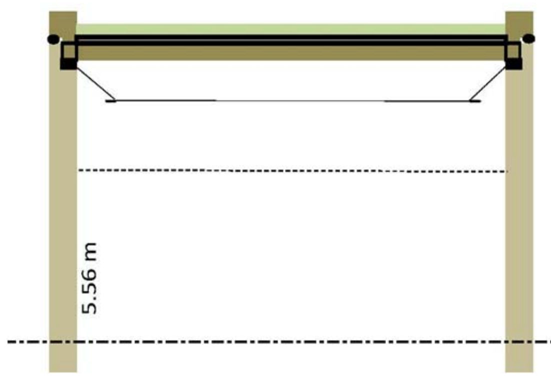

Figure 28 Section diagram of sound transmission suite

Figure 29 Construction of indoor-to-outdoor sound transmission suite

Figure 30 Construction of test roofs A and B

Figure 31 Installation of roofing materials on test roof A

Figure 32 Hoisting of test panel onto sound transmission suite

Figure 33 Installation of first 50 mm depth of substrate over filter fabric

Figure 34 Planting of sedums (P1) on test roof A

Figure 35 Completion of planting of coastal community on test roof B

4.4 Results and Findings

Field facility site (GRRF)

The reference roof and the two vegetated roofs, GR1 and GR2, all exhibited the trend of an increase in transmission loss with frequency (**Figure 36**). There is a broad dip in the transmission loss curve of the reference roof in the 125 Hz band. GR1 exhibited a variable increase in transmission loss relative to the reference roof over the frequency range. However, a reasonably constant increase in transmission loss of GR2 above that of the reference roof is seen.

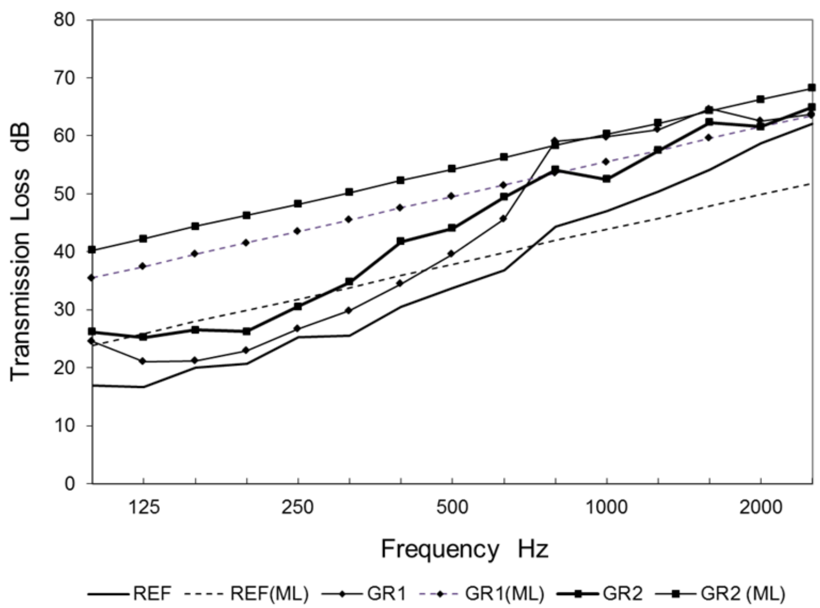

Figure 36 Measured transmission loss - field research facility (GRRF)

The substrate and vegetated roof materials increased the transmission loss over the low-mid frequency range of 50 to 2000 Hz by 5 to 13 dB, and in the higher frequency range by 2 to 8 dB. This translates to a significant decrease in low and mid frequency sound level transmission, a decrease which perceptually equates to reducing the transmitted sound loudness by half. The field-mass law prediction using actual mass/area, is plotted for each curve ('(ML)' in **Figure 36**) and illustrates that mass law does not sufficiently predict the transmission law of these roofs, especially at low frequency.

In general, the transmission loss curves of all vegetated roof systems evaluated on the REMs were higher than that of the reference REM. From the 125 to 2000 Hz frequency bands, the mean increase in transmission loss of the vegetated systems over the REM reference roof was 3.2 dB, and the mean value across all frequencies measured was 11.3 dB (**Figure 37**).

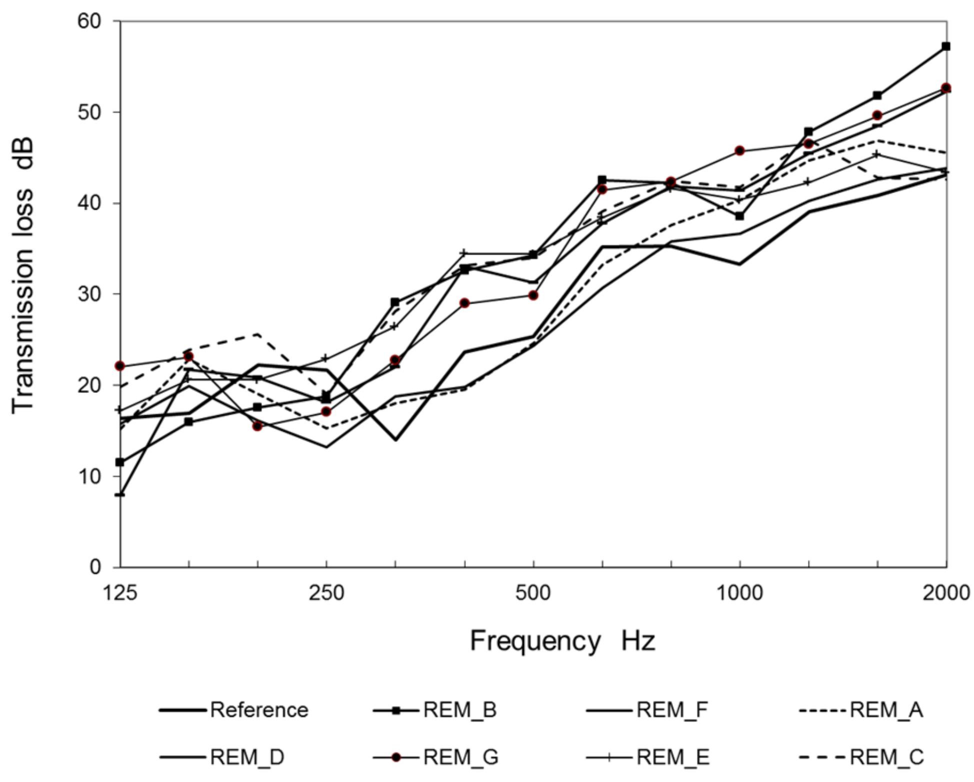

Figure 37 Measured transmission loss - REMs

The vegetated roof, GR2, on the field test facility, is comparable to the vegetated roof of REM_C. The roofs are similar in terms of material layers, substrate mix and depth; however, the plant community and level of establishment varied significantly. As compared to GR2, which had a mixed sedum community at 40 % coverage, the plants on REM_C were well established grasses and fescues with extensive root development. The mean transmission loss of the GRRF roof is 9 dB higher, averaged across the frequency range, than the transmission loss of REM_C (**Figure 38**). The differences in measured transmission losses of GR2 and REM_C are consistent with the difference in transmission losses of the GRRF reference roof and the REM reference roof.

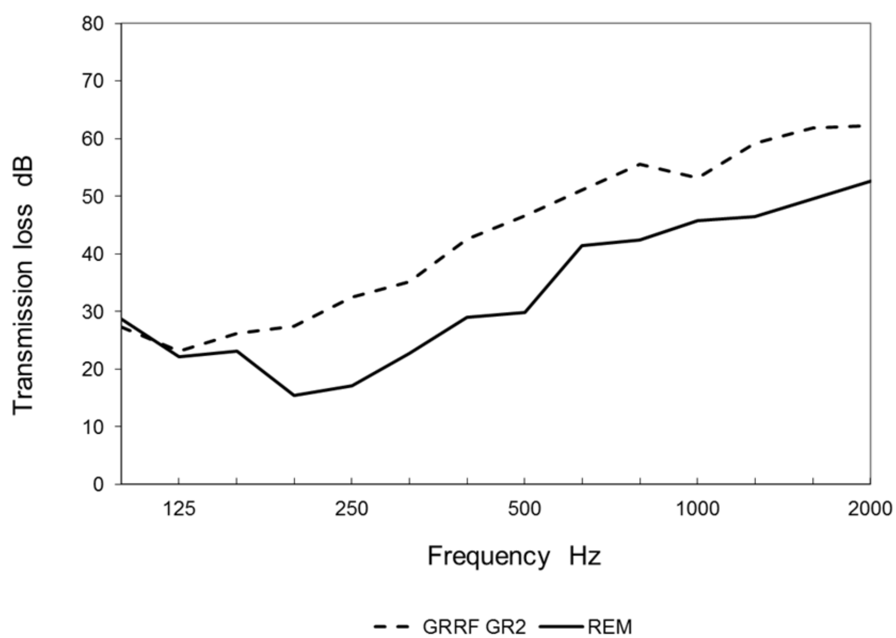

Figure 38 Measured transmission losses of GR2 and REM_C

The additional transmission loss provided by 150 mm substrate depth on GR2 is substantially less than twice that of the 75 mm substrate on GR1. Similarly, the depth increase in a pair of REMS did not increase transmission loss by a proportional amount.

The plant community on REM_C allowed detailed studies relating to the operation and geometry of the intensity probe and its specific position relative to the foliage. **Figure 39** compares the results of locating the microphone probe directly over a fescue plant relative to holding the probe over an exposed substrate area between the foliage and dense root masses.

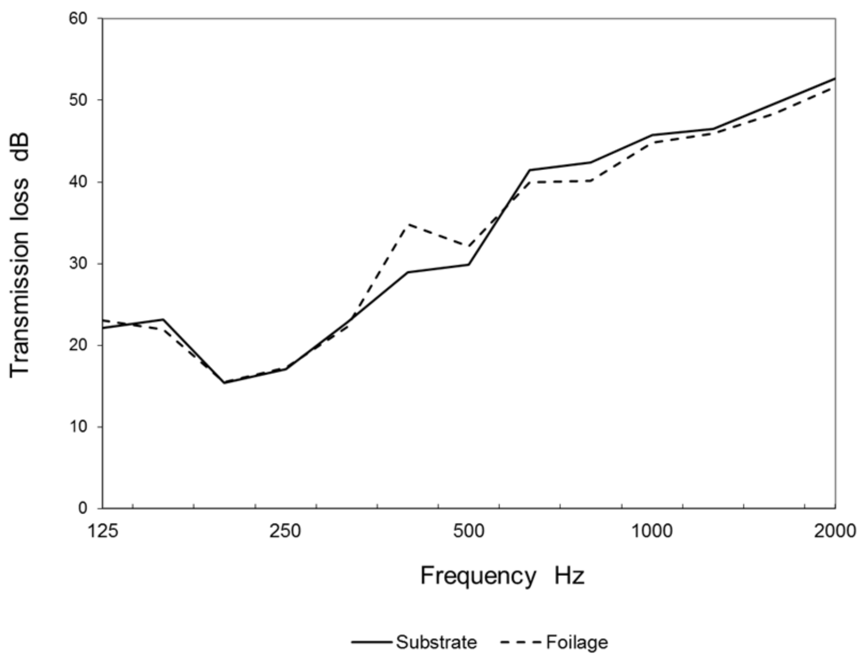

Figure 39 Measured transmission losses over substrate and foliage REM_C

REM_A and REM_D were similar in all aspects of the vegetated roof system, with a significant difference in the depth of substrate. The substrate depths of REM_A and REM_D were 75 and 35 mm, respectively. The transmission loss of REM_A was generally higher than REM_D and the mean increase in transmission loss over the frequency range from 125 to 2000 Hz is less than 2.0 dB (**Figure 40**).

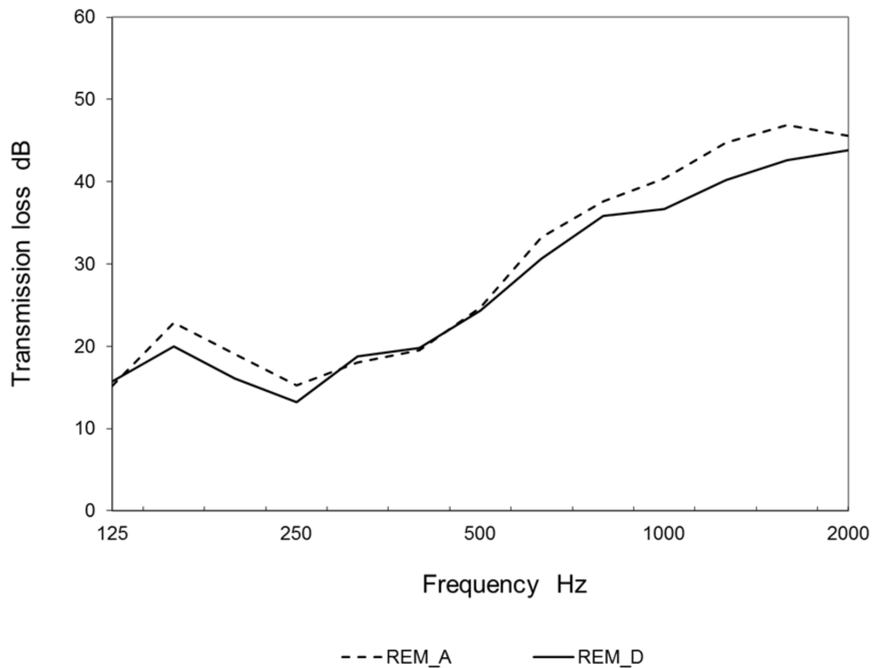

Figure 40 Measured transmission loss – effects of substrate depth on REM_D

Indoor-to-outdoor sound transmission lab

The spatial variation of the reverberation chamber was determined to be sufficiently diffuse above 125 Hz based on a maximum acceptable 1.5 dB standard deviation across all measurement locations, with the exception of the 200 Hz 1/3 octave band in which the standard deviation was 1.9 dB.

In the non-vegetated reference state, the two test roofs had similar measured transmission loss values across the full range of frequencies; the mean difference was 1.4 dB, and the maximum deviation occurred at 160 Hz. This results suggests that the measurement method are highly accurate. The field-mass law (total mass of material layers, m_s=28 kg/m^2) predicted low-frequency transmission loss to be 6 dB greater than the measured transmission loss of the test roof A. This is similar to results from the GRRF (**Figure 36**). With an effective mass (15.5 kg/m^2), the field-mass law predicts transmission law in agreement with the measured values. In the region where the mass impedance is predominant, the slope of the transmission loss curve is 5.5 dB/octave to the 400 Hz band. Above the region of coincidence, the slope was approximately 11 dB/octave and is well predicted by the field-mass equation, with damping term $\eta = 0.9$ (**Figure 41**).

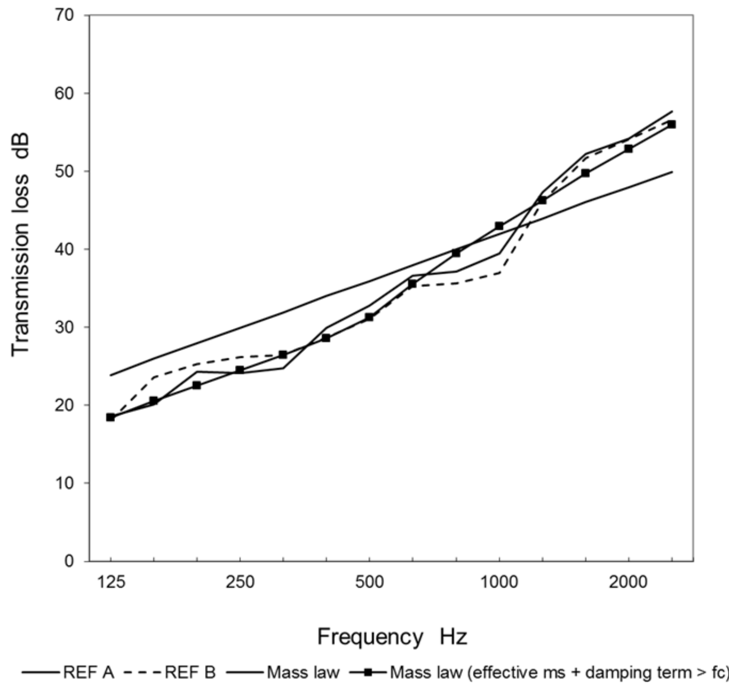

Figure 41 Reference roofs – mass law prediction

The installation of the drainage board, filter cloth/root barrier and 50 mm depth of substrate were evaluated in two states of gravimetric water content (GWC). The 12% difference in gravimetric water content between the two tests did not translate to a substantial difference in transmission loss. The mean difference across the frequency range was 1 dB; the maximum was 2.5 dB at 1000 Hz. The first measurement at 49% GWC was taken on the open deck without the sound barrier enclosure; the ambient noise level limited the measurement of intensity to the 1000 Hz frequency band. The plywood enclosure was installed before the second set of measurements took place, extending the viable measurement range to 2000 Hz (**Figure 42**).

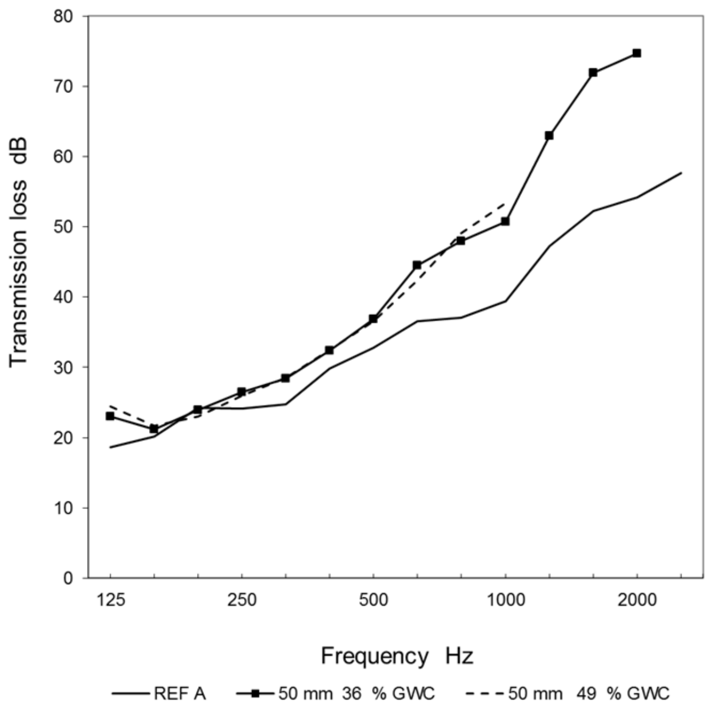

Figure 42 Measured transmission loss – 13% difference in GWC

By mass law, the mass increase from the actual mass of the reference roof (28 kg/m^2) to the addition of 50 mm depth of substrate (79.5 kg/m^2) represented a 9 dB increase flat across the frequency range. The mean increase in transmission losses below 315 Hz, from 125 to 1000 Hz, and above 1000 Hz are 2.6 dB, 7.5 dB and 12.8 dB, respectively, an average of 9.1 dB across the frequency range. This represented a change in slope above 315 Hz from 11 to 17.3 dB per octave band.

The depth of substrate was increased by the addition of a measured volume of substrate and a repeatable process of distribution and compaction then applied. As the substrate depth and mass increased, the ambient noise levels increasingly limited the highest frequency of intensity measurement (**Figure 43**). Repeated measurements illustrated that the common trend across each frequency band from 125 to 500 Hz was that transmission loss increased slightly with depth. The relationship between the increase in transmission loss and the depth / mass of the substrate does not follow field-mass law predictions, which predicts 9 dB for the first 50 mm, and then 2.4, 1.9, 1.6 and 1.3 dB for the additional depths of 75, 100, 125 and 150 mm over the frequency range from 125 to 500 Hz, the increase of transmission loss due to the addition of 50 mm of substrate was 2.6 dB, and the addition of another 100 mm depth to 150 mm yields another 3.6 dB increase (**Figure 44**).

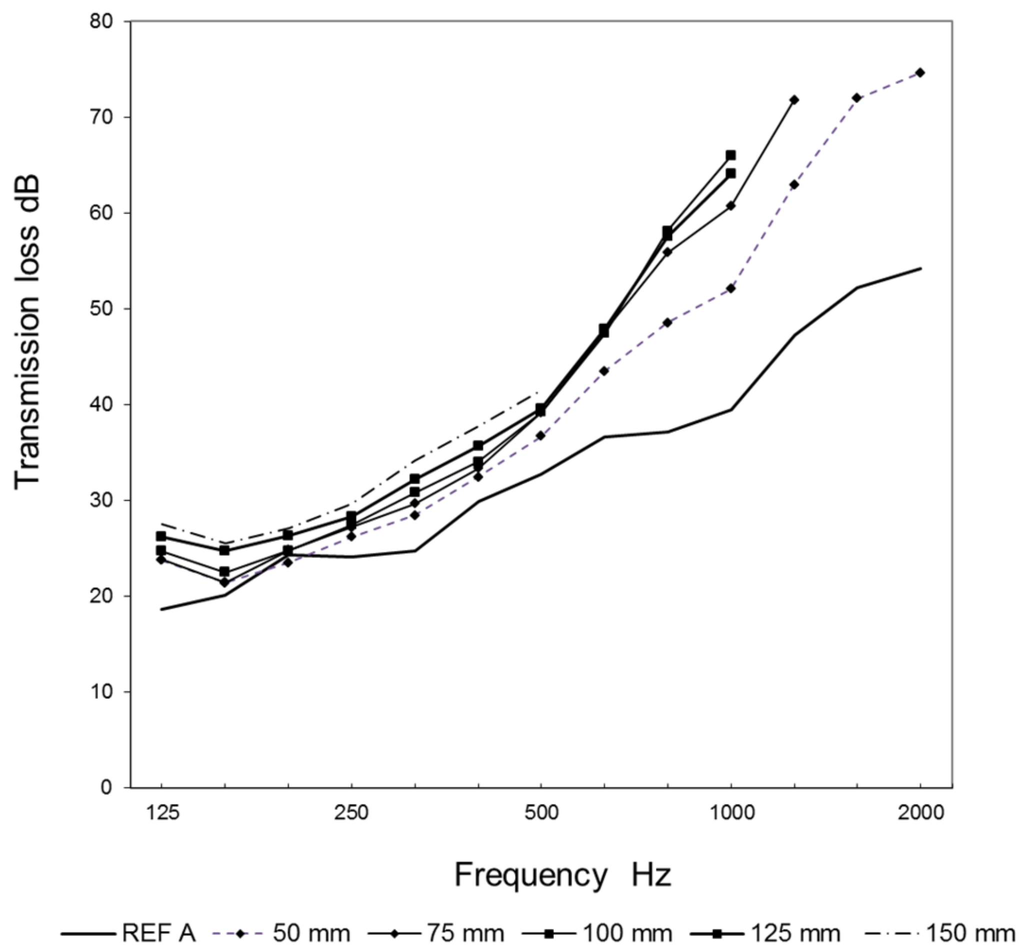

Figure 43 Measured transmission loss of substrate – 25 mm increments of depth

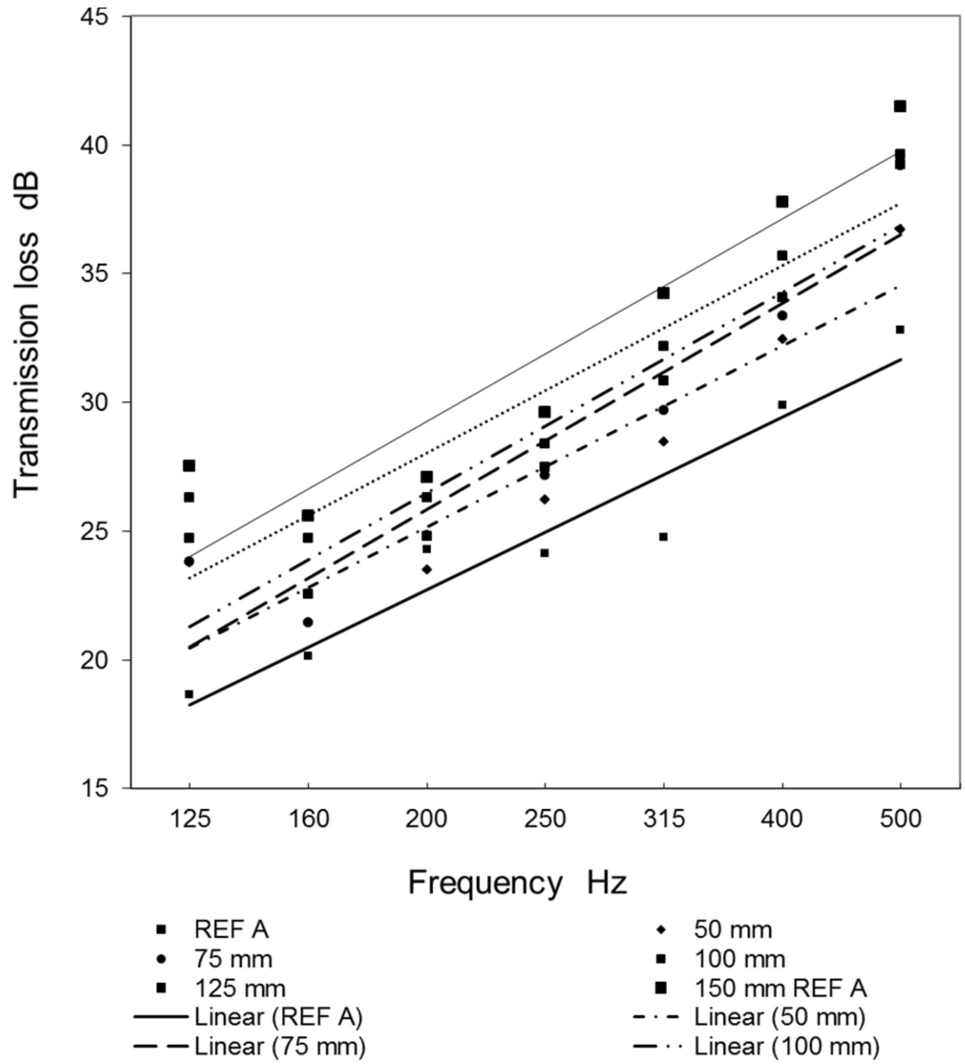

Figure 44 Measured transmission loss trends of substrates depth (125 -500 Hz)

Plant community P1 was evaluated seven days after planting; no change in transmission loss was indicated at the time of testing (**Figure 45**). Plant community P2 was first evaluated fourteen days after planting. The immediate effect after planting was an increase in transmission loss (**Figure 46**).

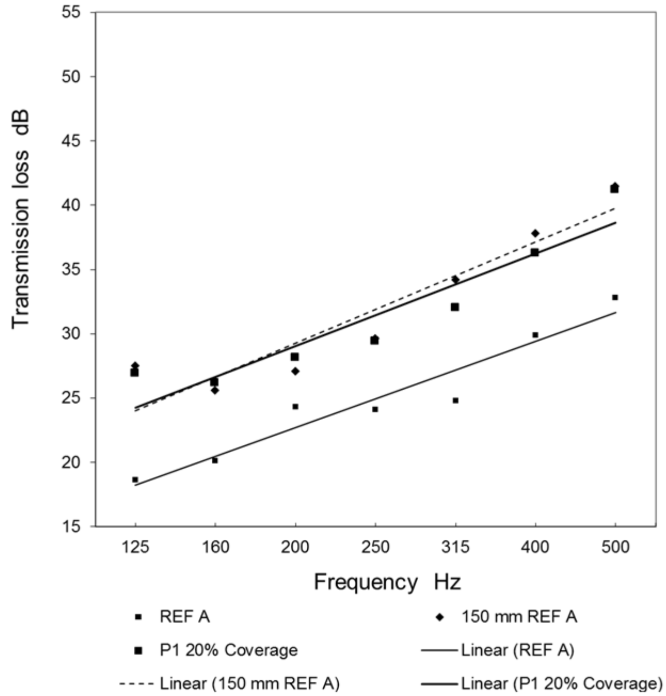

Figure 45 Measured transmission loss of roof A planted with sedum community (P1)

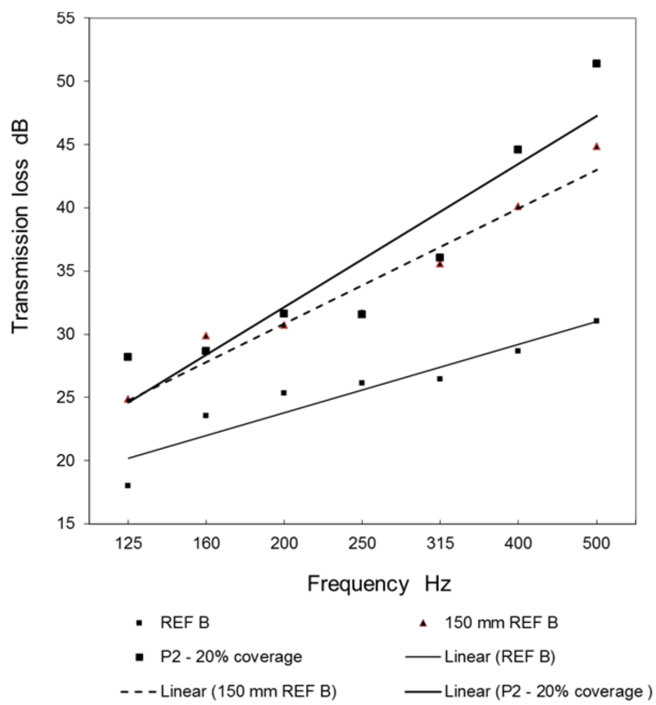

Figure 46 Measured transmission loss of roof B planted with coastal meadow community (P2)

4.5 Discussion

Measured data collected from three sites – the field–test facility, REMs and the indoor-to-outdoor sound transmission suite - confirm that adding vegetated layers reduces the sound transmission of roofs. Light-weight vegetated roofs may increase transmission loss up to 10 dB at low frequency and up to 20 dB at mid-range. The vegetated substrate mass loads the roof and provides additional damping.

In the 125 to 1000 Hz frequency bands, the measured transmission loss results from non-vegetated and vegetated roofs constructed with dimensional lumber were below predictions derived from the diffuse-field mass law. Additionally, in the regions of coincidence, the slopes of the transmission loss curves are 12 to 18 dB per octave, significantly steeper than the 9 dB per octave slope predicted by diffuse-field mass law. The trends exhibited are not unlike transmission loss curves of built-up roofing and material overburden illustrated in reviewed literature (see Appendix C).

The field-mass law accurately predicts the transmission loss values of the non-vegetated test roofs tested at the sound transmission suite constructed for this research. An effective mass was estimated for input to the model, as the total mass of the roof structure in the field-model generated an overstatement of transmission loss. The effective mass is estimated as the total sum of all roofing material mass above the metal deck and the portion of the metal deck profile in plane contact with the composite layer of roofing materials.

The data compiled from all sites provides insight into the impact on transmission loss of the substrate depth, the gravimetric water content and the plant community. Repeated measurements illustrate the common trend across each frequency band that transmission loss increases with depth. The relationship between the increase in transmission loss and depth of substrate is not proportional. The first 50 mm of substrate increased transmission loss at low, mid and high frequencies by 5, 11 and 25 dB, respectively. The subsequent range of increase in transmission loss from at 25 mm gradients was 1 dB/25 mm at low frequency and 4 dB/25 mm at mid frequency.

Measurements were made at different levels of moisture content, which nominally represented the available water content required for plant viability. The inter-particle pores and largest particle pores drained before measurement. The percent change in gravimetric water content represented a 5% change in total mass. There was no measurable change in transmission loss. Initial planting represented an initial 7% increase in total mass. The deep rooted grasses and bulbous roots of the coastal meadow community root contributed to a reduction in sound transmission relative to the shallow rooted sedums. Over time, transmission loss may decrease with the further establishment of root masses.

The measurements did not provide sufficient data to develop a prediction model on the transmission loss of vegetated roofs. In the low frequency range, where mass impedance is predominant, there is sufficient evidence to suggest that the effective mass impedance is a function of the actual mass, and an effect created by the vegetated layer which is related to the establishment of plant specific root structures within the substrate.

During these tests the greatest limitation to the measurement process was ambient noise from traffic and building services. Reduced ambient noise levels would have allowed measurement over a wider frequency range and at greater substrate depths. Measurements immediately before and after the installation of the sound barrier enclosure around the test sample confirmed that the enclosure did not impact the measurement values. A possible revision to the experimental set-up which would compensate for the outdoor location would be a crane-lifted sound box to be placed on the parapet once the test specimen was in place.

The non-representative dimensions in the small-sample REM roof structure create atypical plate stiffness which explains the lower transmission loss in the higher frequency ranges relative to roofs on the field research facility. Additionally, low frequency modal interference compromised the interior diffuse sound field of the REMs. REM testing allowed for the measurement of the impact of system variables on transmission. Although small sample testing decreases the consumption of resources, it was determined that measurement should be carried out on test specimens which are dimensional representative of all materials, framing components and structural spans, such as the test panels at the indoor-to-outdoor sound transmission suite. The process of measurement over a controlled gradient of substrate depth, and on the reference test panels, previously measured for transmission loss, provided insight into the impact of depth and the effect of mass. Similarly, the capacity to measure transmission loss of a vegetated roof as the plant community establishes over time has initiated the investigation of the impact of plant root establishment on transmission loss.

The quantification of the transmission loss validates the use of vegetated roofs as a tangible design solution to reduce sound transmissions. Vegetated roofs have a unique low frequency performance which could not be achieved by the addition of a ceiling to the underside of a roof system. The material resource balance of installing a vegetated roof is the elimination of a ceiling system to mitigate sound transmission. The use of vegetated roofs to mitigate noise can be evaluated during the building design process through preliminary elemental analysis and life-cycle cost assessment. The findings from this research can be utilized in a model which has been developed to incorporate transmission loss data and generate additional property values resulting from the transmission attenuation of vegetated roofs (Tomalty 2009).

In order to further the understanding of transmission loss in terms of mass impedance, the relationship of porosity and depths of a range of substrates must be further investigated to allow the development of a generalized model. Furthermore, an extended time frame is required to understand the relationship of plant root structure to porosity and fully measure the impact of plant establishment on the effective mass.

4.6 Chapter Summary

This chapter presented the investigation of the sound transmission characteristics of vegetated roofs. Sound transmission theory, as it may apply to vegetated roofs, was reviewed; and relevant literature findings on the measurement of sound transmission through roofs, primarily executed in the 1960's when increasing aircraft noise was first determined to be a health related issue, was identified and reviewed for both transmission loss data and methods of evaluation. The review of experimental approaches to evaluate sound transmission through building components identified a reverse indoor-to-outdoor technique, validated through ASTM and ISO standard test methods, which could be adopted to evaluate vegetated roofs. For the purpose of this research, the reverse indoor-to-outdoor method was first implemented at an existing field site for research on vegetated roofs. The detailed implementation at the field site and the findings from the field work supported the development of a purpose-built field-laboratory specifically designed and commissioned as part of this research. The field-laboratory was designed for measurement of interchangeable roof test panels. The design and commissioning of the field laboratory and the test panels are detailed in the methods section as is the sequence of transmission loss measurements. TL measurements were completed on two non-vegetated reference panels, on gradients of substrate depth (25 mm increments) and on two plant communities established in 150 mm of substrate depth.

Increased TL, resulting from the installation of vegetated roof material layers, at the field site (wood frame construction) and at the field laboratory (light-weight metal) generally align in the low and mid frequency range. The increased TL of the wood-frame roof in the 50 to 2000 Hz frequency range is 5 to 13 dB, and the increase in TL was up to 8 dB above 2000 Hz. The increased TL for the light-weight metal deck was up to 10 dB, 20 dB and more in the low, mid and high frequency ranges. Field-mass law, using an effective mass to describe the composite roof deck, predicts TL of the non-vegetated reference roofs. A gradient increase in substrate depth, equated in terms of mass, incrementally increases TL, though, not as predicted by mass law. A variance in the moisture content of the substrate does not translate to a measurable change in TL. Further research on the relationship of plant root structure to porosity and substrate mass, as the vegetation establishes over time, is required in order to measure and fully understand the impact of plant establishment on the effective mass of the additional vegetated roof material layer, substrates and established plant communities.

This is the third chapter which dealt with the empirical measurement and prediction of the acoustical characteristics of vegetated roofs. The effects of absorption and sound transmission on the occupancy of the building or the rooftop are site and building specific. In order to investigate an application of vegetated roofs as it affects the users of programmed space on of a rooftop, a case study methodology evaluation of two projects follows in the next chapter.

CHAPTER 5 Case Study: Soundscape Analysis of Two Rooftops

5.1 Introduction

The research presented in this chapter investigates the capacity of vegetated roofs to change the balance of rooftop soundscapes. At the scale of a rooftop site, vegetated roof systems have the potential to reduce noise and reverberation through surface absorption (see **Chapter 2 and 3**) and to increase natural sounds through bird and animal habitat supported by plants and through the interaction with plants of wind, water, and people. The presented case study compares two programmatically similar rooftops, one with a vegetated roof and one without any significant vegetation.

As contextual research, the case study is important to the overall study of vegetated rooftops. It allows an investigation of relationships within soundscapes–between sounds, materials, building form and user's activities–which is impacted by the inclusion of vegetated roofs in the building design. The case findings identify the contributing role of vegetated roofs to the quality of the rooftop soundscape. The case study is of rooftop outdoor play areas at two child care centres[2]. One motivating factor for selecting this type of rooftop programming is the value of this work to the design of rooftop child care centres. The design of such spaces can impact the development and aural perception of pre-school children. The second motivating factor for selecting outdoor play areas at child care centres, rather than rooftops occupied for relaxation or dining, is the programmatic similarity of the two designs. When these centres were constructed, The City of Vancouver Childcare Design

[2] The location and names of the child-care centres are not presented for privacy and security.

Guidelines[3] and the Childcare Technical Guideline were mandated for the designs of a child care facility owned by the City of Vancouver (City of Vancouver 1993, 2008). The guidelines clarify the minimum standards for building and landscape materials, finishes, furnishings, equipment and acoustics. The guidelines create sufficient programmatic similarity to allow comparison of two otherwise very different design solutions for occupying space on rooftops.

The introduction in this chapter presents a précis of the developmental benefits of outdoor play and a balanced soundscape, known design strategies which support children's cognitive development in outdoor play areas, and the regional context for locating outdoor play areas on rooftops. The methodology reviews the ambient sound analysis which is applied in the case study. The remainder of the chapter presents the findings and a model for design guidelines, linking the physical conditions of outdoor play areas to child development, with consideration to aural perception and soundscape qualities. The model illustrates the acoustical characteristics of vegetated roofs and their potential contribution to building ecology and the soundscape.

The developmental benefits of outdoor play and a balanced soundscape

> *"children outside ….are able to move freely in different ways, they can scream when they are excited or make other loud noises. The outdoors is also a dynamic changing environment. The change is noticeable and enticing to the children". …sounds in our midst can literally nourish or debilitate us; every cell in our body registers sound waves. The acoustics nerve is the major mechanism of reception and integration of perception. Children are wired to respond to all the sound they hear as a form of survival and adaptation to an unfamiliar world. Negative …exposure to repeated loud noises leads to tensed muscles, fatigue, diminished.*

[3] Subsequent to the design and construction of the case study projects the City of Vancouver Child Care Design Guidelines have been replaced with provincial guidelines.

reflex responses and being accident prone. Positive….a harmonious acoustic environment supports good organ and tissue development. Sound is an important source of orientation and security, especially for children. Familiar sound, sound marks of our city, human voices, soft music, birds and breezes are comforting and reassuring (Herrington 2006, Olds 2001, Ceppi 1993,, Schafer 1994)

Noise effects early child cognitive development (Kryter 1994). The design of the interior and outdoor areas of child care centres can support children's aural perception and cognitive development. The acoustical attributes of interior and exterior spaces contribute to cognitive development and quality play (Olds 2011, Ceppi 1993). Fatigue, muscle tension, reduced reflex response and accidents are associated with exposure to continuous and repeated loud noises. Conversely, a balanced soundscape supports organ and tissue development (Day 2008, Cooper- Marcus 1999).

Children are wired to respond to all the sound they hear as a form of survival and adaptation to an unfamiliar world. Sound is an important source of orientation and security, especially for children. Familiar sound, sound marks of our city, human voices, soft music, birds and breezes are comforting and reassuring (Olds 2001, Taylor 2001).

Design strategies to support child cognitive development in outdoor play areas

The outdoor play areas of child care centres provide a setting where children can have access to natural elements which support children's cognitive development and primary education goals. Existing design strategies support children's cognitive development during outdoor play (Herrington 1998). Design strategies are known at the site scale: avoiding sites adjacent to transportation routes, nodes and other identified noise sources, use construction and landscape techniques such as mass, buffering zones and sound absorptive strategies to mitigate noise intrusion (Olds 2001, Day 2008). In children's play areas, spatial transitions can be designed specifically to address the acoustical qualities of the different environments. Sonic spaces can be designed through the use of spatial definition and material manipulation; the use of sound absorptive natural and manufactured materials can be used to reduce reverberation; with a goal to design areas for outdoor quiet and privacy. At cross-scales, inclusive of the micro-sonic scale around the child, it is imperative to introduce pleasant sounds. The design strategy should create bird habitat (invite bird song), vegetation with sound generation (reeds and tall grasses that whisper in the wind), and emphasize rainfall (catch rainwater from upper roofs and make a natural waterfall), celebrate known sound marks (city bells) or create new ones such as wind chimes (Olds 2001, Day 2008, Neuburger 2004).

The form and materials of rooftop outdoor play areas have the potential to expose or shield children from sounds and noise generated from beyond the site boundaries (road noise, street events and rooftop mechanical equipment). Some of the sounds we elect to eliminate through noise isolation are sonic pollution; however, some sounds contain proprioceptive information, the subtle peripheral information sounds we extract from our surroundings. Sonic proprioceptive information is delivered in the form of the low amplitude and/or high frequency waves, delayed reflected or diffracted sound waves, and from sound waves which have propagated over great distance (Schafer 1977).

Rooftops as outdoor play area

Lack of outdoor space in child care centres is a main reason why children spend less active time engaged in outdoor play and why they are spending less time with natural elements (Herrignton 2006). Child care centres are required to meet a minimum area per child of outdoor play space in the City of Vancouver. The development of rooftops as play areas for children at child care facilities in the City of Vancouver is increasing due to the City's EcoDensity strategies. The migration of outdoor play areas to rooftops is a formal design response to the initiative to provide family amenities and the densification of the urban centre.

Studying the contributions of vegetated rooftops will be useful to child care providers, early childhood educators, parents, as well as the architects, landscape architects, and engineers who design spaces for children. Outcomes will inform the design process, assisting designers to create harmonious soundscapes which help develop aural perception and the ability to listen to and appreciate sounds. The case study will address the question of whether vegetated roofs will mitigate noise build-up from the children's activities of play and introduce a higher diversity of natural and information sound to the children.

5.2 Case Study Methodology

The case study method is a research strategy that investigates phenomena within real life contexts. Case study research includes quantitative evidence, relies on multiple sources of evidence, and benefits from empirical measurements and the developed theoretical proposition (Cresswell 2007). This case study is a cross-case ambient environmental analysis of two rooftop outdoor play areas associated with child-care centres and allows some generalization on the positive impact of introducing vegetated roof systems to the rooftop soundscape. The case study includes two main research components, an ambient sound analysis, and a design evaluation of the rooftop outdoor play areas.

Ambient sound analysis - acoustics and soundscape

Acoustics and empirical evaluation

The single acoustical performance criterion for outdoor play areas in the city of Vancouver Child Care Design Guidelines is: "Outdoor play area to be effectively acoustically buffered from any noise from traffic, mechanical equipment or other disruptive noises to achieve a maximum sound pressure level of 55 $L_{24\ hr\ eq}$ dB(A)" (City of Vancouver 2008).

The temporally quantified A-weighted sound levels are independent of the physical or semantic characteristics of the sound sources. In the sonic environment there are many sounds taking place at any one time, and all of these sounds are communicating information destined for a receiving organism. When the sound is amplified or masked, the information is not communicated with clarity or effectiveness (Truax 1978, 2008). The resulting human experience (perception) of whether a noise level is acceptable or not generally depends on the perceived loudness of the noise relative to that of the intended activities and the quality of the noise.

Loudness levels alone are not sufficient to predict a level of annoyance since different sources are perceived quite differently. Human perception is not absolute and mainly relies of the meaning of sound in relations to the sources, the people receiving it and their expectation (Truax 2008). For example, in some social and cultural contexts, human sounds are judged as positive and mechanical inanimate sounds are reported as negative (Carles 1997, Yang 2005, Yu 2010). With personal value assignment, public transportation noise is less annoying than individual vehicle noise at similar loudness levels (Guastavino 2007). Natural sounds from parks, gardens and sources such as birds, water and wind structures increase sound levels and simultaneously reduce the annoyance of transportation noise from major roads and offset the effects of urban noise (Leventhall, 2004, Li 2010).

Scientific methods of analysis, design solutions using specific materials are available to reduce single or multi-source noise annoyance and meet specified noise level criteria. Yet, solutions reduce, without prejudice, the energy of all sounds including sounds which are cognitively beneficial and informational within the soundscape (of outdoor play) a soundscape approached is required to address the broader concepts of sound quality and a balanced soundscape (Schulte-Fortkamp 2002, 2007).

Sound type categorization

The acoustical characteristic of an environment can in part be defined by the categorizing of sounds, identifying the meaning of sounds and assessing the context in which the sounds are perceived. The goal of soundscape analysis and pattern identification is to discover relationships of sounds to the context. Extracted findings can be used by designers and planners for the design of higher quality soundscapes. At the genesis of soundscape analysis, sound types were categorized with an object-centered approach, providing spatial and temporal information about the soundscape (Raimbault 2005).

Object-centered categorization, derived primarily from the discipline of psychoacoustics, is processed in a number of permutations; physical classification (frequency, duration, fluctuations, dynamics); classification of referential aspects to study the meaning of sound (natural, human, sounds of society, mechanical, and specific indicator sound types such as bell or alarms) and classification according to aesthetic qualities (Southwork 1969, Schafer 1977). The original categorization strategies determined that due to the loss in soundscape diversity and complexity, our need for sensory complexity is not being met within the aural modality of our urbanity (Porteous 1985).

Ambient sound analysis approach

In current research directions, the ambient environmental analysis approach to sound type categorization is subject-centered, as opposed to object-centered, relating the activities, which generate sounds, to the urban-scale soundscape. The activity modalities within the soundscape are semantically and temporally analyzed for patterns and relationship. Additionally, physical measurements are made to empirically quantify characteristics of sounds which are of the highest interest and to empirically quantify the acoustical qualities of the soundscape's formal and material characteristics. At the scale of urban planning, the collective compilation of information provides evidence to relate soundscape experiences to typified urban areas and facilitates the construction as a mapping tool for cross-scale planning analysis (Raimbault 2005).

There are limits to the subjective evaluation embedded within the categorization strategies. This is in most part due to the non-acoustical characteristics of place which, in a live multi-modal context, affect the assessment of the soundscape. It is in this context that the delineation of negative and positive referral to noise and sound is diminished (Porteaus 1985). It has been shown that there is a relationship between visual perception and the perceived degree of noise annoyance (Watts 1999, Morin 2009). Likewise, a correlation exists between the perceived level of tranquility of a soundscape and the amount of natural influences on the surrounding context, which in turn influences the overall desirability rating of the landscape (Pheasant 2010, Kang 2010).

Setting

The case study relies, in part, on the secondary use of research data collected for the CHILD project. The CHILD project stands for The Consortium for Health, Intervention, Learning and Development (CHILD). It was a multi-disciplinary, academic-community partnership of ten projects established to undertake research that responded to identified community needs for the health of children up to six years of age in British Columbia. The Outside Criteria study, one of the ten projects for CHILD, examined the ways outdoor play spaces at child care centres in Vancouver contributed or hindered children’s development. Using extensive videotaping, site analyses, and interviews, the project resulted in numerous journal articles, book chapters, and local and international presentations. The findings of this research are called The Seven C’s and can be viewed at the Westcoast Child Care Resource Centre (Herrington 2006).

The CHILD project used an evaluation checklist, based on seven criteria (7 C's), to rate the design of outdoor play areas. Seventeen outdoor play areas were investigated by CHILD. Five were at the rooftop level, and of those, only one had vegetative roofs as part of the outdoor play area and on roof levels above and below the outdoor play area. The single site with a vegetated roof was selected for the case study. The selection criteria for a programmatic comparative site from the remaining four rooftop sites, was based on location (in the downtown core), contrast (least amount of vegetation) and availability to detailed design and material information. The CHILD project ultimately provided details of the outdoor physical factors that contribute to early childhood cognitive development and made design recommendations to create environments which provide for quality outdoor play at child care centres (Herrington 2006).

Procedure

The case study ambient sound analysis includes the following aspects:

- An examination of the urban context in terms of traffic background noise level at three scales; the urban scale, the nine city block scale, and the site scale – specifically at the perimeter of the rooftop outdoor play.
- An examination of the spatial and material qualities of the outdoor play areas; identification of acoustic subzones and the inter-relationship between the architecture and sounds.
- Sound type categorization, investigation of approaches which describe the components and structure of the soundscape appropriate to the scale of the outdoor play areas.
- Evaluation of the subjective impression of the soundscape by the CHILD researchers, the transcripts of CHILD interviews and of the sound recordings from the two sites.

The case study ambient sound analysis provides evidence of the contributions of the acoustical characteristics of vegetated roofs to the building ecology and the soundscape of the child care centres. In the discussion these findings provide evidence to expand the 7 C's criteria with an additional focus considering the aural modality of children's play and design. The criteria then stand as a model for how design guidelines might incorporate the aural environment. These findings are generalized to architecture and urban planning in the concluding chapter of this dissertation.

Detailed Methods

Background sound levels from traffic road noise

Background sound levels from traffic road noise provide a context for the exploration between the soundscape of the outdoor play area and the sonic community. Traffic road noise is the dominate source of community noise in Metro Vancouver (City of Vancouver 1997). CadnaA (Computer Aided Noise Abatement), a model-based computer mapping program is used for community noise prediction and assessment (Samuels 2006). Road noise maps of the two sites and the immediate urban context were constructed from average A-weighted equivalent continuous noise levels (L_{day} dB(A)) based on average daily traffic volumes. The average daily traffic volumes were estimated by EMME/2 (INRO Consultants, Montreal, Canada), a transportation planning modeling software used by Metro Vancouver's regional transportation authority. The sound pressure level ($L_{24\ hr.\ eq}$ dB(A)) was modeled one meter above the roof level at the perimeter of the outdoor play area.

Spatial and material analysis

In order to understand the contributions of the form and materiality of the rooftop outdoor play areas to the soundscape, the physical attributes of the areas were analysed through plan view drawings - delineating the area, enclosures, play equipment, storage and exits. The ground plane materials, ground vegetation, planters, trees and other features were documented from photographs and videos. The surfaces of the materials were inventoried with sound-scattering objects, such as play structures. From the spatial and material analysis, acoustical subzones were determined and illustrated in plan-view drawings

Sound type classification – components and structure

From a total of 359 minutes of video-sound recordings, twenty 60-second segments were randomly extracted for analysis for each of the two rooftop outdoor play areas. The segments represent playtime activities throughout the day and the wet and dry seasons of the year. The list of sound types for the log sheet was created from my aural perception whilst on vegetated and non-vegetative rooftops located in major urban centres. A cross section of commercial, industrial, institutional and residential building types and city zones was used to create the log. The general grouping of sound types for the log was for ease of data entry; following are the groups:

insect buzz	*footfall on substrate*	*amplified music*
bird calls	*footfall on roof deck*	*HVAC systems*
bird song	*talking, yelling*	*road traffic*
tree whispers	*play equipment*	*special vehicles*
grass interactions	*interactions with building*	*(fire trucks)*
water	*(slamming doors/windows)*	*aircraft*
wind		*sounds of accidents*
		construction
		building related
		electric hums

During the process of listening to each 60-second segment, each identified sound was assigned a value for duration (short, short and number of instances, or continuous), intensity (very soft, soft, moderate, loud, and very loud) and frequency range (low, medium or high). These event descriptions were later transcribed for comparative analysis into numeric values (on a scale of 1 to 5) for categorization. The categories are illustrated in graphs in which sound types are represented on X-axes and the duration, amplitude and frequency are represented on the Y-axes. Gabor spectrographs of segments of the recordings were generated to provide visual illustration of the two soundscapes. The Gabor spectrogram is a time-frequency distribution series which illustrates the amplitudes of frequencies over a selected time frame. Matching an illustration of a time series to a recording segment creates a visual map of the sonic environment and highlights sound type diversity. The sound types were later categorized by both the previously described object-centred and subject-centred approaches. The two approaches were investigated to determine which best defined the relationships between sounds, spaces and materials and which can be best incorporated into future design methods.

Subjective evaluation of the soundscape

Subjective impressions of the centre's soundscape were provided from limited sources: the ratings evaluations executed by the CHILD researchers, the observations and the interview notes by the same researchers, and my interpretation of the sound recording. The CHILD project evaluation results were re-examined with a consideration to the soundscape analysis and to provide additional evidence on the relationship between soundscape, vegetation and the overall rating of the outdoor play areas. This evidence, as identified, is simply reported without manipulation or further qualification.

5.3 Findings

The Urban Context, Road Traffic Noise

Road noise levels at the sites were investigated at three scales; the downtown area, one block in all directions surrounding the site, and at the building site. At the site, scale road noise levels were modeled at one meter above the roof elevation along the perimeter of the outdoor play area ($L_{24\text{ hr. eq}}$ dB(A)).

The noise level maps of the downtown areas of the City of Vancouver, generated on 10 m grids with 5 dB intervals (**Figure 47**) and the site context map, generated on 5 m grids with 2 dB intervals The road noise, defined in a twelve hour day between 0600 – 1800 hours, L_{day} dB (A), was selected to represent the time frame in which the child care centers operate. Aircraft noise is not included in the noise map and would create additional sound energy for the short durations of the fly-over, however, neither site is under a direct flight path. The noise from the rail lines and docks do not create additional sound energy at either of the two sites in day-time hours. The noise map describes road noise only; both sites are located within commercially zoned districts. Centre 1 is in the Downtown–Eastside/Oppenheimer District. The intent of this district is to provide new, and retain existing housing with compatible commercial and industrial use within the district. The location of Centre 1 within the District meets the zoning intent; the building site is on a high-count truck route, which is used to service downtown Vancouver. Centre 2 is located in the Downtown district, and the building site and use meet the intent of the comprehensive development plan that all buildings are to meet the highest standards of design and amenity for the benefit of all users who work, shop or visit the downtown district.

Mapping the background road traffic noise (5 m grids with 2 dB intervals) illustrates the sonic environment through which sounds are aurally perceived at the roof-top level of the play areas. Centre 1 is constructed to the property line; there is no additional space between the sidewalk and the building perimeter which would permit social gatherings. There are no street trees, grassy areas or boulevard vegetation on the child care centre side of the city block. The 5 m high street trees on the opposite side have a maximum 1.2 m canopy.

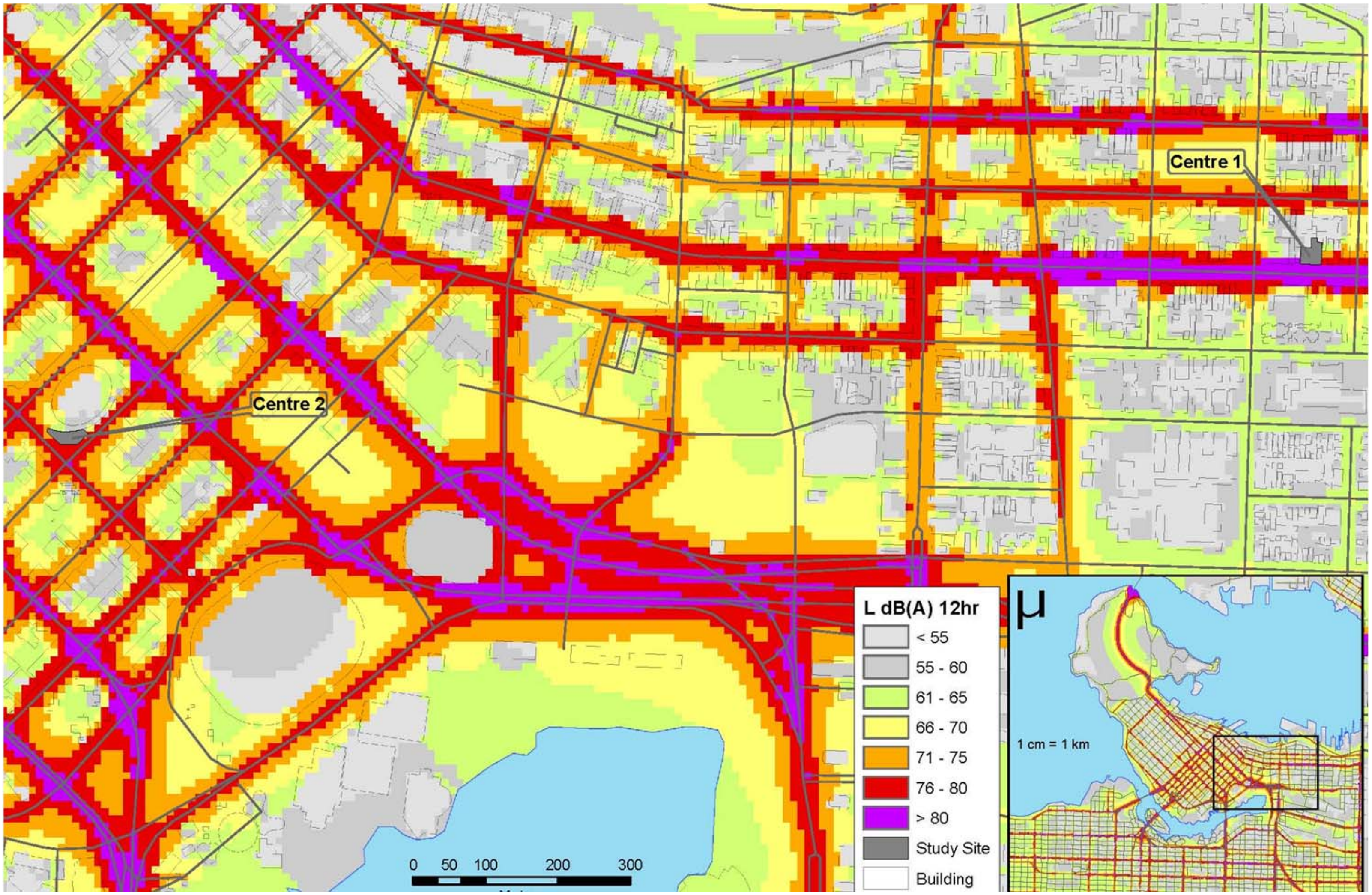

Figure 47 Road Traffic Noise Levels - Downtown Vancouver

Centre 1 is situated one level above the single loudest series of street blocks in the downtown, exceeding 80 L_{day} dB (A). This street is a six lane designated truck and transit route, facilitating commuter rush hour traffic, truck deliveries to downtown, and express commuter buses. The parallel street, one block south of the primary aspect of the outdoor play area, is relatively quiet and the road noise level is in the range of 59 – 62 L_{day} dB (A). Noise levels on the north street of the block are in the range of 71 - 78 L_{day} dB(A), and on the east and west adjacent streets are in the range of 66 - 75 L_{day} dB(A). Noise levels at the street intersections range can exceed 80 L_{day} dB(A) (**Figure 48**). The second aspect of the play area overlooks the roof of the adjoining one-story building. At the perimeter of the outdoor play area, 1m above the floor level, the road noise was modeled at 78.3 L_{day} dB (A) or 75.5 $L_{24\ hr\ eq.}$ dB (A) on the street aspect and 73.7 L_{day} dB (A), or 70.9 $L_{24\ hr\ eq}$ dB (A) on the second aspect. The resulting road noise without mitigation would be 76.8 $L_{24\ hr\ eq.}$dB (A)

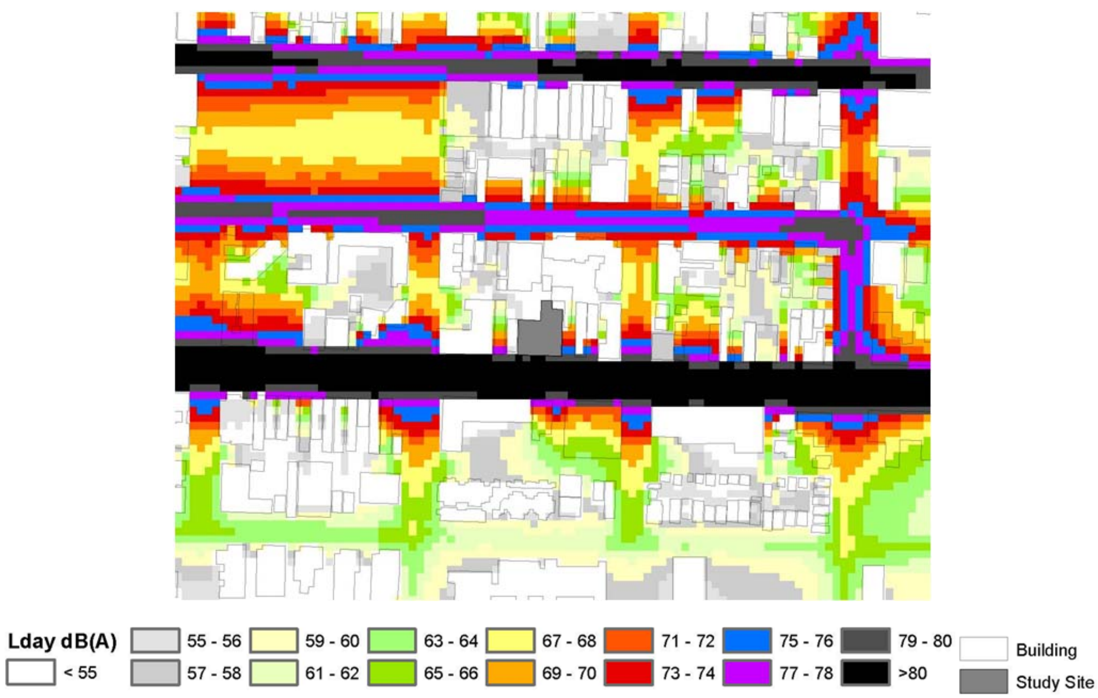

Figure 48 Centre 1 Road Noise Level

Centre 2 is situated five levels above a corner intersection, with a single curved aspect set back 18 metres from the intersection. At Centre 2, the gathering area at the site street level facilitates a diversity of events inclusive of busking (music and entertainment), tourism events, community celebrations, demonstrations and impromptu street events. 10m high street trees are regular features in the urban fabric. Established extensive and intensive green roofs are located on neighbouring buildings as well as on multiple levels of the building which houses Centre 2.

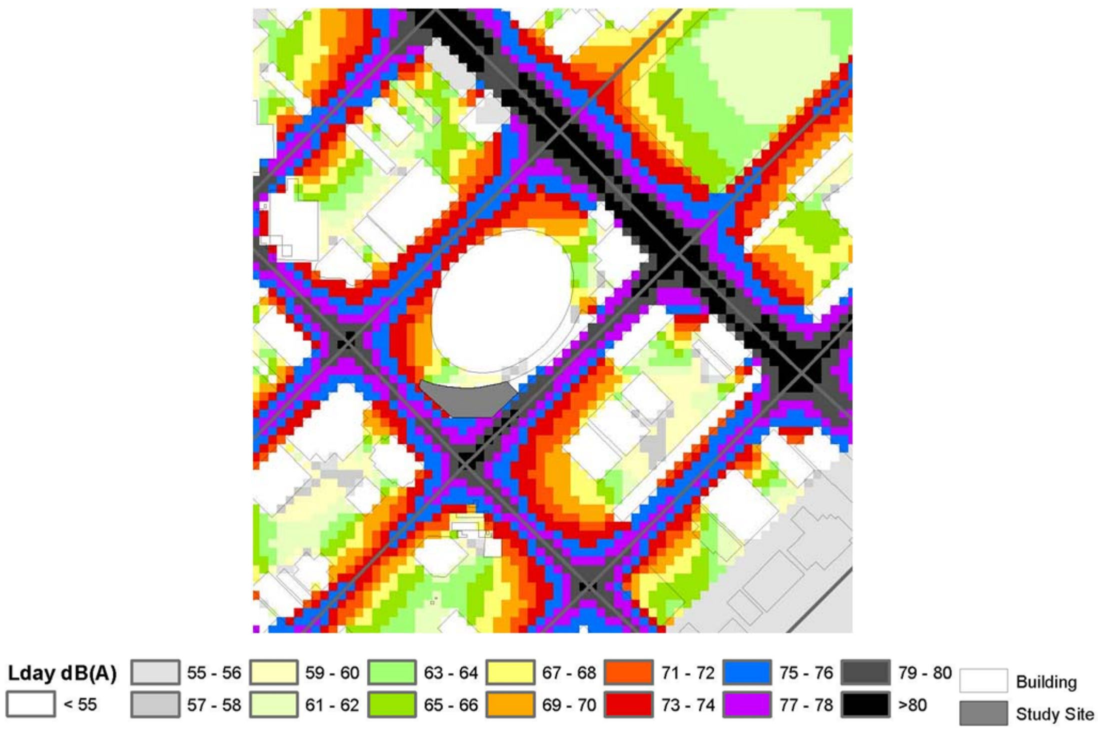

Figure 49 Centre 2 Road Noise Level

The traffic generating road noise is predominately community-focused consisting of personal vehicles, service and delivery vehicles and non-express bus traffic. The noise levels at the sidewalk below the centre are in the range of 71 - 78 L_{day} dB (A). Road noise levels on the SW street and SE streets are in the range of 71 -78 L_{day} dB (A) with intersections exceeding 80 L_{day} dB (A). The noise level of the adjacent streets are typical of the immediate neighbourhood and block surrounding the site and are generally 78 L_{day} dB(A), with the exception of the north end of the site block where noise levels exceed 80 L_{day} dB(A) (**Figure 49**). At the perimeter of the outdoor play area, 1m above the floor level, the road noise was modeled at 65.1 L_{day} dB(A) or 62.3 $L_{24\ hr\ eq}$ dB(A).

Spatial and Materials Qualities

The spatial and material analyses, along with the analysis of the soundscape components and structure, allow for the identification of the acoustical subzones and their characteristics. The location of the ground materials and the layout define paths and nodes of play activities. The activities generate specific sound types.

Centre 1

Centre 1 rooftop play area is primarily characterized by its architectural enclosures and the concept of the outside room.. The open-to-the-sky play area is enclosed on two aspects by the building itself and on the street and lane aspects by 4.2m high stucco or rough cut block walls with glazed openings. The enclosure was designed as a wall to meet the intent of the municipal by-law requirement to reduce noise level exposure from road noise to 55 $L_{24\ hr.eq}$ dB (A). However, the enclosure is designed as a barrier over which sound can freely propagate and diffract. The outdoor covered play area has a 3.6m ceiling; the surrounding enclosure is a combination of stucco walls and glazing. The spatial impact of the enclosures and towering building elevation is significant enough to eliminate the unique sensory perceptions generally associated with rooftops. These are the touch of the wind, distance vista and elevated perspectives, oral factorial perceptions and the sound clarity of a free-field condition typically experienced on rooftops.

The floor materials are a combination of concrete pavers and rubber tiles. The natural materials introduced into the outdoor play area include wooden slat decks, bridges and bamboo fencing to define specific areas of play. Minimal vegetation within the play area is confined to three planter boxes. Although the floor plane is only 4m above the ground plane, there is no association to the ground or ground based vegetation, such as trees and vines, either physically or perceptually.

With the exception of the very limited amount of play sand and plant substrate, the materials of the walls, floors, ceiling and play objects are all highly reflective. Sound scattering objects in the outdoor play area, which have a significant role in the redirection of sound within the space, include a wooden climbing structure, playhouses, an arbour, as well as the bamboo fencing and the concrete columns.

The spatial and material qualities of the outdoor play areas create the acoustical subzones. The activity modalities of play were analyzed for patterns and relationship to materials and the acoustic subzones (**Figure 50**). Activities, play structures and micro-climatic contribute to the form of the acoustical subzones within the soundscape of play (**Figure 51**). The area within the fence was not investigated as it was not used for pre-school age children.

A conflict is easily identified in **Figure 50**. The acoustical subzones, under the arbour and the play climber, are primarily spatially defined, and are where children could have individual quiet time or quiet discussion in close proximity to one other child. However, these subzones are located within the most dominate acoustical subzones, the open-to-sky area with a tricycle loop (**Figure 52**). The subzone within the covered play area is highly reverberant. This area experiences a high density of children when it is raining, a density substantially greater than guideline recommendations (**Figure 53**).

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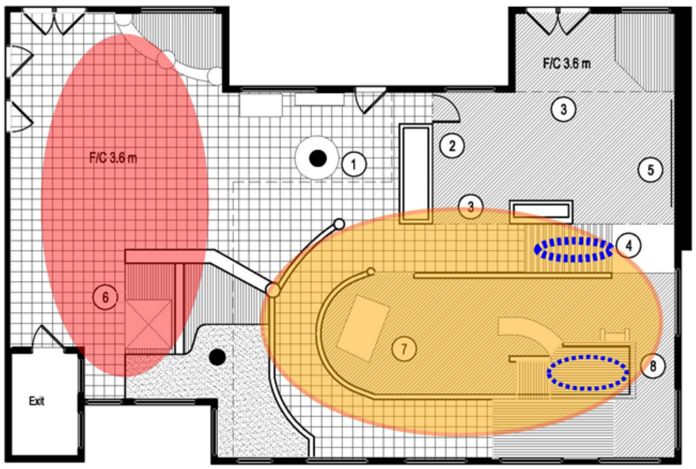
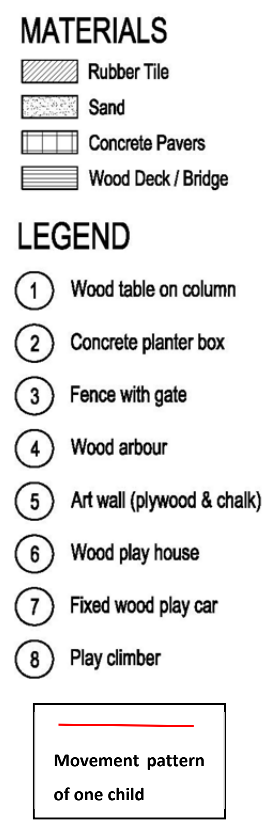


Figure 50 Centre 1 Plan layout and acoustic subzones

(Drawing adapted from Kate Stefiuk 1998)



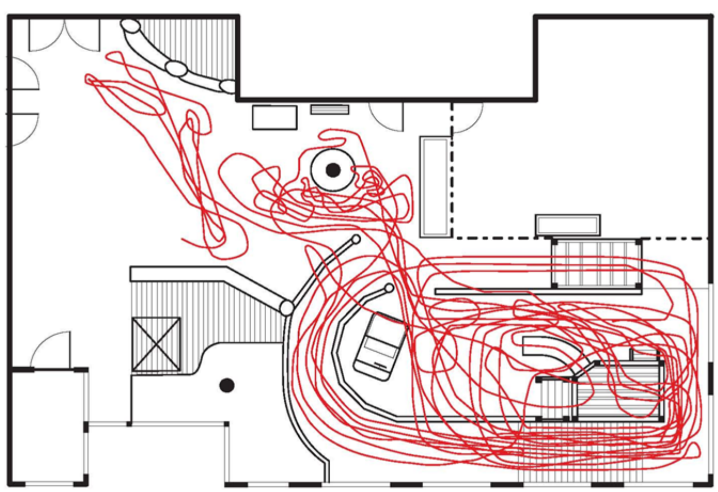


Figure 51 Centre 1 Activity path

(Drawing adapted from Kate Stefiuk 1998)

Figure 52 Centre 1 An outside room

(Photo credit: Outdoor Criteria)

Figure 53 Centre 1 A covered play area

(Photo credit: Outdoor Criteria)

A high level of reverberation and noise build-up was perceived by Centre staff, CHILD researchers and on the audio recordings. The spatial and material attributes were investigated through calculating the reverberation time (RT), using the Eyring reverberation time equation as a first approximation:

$$\boldsymbol{RT} = \frac{55.2V}{c\,S\,ln(1-\propto_{av})^{-1}} \qquad \textbf{Equation 18}$$

The open-to-sky ceiling plane assumed 100% absorption. The formulation assumes a diffuse sound field and a relative equivalent distribution of absorption. The Eyring equation was selected; over the Sabine equation because the Eyring formulation is considered to be a closer approximation than the Sabine formulation in cases where the room is highly absorptive, and where a coupling of two rooms is under consideration (Long 2006). A coupling approximation of the open-to-sky play area and the covered play area of the RT was calculated and found to be typical of the reverberation time recommended for school gymnasia. The aural perception of this level of reverberation is not generally associated with outdoor space and the nonconforming context may have highlighted the perceived effect of the highly reflective material throughout the outdoor play area.

Centre 2

Centre 2 rooftop play area is characterized by the language of post-modern architecture, which spatially defines the outdoor play areas. The open-to-sky play area is enclosed on one of the two major aspects by the building itself and on the major street aspect by a transparent rail. The spatial impact of the building elevation and the architectural columns is significant and integral to the play activities. The open aspect overlooks the street court. At the fifth floor level, the sensory perceptions generally associated with rooftop habitats are highly perceptible.

The floor materials are primarily brick pavers, rubber tiles and a grassy play area with a large specimen tree. Ground cover surrounds the acoustically transparent wire mesh guardrail, aligned with 12 deciduous trees. The natural materials introduced into the outdoor play area include a wooden slat bridge and bamboo fencing to define specific areas, and additional vegetation exists in planters. The uppermost roof of the building supports a fully semi-extensive vegetated roof and additional specimen trees are planted one level above the outdoor play area.

The architectural buttresses and the open aspects make a more significant contribution to the re-distribution and propagation of sound to the acoustical subzones than the play structures or hardscape ground materials (**Figure 54**). The size of the vegetated roof limits its sonic impact to the acoustical subzones it delineates. The predominately highly reflective building materials are offset by the vegetated open aspect overlooking the street. Along with the activities of the children's play, bird song supported by the tree habitat and other vegetation contributes to the zoning of the soundscape (**Figure 55**).

The small acoustic subzones, defined primarily by the architectural buttresses and ceiling line above, are appropriately sized and placed away from the open aspect to the street (**Figure 56**). The subzone defined by the sand box and wooden bridge is designed for an activity hub of 4 to 6 children. The need to learn to cooperate at play necessarily extends to aural perception and development whilst making sounds with sand toys and playing on the wooden bridge and engaging in communication. The acoustical subzone along the edge of the open aspect of the outdoor play area is created by the interface with the urban soundscape and provides a stage for the informational sound which the children experience. Lastly, the subzone defined by the vegetated roofs, the large specimen tree and the water hose bib with access to gardening tools is a quieter place (**Figure 57**). The highly absorptive material of the turf area eliminates the sound of footfall; interaction with the tree - from the wind, climbing or rustling dry leaves - creates sounds as do the birds in the tree. The interaction with water for the viability of all the plants on the roof brings another natural sound to the fore.

Figure 54 Centre 2 Layout and acoustical subzones

(Drawing adapted from Kate Stefiuk 1998)

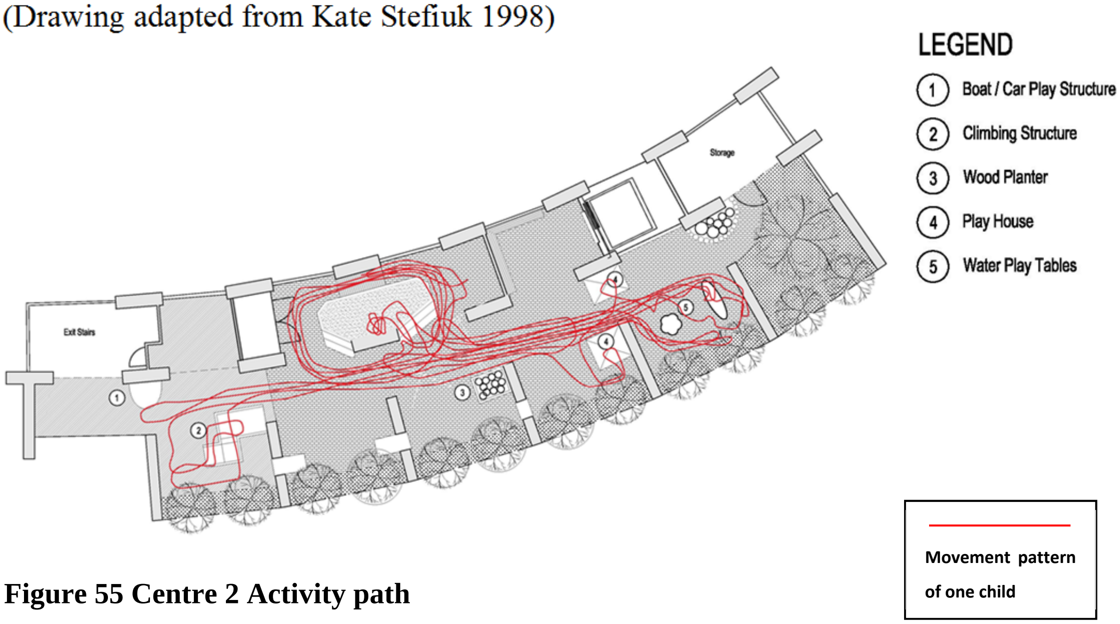


Figure 55 Centre 2 Activity path

(Drawing adapted from Kate Stefiuk 1998)

Figure 56 Centre 2 Radial centre path

(Photo credit: Outdoor Criteria)

Figure 57 Centre 2 Vegetated roof and trees

(Photo credit: Outdoor Criteria)

Sound Classification

Of the sound types listed in the log sheet, four were below the threshold of the recording device; these were insect buzz, tree whispers, grass interaction and wind. Four sound types were not in the samples randomly selected; these were amplified music, HVAC, aircraft and electric hums. In total, 13 sound types were identified between the two centres and 10 sound types were identified at both centres for comparison. The summary of values numerates the total number of seconds out of a possible 1200 seconds of recorded sound, the number of instances the sound was perceived, if not continuous, and the relative amplitude on a scale of 1 to 5 and the frequency range on a scale of 1 to 5 (**Table 14**).

During the listening process, 15% fewer sounds were documented in terms of total duration at Centre 1 than at Centre 2. This is attributed to a number of factors. First, the open aspects of Centre 2 to the street did not mitigate propagation of traffic noise, special vehicle sounds, and neighbouring construction at the perimeter of the outdoor play area. The surrounding enclosure at Centre 1 reduced traffic noise to a low amplitude steady state which was not discernable on all the recording segments and the enclosure effectively eliminated miscellaneous sounds from the neighbourhood. Second, the vegetation within and surrounding Centre 2 provided habitat for birds and created the requirement to use water from hoses for irrigation and clean-up. Third, noise build-up and reverberation possibly masked over other sound types on the recordings and contributed to limits of the listening process.

Table 14 Summary of sound events

	Centre 1				Centre 2			
Identified Sounds	Sec[1]	n[2]	a[3]	f[4]	Sec[1]	n[2]	a[3]	f[4]
bird calls	35	3	3.5	4.7	5	1	3.0	5.0
bird song	5	1	3.0	5.0	110	4	3.0	4.8
water	5	1	3.0	3.0	195	6	2.5	2.8
footfall/substrate	25	5	2.0	3.0	170	5	2.0	3.0
footfall/roof deck	70	4	1.8	3.3	265	15	2.1	3.0
talking, yelling	1160	Cont[2].	3.4	3.5	975	Cont[2].	2.9	3.2
play equipment	785	Cont[2].	2.9	3.3	294	27	1.5	1.9
interactions with building	45	1	2.5	5.0	20	4	2.8	3.0
road traffic	320	8	2.1	1.0	935	Cont[2].	1.8	1.0
special vehicles	0	0	0.0	0.0	2	1	3.0	4.0
street accidents	5	1	3.0	4.0	34	3	1.7	3.0
construction	0	0	0	0	180	3	2.0	3.0
building related	300	5	1.0	1.0	0	0	0	0
TOTAL Count	2755	72	2.6	2.8	3185	104	2.1	2.5

Note 1: Total duration of sound type (seconds).

Note 2: Number of instances of sound type,a sound was considered continuous if it was perceived greater than 65% of the time over the full duration of the sample.

Note 3: Amplitude of sound type, scale 1 to 5, averaged by count.

Note 4: Frequency of sound type, scale 1 to 5, averaged by count.

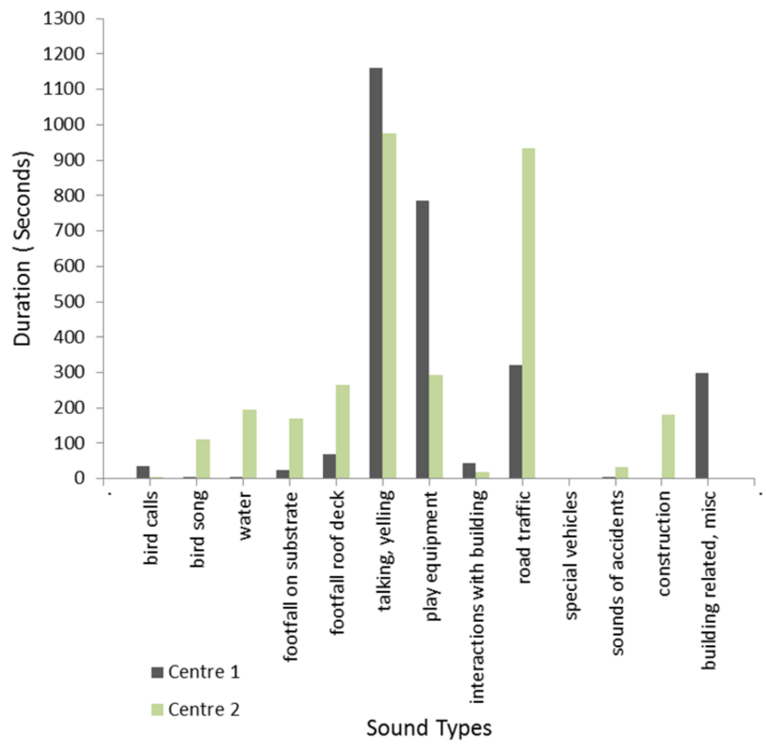


Figure 58 Total duration of sound type over 40 samples

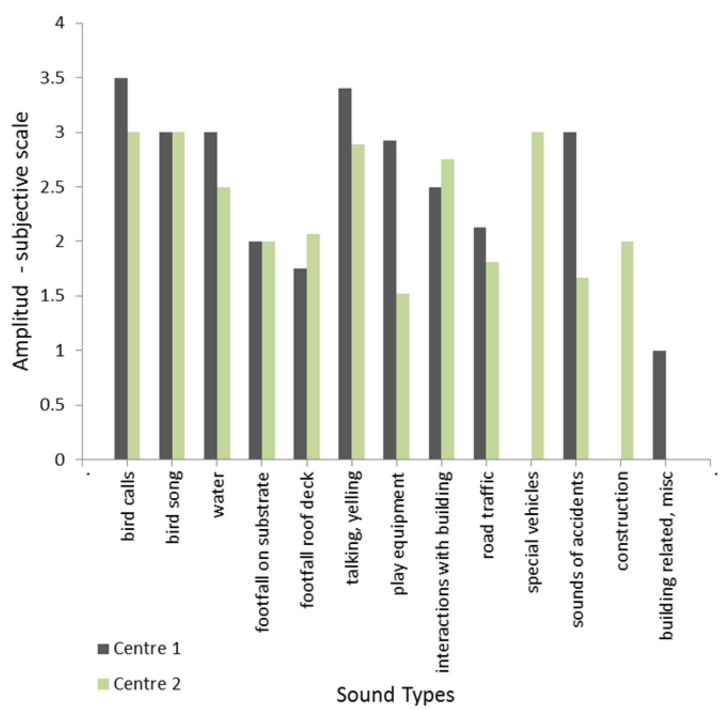


Figure 59 Subjective amplitude of sound types

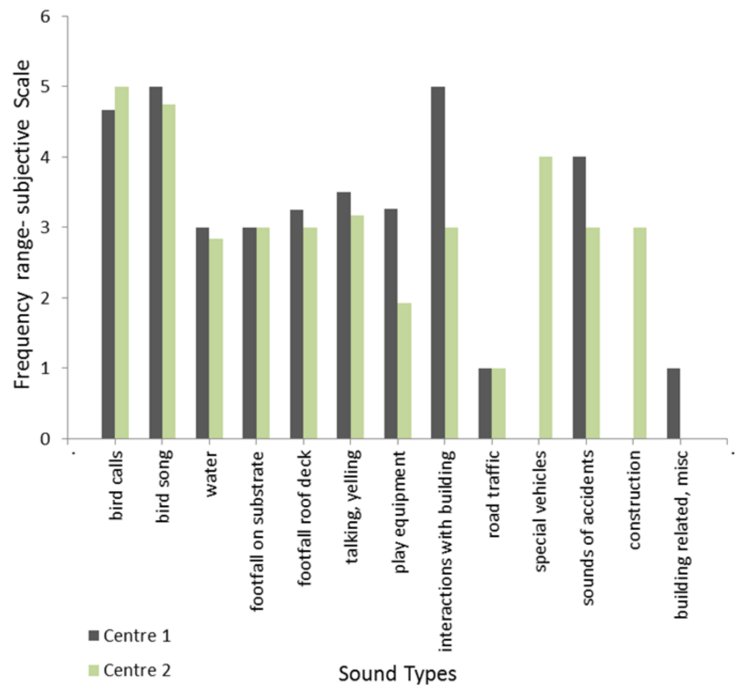


Figure 60 Frequency range of sound types

Comparing sound types common between the two outdoor play areas without a categorization approach illustrates that Centre 1 had a greater total duration of talking/yelling, sound from play equipment (primarily hard wheels on pavers) and interactions with the building (**Figure 58**); whereas Centre 2 had total durations over a broader diversity of sound types: bird song, water sounds, footfall, road traffic and sounds of accidents. The amplitudes of the comparable sound types were typically louder at Centre 1 than at Centre 2 with the notable exception of special vehicles and construction (**Figure 59**). The frequency ranges of the sounds were typically slightly higher at Centre 1 than at Centre 2 with the exception of play equipment and interactions with the gates and doors which were notably higher (**Figure 60**).

The significant differences in the subtotals are the pre-text to the exploration of the categorization of sound type. The sound types were categorized by both the object-centered and subject-centred approach.

Categorization by the object-centred approach indicated that Human (vocal), Activity and Infrastructure were greater at Centre 1 than at Centre 2. Centre 2 had a greater total duration of these sound types: Natural, Indicator, and Neighbour (**Table 12**).

Table 15 Object-centre categorization

Total duration of sound types (seconds)

Category	Sound Type	Centre 1	Centre 2
Natural	bird calls, bird song, water	45	310
Human (vocal)	talking, yelling	1160	975
Motor	road traffic, special vehicles	320	937
Activity	footfall on substrate, roof deck, play equipment, interaction with buildings	925	749
Indicator	sounds of accidents	5	34
Neighbour	construction	0	180
Infrastructure	building related	300	0

Categorization by the subject-centre approach was completed at two levels of refinement. Activity based sound types categorized as Transportation/Work are in greater density at Centre 2 than at Centre 1, and activity based sound types as People Present are nominally the same for both (**Table 15**).

Table 16 Subject-centre categorization Level 1

Total duration of sound types (seconds)

Category	Sound Type	Centre 1	Centre 2
Transportation /Work	road traffic, special vehicles, sounds of accidents, construction, building related, interaction with building	670	1171
People Present	bird calls, bird song, water, footfall on substrate, footfall on roof deck, talking, yelling, play equipment	2085	2014

At the second tier of subject-centred categorization, introducing the People Present categories illustrate that *relaxing* + *nature* sound types occur in greater density at Centre 2 than at Centre 1, and the informational content of sounds, contextual at the neighbourhood scale, in the Transportation/Work - *w/people* is identified at Level 2 as it is isolated in subsets from the sound of road traffic (**Table16**).

Table 17 Subject-centre categorization Level 2

Total duration of sound types (seconds)

Category	Sub category	Sound Types	Centre 1	Centre 2
Transportation /Work	w/people	special vehicles, sounds of accidents, construction, interactions with building	50	236
	w/o people	road traffic, building related, talking, yelling	620	935
People Present	lively	footfall on substrate, footfall roof deck, play equipment	2040	1704
	relaxing + nature	bird calls, bird song, water	45	310

Gabor spectrographs of recording segments from the two soundscapes were generated to provide visual illustrations of diversity of amplitude and frequency within the frequency range from 125 to 4000 Hz. The 10 second sonic snapshots illustrate the overall greater amplitude of sound energy at Centre 1. The traffic background noise at Centre 1 is reduced by the wall enclosure, and one would expect reduced sound energy between 500 to 1000 Hz. However, the noise build- up from the play activities in the highly reverberant space generated higher sound level in the 500 and 1000 Hz band than at Centre 2, where the traffic noise was not mitigated.

Both of these 10 second recordings have children's voices and sounds of their play activities dispersed in the 250 to 500 Hz range and they are distinct in the recordings. The greater diversity is illustrated in the high frequency ranges above 1.5 KHz. At Centre 1, the higher frequency sound energy generated from play activities added to the overall sound energy. At Centre 2, the higher frequency, high amplitude clips of bird song are distinct (**Figure 61** and **Figure 62**).

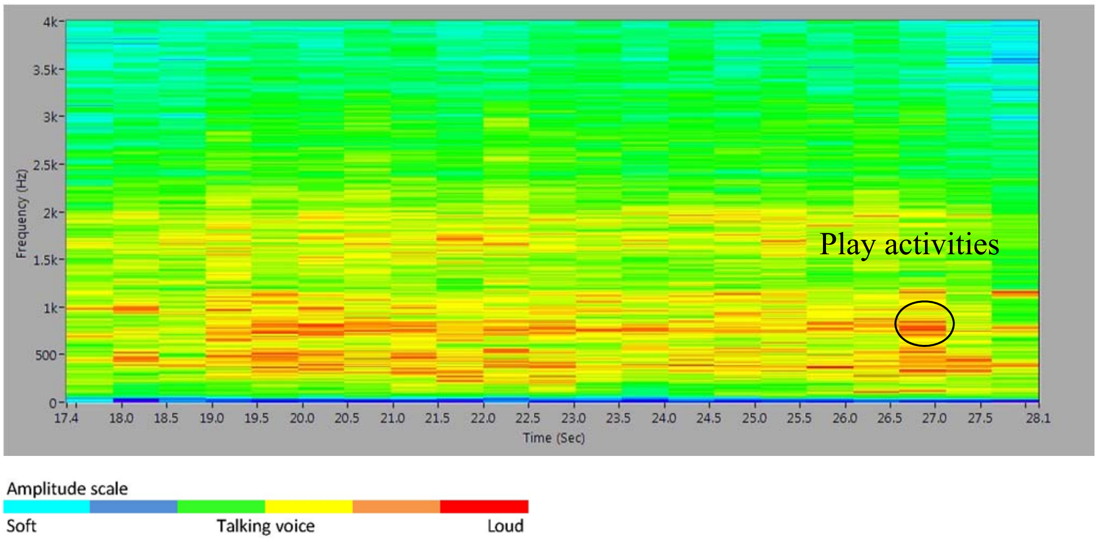


Figure 61 Centre 1- 10 second Gabor spectrogram

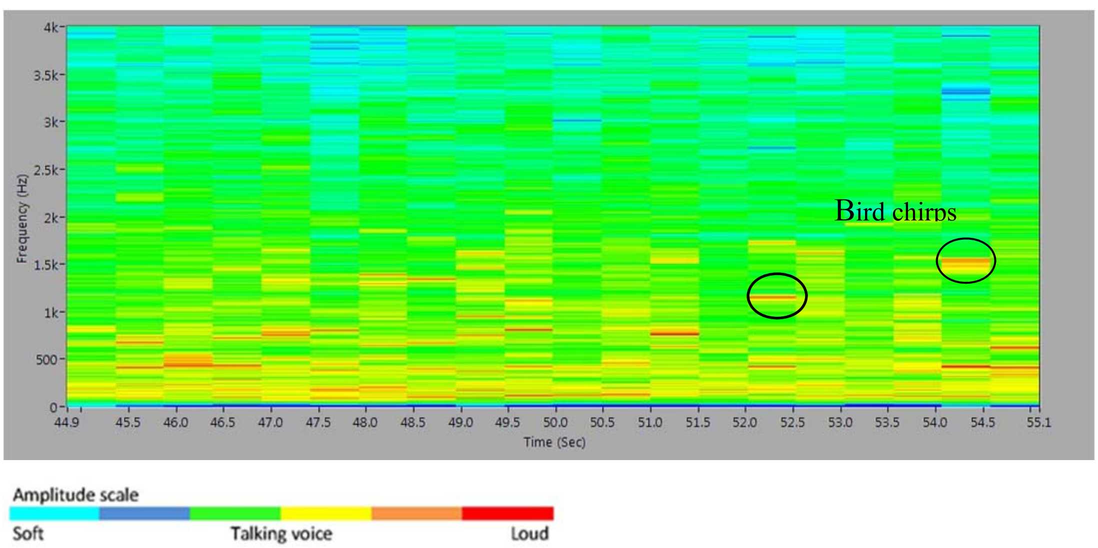


Figure 62 Centre 2- 10 second Gabor spectrogram

Subjective impression of the soundscape

The CHILD researcher's impression

A subjective impression of the soundscape can be extracted from the CHILD evaluation study. The results reflect the researchers' impressions of the soundscapes. The CHILD project 7 C's framework consisted of a 30 point binary rating. "Sound clarity," was the only specific point which rated the quality of the soundscape. The concluding discussion of this chapter presents an extension to the criteria to include the aural modality of perception within the criteria subsets.

Six of the seventeen outdoor play areas in the CHILD project received point rating for sound clarity. Centre 1 received 0 for sound clarity, whereas Centre 2 received 1. The following are excerpts from the transcript of interviews with the employees of the child care centres providing subjective evidence.

- Centre 1 – Staff relay the comparative difference of the rooftop outdoor play to the park. Citing the park as where music and public performances were available to enrich the sonic environment.

- Centre 2 – There was a noted appreciation of the layout of 'quiet areas' and of the soft floor materials and rubber tires of wheeled toys. Also noted was a need to improve the communication between the outdoor play area and the interior of the child care centre.

Subjective interpretation during sound type classification

In order to classify the sound types, this researcher listened to forty 60 second files. The reverberation level of sound at Centre 1 was unusually high. The reverberation and the continuity of some sound types created significant noise build-up which may have masked other sounds generated within the time duration of the recordings. This presents a limit to the sound classification study.

5.4 Discussion

The 7 C's – design guidelines linking the physical conditions of outdoor play areas to child development are presented in this discussion as a model, with an expanded focus on the acoustical and soundscape qualities of the two outdoor play areas. The 7 C's are: Character, Context, Connectivity and Change, Chance, Clarity and Challenge. Descriptions of the 7 C's developed by CHILD are explained in Appendix D. The model illustrates the contribution of vegetated roofs to acoustical ecology and the interactive soundscape.

Summary of CHILD evaluation

An additional investigation of specific and overall ratings of the 17 centres in the CHILD project illustrates the compounded perceptual relationship between the visual and aural modalities of the soundscape. The specific ratings of interest include: softness of material, presence of vegetation and sound clarity. Centre 1 received 0 points for each of sound clarity, softness of materials and vegetation, Centre 2 received 1 point for each of the same. Centre 1 and Centre 2 received a total rating of 10 and 18 respectively out of 30 possible points. The minimum, medium, and maximum overall ratings for the Centres in the CHILD project were 3, 14 and 25 respectively.

The materials of the outdoor play areas were rated in terms of "softness of materials" within the Character criterion. The presence of vegetation was rated in the Change criterion. Six of the seventeen outdoor play areas received a point for "Sound Clarity". Each of the six centres in the CHILD project which received a point for Sound Clarity also received a point for softness of materials and for the presence of vegetation. Of the remaining eleven Centres in the CHILD project which did not receive a point for sound clarity only one received a point for softness of materials and a point for presence vegetation. The relationship between the three parameters provides strong evidence to the known limits of evaluating aural perception within the multi-modal context.

Out of the seven criteria only one criterion (clarity) had evaluation factors which related to the acoustical environment, and only one criterion (clarity) had an evaluation factor for the inclusion of vegetation. However, six of the criteria have the potential to explicitly evaluate the acoustical characteristics of the outdoor play areas and the dynamics of the soundscape. The case study illustrates how the acoustical characteristics and soundscape of the outdoor play areas are affected by the presence of vegetated roofs. The acoustical and soundscape impact of vegetation on rooftops is evident in the spatial and material analyses, the sound type categorization and the subjective analysis.

The investigative components of the ambient sound analysis (background noise levels from road and traffic noise, spatial and material analysis, sound type classification and subjective evaluation) provide the framework and the evidence to expand the seven criteria to include the sonic aspects and the aural perception of the outdoor play areas. If these criteria are revisited by future researchers – the additional sonic information may yield a richer assessment tool.

The cross-scale investigation of background noises defines the factors of the Context and connectivity criteria. The spatial and material analysis provides the evidence to evaluate the elements with the criteria of Character, Connectivity, Chance and Challenge. The work completed on sound type categorization contributes to the evaluation of Context, Connectivity and Change. The subjective evaluation provides evidence to evaluate sound clarity.

Character

The five archetypes of the Character criterion (‘late modern’, ‘modular’, ‘organic’, ‘metaphor’ and ‘re-use’) have a visual design bias, and as such, not all of them can be wholly applied to the aural modality of landscape and architectural design. The form and materials of a space which evoke the character of a space also define the boundaries and objects which transmit, absorb, reflect, diffract and diffuse sound within the space.

In terms of the sound character, three of the archetypes can be considered acoustically descriptive. 'Late modern' and 'modular' denote manufactured systems, and smooth reflective architectural materials. These archetypes also suggest a sonic character of low sound diversity and high reverb. The 'organic' archetype denotes natural materials and a sinuous layout, as well as a sonic character which is non-reflective, quiet, and has a high level of sound diversity. Vegetated roofs nominally fit within this archetype. Neither the 'metaphor' nor 're-use' archetypes have an independent association specific to sonic characteristics.

The spatial and material analysis identifies the acoustical subzones, the contribution of the reflective and absorptive materials and the vegetation to the sonic character of the centres. Centre 1 was categorized as 'modular' and Centre 2 as 'late modern' by CHILD. The categorization of 'modular' is acoustically valid for Centre 1 as the reverberant quality of the outdoor space is analogous to an interior space. The acoustical subzones of Centre 2, defined by the colossal architecture, can be aligned sonically with the 'late modern' archetypes as designated by CHILD. As a whole, the outdoor play area is coupled with the exterior environment, through the vegetated edge. The interface with the urban soundscape occurs within the edge subzones defined by the architecture and vegetation. The small grass vegetated roof and tree canopy creates and defines a unique acoustic subzone.

Context

Each of the three defining aspects of the Context criterion has an acoustical association. These are site location and transparency within the city, the number of children/area of play, and the microclimate. The site location provides the context for the urban soundscape. The materials which define the transparency between outdoor play areas and the city ultimately affect the propagation of sounds from the community. The background noise level analysis and the sound type classification are used to describe the sonic context. In any context, information can be extracted from the soundscape. From the children's perspective, what is the type of vehicle? Why are they here/there? Is the vehicle here for the site or passing on a route through the neighbourhood? What is happening around the play area? How does rush hour and the rhythm of the traffic relate to the cycle of the day?

The enclosure at Centre 1 was designed around the open perimeter to limit road and traffic noise to a maximum of 55 $L_{24\ hr.\ eq}$ dB(A). This barrier reduces road traffic noise and limits valuable information being transmitted to the play area. With or without the wall, enclosure noise levels from the community any further than a block away would rarely reach the ears of the children on the rooftop. Whereas, for Centre 2, the road noise level is relatively the same throughout the immediate neighbourhood up to one block on each side and further in the front and side aspects. The events which happen in the far distance, fire trucks and ambulances, street events and even the change in traffic flow due to events at the hockey venue, would be informed to the children through aural perception. The roof vegetation at Centre 2, creates an acoustical interface with the street trees below facilitating bird song and seasonal variation of natural sounds.

The sound type classification also informs us of the contribution of the children's play to the soundscape and the capacity of a vegetated roof to introduce a higher diversity of sound types to the rooftop area. The children are central to their soundscape. The density of children in an area and the diversity of individuals alter the sound level and the frequency spectrum of speech for communications and vocal dynamics of play. Increasing vocal sound levels as a response to the sound level of surrounding voices is generally known as the Lombard effect (Janqua 1996). Vegetated roofs can provide increased absorption and reduce noise build-up in an acoustical subzone, attenuating the Lombard effect.

In the same manner that spaces are exposed to sun or are in the shadows, spaces can expose or shield a child from noises and sounds. The micro-climate of the play area also creates sonic characteristics with the play area, such as wind and all types of precipitation.

At Centre 1 the sonic transparency with the urban fabric is not fully eliminated by the window wall enclosure. However, the sounds are perceived as external as they transmit through the glazing and diffract over the wall. The Centre is located at the sidewalk edge and mid-block of a six-lane arterial street with intersections within 100 metres at either end of the play area. The enclosure effectively eliminates vocal level (50 – 60 $L_{24\ hr.\ eq.}$ dB(A) sounds from the sidewalk. The traffic background noise, as indicated on the noise level mapping, masks informational sounds from sources located more than one city block away. As such, the urban context is acoustically foreshortened to the immediate surroundings. The area per child at 8.75 m^2 is higher than the recommended density. The acoustical impact of the higher density is further compounded by the full enclosure and the acoustical subzones. The large acoustical subzones of the ceiling area could enable children in protected areas to engage in listening to sounds of nature such as raindrops as they fall on the hard ground in the open area. The enclosure eliminates the potential for sounds which could be generated by the wind, such as chimes or bells.

The children's soundscape at Centre 2 extends east and west of the outdoor play area by several city blocks. Informational traffic sounds, such as sirens from several blocks away and the sounds of vehicle back-up signals from at least one block away, can be perceived in the play area. The informational sounds can be heard because of the sonic coupling of the outdoor play area to the community and the noise level contours. The density, 10.6 m^2 per child, is acoustically mitigated by the diversity and distinction of the acoustical subzones and, when dynamics of the children's interaction permits, quiet subzones can be realized. The subzones defined by the architectural form can provide limited shielding from other activities and the traffic background noise. The vegetated roof area, the vegetation in the play area boundaries and the perimeter trees provide a connection to the street trees within the urban fabric. The birds which visit the trees and ground coverings are evidence of nature and the extended community.

Connectivity

The sounds which transmit between indoor and outdoor spaces contribute to the connection between the two spaces and provide the opportunity to exercise aural senses, and an increase in the use of proprioceptive information. The sound of wind or rain is information suggesting more layers of clothing are required before going out to play. Similarly, the sounds of pots and pans of lunch time or snack preparation are informational and indicate that a transition is about to occur.

The form and materials of acoustical subspaces can support communications and provide connectivity between places and elements within the outdoor play area. Pathways and elements in the outdoor play area could be designed to a scale responding to the children's spatial and temporal levels of aural perception and communication to provide opportunities and security within the soundscape.

The acoustical connectivity between the interior and exterior area at Centre 1 can be controlled through the doors and windows. The acoustical connectivity between the places and elements in the outdoor play area itself is high and may in fact not be clear due to the embedded layout of the acoustical subzones. The sound mark of the elevator is effectively the only acoustical relationship between the interior and the exterior areas of Centre 2. The radial centre path through the outdoor play areas facilitates communication, connects activities and connects the acoustical subzones.

Change

In terms of the acoustic environment, the criterion of change evaluates the play area's capacity to accommodate the children's needs to find aural variations. For example, quiet spaces, private spaces for communication in pairs or small groups, spaces to create exciting loud sounds and spaces to engage with the extended urban soundscape. As the children move through the soundscape, they have the opportunity to be self-empowered and have a sense of control in how they are involved with the soundscape. The acoustical subzones illustrated identify the relationship between the materiality of a space and the children's activities within it.

The children's aural perception can also identify change in the temporal cycles of activities and change associated with the sonic characteristics of plants, grasses and tress. Vegetation is not only habitat for songbirds, it also provides opportunities for children to create different sound through the seasons, stepping through long grasses, crunching leaves and splattering mud, for example.

The acoustical subzones in the outdoor play area at Centre 1 are not sufficiently isolated to create quiet areas; however, the wood deck corners and the inside of the play house and climbing structure would allow for intimate communication between two or three children. The ground material and activity circuit with tricycles promote the generation of loud sounds in the open portion of the play area. The seasonal changes of vegetation as they contribute to the soundscape are not apparent at Centre 1. The form of Centre 2 and the acoustical subspaces as they overlap with the green roof, vegetation and perimeter trees and ground covering provide seasonal changes in the soundscape through seasonal habitat, children's interaction with grasses, the leaves in different states and the wind song through the trees.

Chance

In terms of the aural modality of Chance, play can facilitate the opportunity to create sounds and to explore the spatial and temporal continuities of sound through material manipulation and physical interaction with building components and within different acoustical subzones.

'Sonic playgrounds' are designed specifically for creativity and exploration through aural perception. Building materials can be designed as play equipment such that active interface generates sounds which are enjoyable and within a frequency range and amplitude appropriate for the acoustical subzone. An example of sonic play equipment includes board walks and tubular rails of taut wires supporting vertical plant growth and objects which respond sonically to wind and rain. Although the sounds generated from shaking and tapping robust trees and shrubs and crunching fallen leaves cannot be tuned, they can be experienced by chance.

In both centres, riding the tricycles on the wooden deck bridges and pavers generate sound. However, in neither centre was this purposefully designed towards a desired sonic outcome. In fact, at Center 1, the plastic tires of the tricycles generate many of the undesirable sounds which create noise build-up. Neither centre purposefully embraced the concept of the sonic playground with form, building materials, sound objects or vegetation.

Clarity

Clarity is the single criterion which explicitly addresses the soundscape. The primary research evaluation requested a rating of the 'sound clarity' of the out-door play area.

"The nosier outdoor play spaces created a general atmosphere of confusion and stress was noted in both early childhood educators and the children." (Herrignton 2006).

Centre 1 did not receive a rating point for sound clarity. Sound clarity was considered compromised at Centre 1 due to the perceived level of reverberation and the noise build-up from the tricycle wheels on pavers. Centre 2 received a sound clarity rating.

Challenge

The association with this criterion aligns again to the concept of a sonic playground, where the use of materials and form can provide positive challenges in play and provide the potential for children to contribute knowingly to the soundscape. For example, some playgrounds have pipes that allow for communication across the playground space. Challenge could be found in parabolic shaped walls, built to the scale of a child, which amplify whispers and challenge the spatial dimension of communication, or focal points notated in the ground plane for interactive sonic play. When a child is offered the challenge of listening to nature as offered by vegetated rooftops, the challenge will exist. Centre 2 has a significantly greater opportunity than Centre 1 to realize the early childhood education programs of listening to and interpreting informational sounds and sounds from nature.

5.5 Chapter Summary

This chapter presents case study research on the capacity of vegetated roofs to change the balance of the rooftop soundscapes. A detailed investigation of two programmatically similar rooftop spaces was advanced to investigate relationships within the soundscape – among contextual sound, sounds generated by the users' activities, architectural form, building materials, and vegetation. The two rooftop sites selected each have a child-care centre outdoor playground.

The chapter précis to the research includes a literature review on the developmental benefits of outdoor play and a balanced soundscape (a soundscape which includes natural and mechanical generated sounds); and a review of design strategies to support child cognitive development in outdoor play areas. The case study method includes a four-part ambient sound analysis; an examination of the urban context in terms of traffic background noise, an examination of the spatial and material qualities of the outdoor play areas which identified the inter-relationship between the architecture and sounds, two trials of sound type categorization, and an evaluation of subjective aural impressions of the soundscape.

The centre without a vegetated roof had a wall enclosure designed to mitigate road traffic noise (Centre 1). The centre with a vegetated roof in the outdoor play area and on roof of on upper stories had an open aspect to the street below, which was further defined by ground covering and an edge row of specimen trees (Center 2). The road traffic noise was modeled to be above the 55 dB(A) as required by municipal guidelines. The illustrations which resulted from the spatial and material analysis notate the acoustical subspaces at the centres and the contribution of the vegetated roofs to sonic definitions of spaces. 15% fewer sounds were documented in terms of total duration at the Centre 1 than at Centre 2. The plants within and surrounding Centre 2 provided habitat for birds and created the requirement to use water from hoses for irrigation and clean-up. The amplitude and the frequency range of the identified sounds at the Centre 1 were typically higher compared to Centre 2. Clarity, diversity and distinction of sound types and communication and were noted in the subjective analysis.

The research benefited from the secondary use of findings from a non-acoustical study of the same sites by the CHILD research consortium. In turn, the final outcome of the research provides an expansion, in an aural modality, to the 7 C's design guidelines which the CHILD consortium developed to link the physical conditions of outdoor play areas to child development. The 7 C's are: *Character, Context, Connectivity and Change, Chance, Clarity and Challenge*.

The investigation identifies that background sound from road traffic noise provides information on the site *context* and *connectivity* to the extended community. Vegetation at the roof top level creates a continuum of bird and insect habitat from the street level tree canopies to the rooftop. The contribution of contextual sounds and bird sounds to the soundscape was numerated in the sound type categorization process. The vegetation on the roof level contributes to the aural concept of *change*. The change in the child's environment that is attributed to vegetation is experiential; the material interface introduced by a vegetated roof impacts activity generated sounds. The sonic attributes of the vegetation are altered through seasonal and life cycles. Interactions, such as running through grasses, searching through plants, maintaining and nurturing vegetated roofs and plants, increase the *chance* and *challenge* opportunities for children to create and identify sounds. The vegetated roof's capacity to decrease sound reflection contributed to the sonic *clarity* of the outdoor play area.

CHAPTER 6 Conclusion - Considerations towards Design

This research quantifies the multiple acoustical benefits of vegetated roofs. The capacity of vegetated roofs to increase the ecological performance of buildings and contribute in a positive manner to the urban soundscape was determined by investigating the acoustical characteristics of vegetated roofs. The four major investigations within the scope of this dissertation research identified the acoustically relevant specifications for the blending of substrates used on roofs, measured the sound absorption of vegetated roofs, contributed to the research on sound transmission through building envelopes by completion of novel measurements over gradients of substrate depth and plant establishment and introduced the concept of rooftop soundscapes demonstrating that vegetated roofs alter the balance of sound within the urban soundscape. The research has confirmed the original working hypothesis that vegetated roofs increase the sound transmission loss of roof systems, increase the sound absorption of the roof surface, and alter the urban soundscape as it is perceived whilst inhabiting rooftops.

This final chapter outlines the key findings of each research project and the manner in which each project relates to the interdisciplinary study of vegetated roofs and architectural design. The findings are presented in an interdisciplinary manner as instructional design principles for landscape/architects that may employ vegetated roofs as an ecologically-based technology to address the acoustical qualities of the interior of buildings and of soundscapes on rooftops. The overall significance of the research to the architectural acoustics and soundscape planning of rooftops is presented in a discussion of the application of research findings to the design process. Future research directions related to the interdisciplinary nature of vegetated roofs, acoustics, soundscapes, landscape and architectural design are also presented.

6.1 Research Findings Translated to Design Principles and Applications

Vegetated roof substrates

Substrates can be specified with a blend of materials that optimizes their sound absorptive qualities. The key findings from the measurement of a range of vegetated roof substrates include determination of the sound absorption (NRC) of the substrates, confirming that they can provide significant sound absorption, and the determination of the acoustically relevant characteristics and properties of the substrate which have significant impact on absorption (porosity, percentage of organic matter and moisture content).

- *More organic matter in the substrate will increase sound absorption.* Typically, extensive vegetated roofs have a low percentage of organic matter. In the Pacific Northwest, the mean percent of organic matter specified is 14%. However, in Germany, 8% organic matter is recommended (FLL 2002). Intensive vegetated roofs, which support shrubs and trees, have as much as 5% higher percentage of organic matter. The low percentage of organic matter is beneficial to the viability of specific plant communities, such as sedums, and allows a reduced maintenance regime by lowering the survival of volunteer species and insuring the structural integrity of the substrate over an extended time (Dunnett 2004). However, these findings suggest that in order to optimize the sound absorption potential of vegetated roofs, a higher percentage of organic matter is beneficial.

- *A decrease in water content will increase the sound absorption of the substrate.* Typically the substrates used in extensive vegetative roofs have a lower maximum water holding capacity than in intensive roofs. The results confirm that sound absorption decreases with the moisture content. Therefore, an AWC with a lower wilting capacity, which can support a carefully selected palette of drought tolerant plants, is also beneficial for sound absorption. Likewise ensuring proper drainage through roof slope and a drainage board layer is not only critical for plant viability but also for improved sound absorption.

- C*ompaction reduces the absorptive properties of the substrate.* Strategies to reduce excessive compaction during construction and occupancy, such as dedicated or elevated walkways, are in the interest of maintaining the structural integrity of the substrate for plant viability and maintaining the substrate sound absorption characteristics.

A frequency dependent multi-variable regression model was developed to predict the normal incidence absorption coefficient of substrates. Soil test parameters common in the specification of substrate blends are used as the required inputs. These are percentage of organic matter, porosity, moisture content for the ranges of plant viability (at wilting and field capacity) and a factor describing the state of compaction. Increasing the amount of organic matter by 12.5% causes a proportional increase in the absorption coefficient of 9%. As the moisture content of the substrate increases within the range for plant viability, from wilting capacity to field capacity, the percentage of sound attenuated by absorption decreases by up to 26%. In-situ compaction reduces sound absorption by 10%.

The vegetated roof acts as a sound attenuating absorptive ground on the roof

Although porosity and VWC were identified as the acoustically relevant parameters affecting the substrates, the in-situ roofs represented the complexity of porosity and moisture content in established plant communities. The effect of vegetation in soil on vegetated roofs is through the biological and physical inter-relationships of organic matter, aggregates, organism in the soil and soil temperature (van der Heijden 1983). Vegetation types and coverage affect the porosity of the vegetated layer and water content to a different degree in each gradient depth of substrate.

- *The absorption coefficients of vegetated roofs range significantly over the frequency range of interest.* The findings from the measurement of the sound absorption of in-situ rooftop plots indicate that vegetative roofs have the potential to absorb between 20 and 60% of the incident sound energy. Sound absorption increased with frequency up to 1000 Hz and then remained constant up to 4000 Hz.

- *The absorption coefficient was not dependent on the gradient of depth in vegetated roofs.* Although measurement of a gradient of non-vegetated substrate depth indicated an association between absorption and depth, it was found by measurement on three established plant communities that the NRC does not have an independent association with the depth of substrate *between 50 and 200 mm*.

- *The type and establishment of the plant community on vegetated roofs affect the level of sound absorption of a vegetated roof.* The established moss-sedum communities reduced the sound absorption relative to unplanted substrate and relative to low coverage vegetative roofs (20%). Moss retains water at the surface level as it does not have roots to retrieve the water from deep in the substrate. This presented a greater change in the impedance to the sound waves relative to the porosity of the substrate. The deep rooted species coastal meadow community and the grasses community had higher levels of absorption relative to the mosses.

- *The vegetated roof with highly absorptive properties can be used as a source control for rooftop mechanical equipment noise propagating over the roof plane.* Total sound pressure from a source as it propagates over distance is attenuated by a combination of effects. On a rooftop, without the interruption of a physical barrier such as a parapet wall or other rooftop apertures, a vegetated roof, as a highly absorptive surface, will provide additional attenuation at all frequencies due to its absorptive characteristics (known as ground effect), and will have an additional effect on sound waves propagating over the rooftop at angles less than

5° (known as grazing effect). The attenuation due to grazing will have an additional impact on the roof level especially as distances on a roof are generally short relative to the wavelength of the lower frequency bands of noise that mechanical equipment emits.

- *Street level noise will be attenuated as it propagates across the vegetated roof.* Current research by others indicates that the absorptive characteristics of vegetated roofs reduce the propagation of road traffic noise and isolated point source noise which diffracts over the roof edge from street level (van Renterghem 2011).

- *The absorption capacity of vegetated roofs will reduce reverberation within roof top spaces enclosed by walls*. The absorption of the noise on the vegetated roof surface will mitigate reverberation and noise build-up by reducing the reflection of sounds from equipment and activity, such as foot traffic and movable equipment, from typically highly reflective building materials. The degree of enclosure, the materials and vegetation affect sound reverberation within the space. Rooftop architecture can be archetypically categorized by physical form - 'free-field', 'podium' or 'rooftop court' - each having different acoustical characteristics. Vegetated roofs can contribute to the acoustical quality and soundscape of each of these archetypes to varying degrees.

The freefield rooftop is defined as such when only the roof plane exists (precluding the impact from access stairs or elevators). This space has no reverberation and without enclosures only the vegetated roof can contribute to an attenuation of intrusive sounds from beyond its boundary. A podium rooftop has one adjacent wall which can be shielding to intrusive noise, and can provide sound enforcement and directivity. The rooftop court is an outdoor room enclosed by four walls. This enclosure can reduce intrusive sounds from beyond its boundaries; however, even with an open-to-the-sky ceiling, the space can have high reverberation due to the reflective properties of typical building envelope materials. Introducing vegetated roofs into this space can increase the total absorption in proportion to the floor area divided by the total wall and floor surface area.

Adding a vegetated layer to a roof reduces sound transmission

- *Extensive vegetated roofs increase transmission loss up to 10 dB at low frequency, up to 20 dB at mid frequency, and more at high frequencies, relative to a comparable reference roof.* Field transmission loss measurements were completed on vegetated and non-vegetated roof systems; the wood-framed roof decks at the field site and light-weight steel decks at the indoor-to-outdoor transmission facility are in general agreement. The transmission loss of the vegetated roof increases with frequency at 5.5 dB/octave in the lower frequencies; above 500 Hz transmission loss increases at 11 dB/octave. In the lower frequencies, the additional material layers, substrate and plants increase the mass impedance and, above the coincidence frequency, the vegetated layer increases the bending stiffness impedance. The composite impedances increase with depth of substrate.

- *Transmission loss prediction of the vegetated roof does not adhere to mass law prediction.* Roofs can be modeled as single-panel partitions and, as such, at frequencies below the region of coincidence, where mass impedance is predominant, additional mass per unit area is predicted to increase transmission loss by approximately 6 dB/doubling of mass and at an increase of 6 dB octave band. However, measurements of transmission loss of vegetated roofs are not in agreement with mass law. Mass law assumes a solid mass and the porosity of the substrate and the vegetated layer reduces the effective mass. Root masses which significantly increase the porosity of the vegetated layer reduce transmission loss as the plant community establishes.

- *The measured transmission loss values presented here will allow architects to purposefully select the vegetated roof as a material solution to reduce the transmission of noise sources through the building envelope.* These results can be specifically applied towards architectural situations requiring mitigation of low frequency noise. The noise may be external and the program criteria meet a maximum acceptable noise level of exterior noise within an interior space, such as in residential and mixed-use densification development below urban flight paths. Alternatively, the noise level may be internal, and the acoustical design objective to meet city noise level ordinances and zoning requirements; night clubs in mixed-use down-town zones and district water pump stations which operate through the night in residential communities are examples of building occupancies which could benefit from vegetated roof technology.

- *The vegetated roof has higher performance in mitigating low-frequency noise than many non-vegetated roof systems and ceiling combinations.* The vegetated system can be used to eliminate the requirement for insulated ceiling plenums commonly used to mitigate sound transmission. This allows a freedom in the design of the interior spaces and, given the consideration to the multiple benefits of vegetated roofs, a reduction of material and cost resources may be realized.

The urban soundscape experience on the rooftop is altered by a vegetated roof

- *The balance of natural sounds changes with the inclusion of the plants on the roof.* In the case studies investigated, the centre with plants, trees and vegetated roofs in the occupied areas and on roof levels above had more than six-times the incidence of bird calls, bird sound and sounds of water than the centre without vegetation.

- *The soundscape is altered by the absorptive characteristics of the vegetated roof,* In the case study, a 15% reduction in footfall, with a discernable difference between the frequency of footfall on substrate and footfall on hard deck, and a similar reduction in voices and sound from play equipment, can be attributed in part to the absorptive floor deck. The floor deck was in part vegetated roof and in part rubber tile, both of which had a NRC greater than 0.3. The absorptive characteristics of the vegetated roof are discussed above.

- *The attenuation of the street level sounds alters the contextual soundscape.* Sounds with semantic content define the context of the site. Sounds are attenuated by distance from street level to the roofs and can be further attenuated across the field of the vegetated roof.

- *The interaction people have with the vegetated roofs - walking through them, watering and maintaining the plants - alter the soundscape.* On the rooftop, natural sounds can be introduced through plants, the habitat supported by plants and through peoples' interactions with the plants. The sound of windblown plants and trees contains context information regarding the external environment and the plants - as different leaf and branch structures generated sounds at different frequencies and rhythms (Dramstad 1996). The sounds of water, an integral element for the viability of vegetated roofs, can be enhanced through the design of water harvesting and distribution.

- *Birds and insects which inhabit vegetated roofs introduce new sounds to the roof level soundscape.* Appropriate vegetated roof plant species will provide habitat for songbirds, bees and even crickets. Land transformation changes in the materiality of the sonic environment in which birds communicate. Communication between birds is predominantly free-field orientated; at an urban scale, changes in the acoustical properties of the urban environment have affected the ability of bird species to communicate (Gedge 2005, Luther 2010).

6.2 Application to the Design Process

The demand for vegetated rooftops will increase with the escalation of urban densification. The acoustical and soundscape benefits of vegetated roofs will only be realized if design professionals (urban planners, landscape architects, architects and engineers) recognize the potential of vegetated roofs and embrace a design program in which the sonic quality of occupied spaces on rooftops is of concern. These findings determining the transmission of vegetated roofs can contribute to standards and codes pertaining to sound transmission performance. Landscape/architectural design teams require more vocabulary and parametric design processes to assess and respond to the sonic environment (de Coensel 2005). Additionally, acoustical performance criteria and soundscape planning are required for programmed space on rooftops in design processes and urban planning policies. Acoustical design guidelines for dynamic non-classroom learning spaces and soundscape planning for outdoor space are currently developing as research interests in the interdisciplinary fields of acoustics, communication and education.

The case study findings will contribute to the enhancement of aural perception as it affects childhood cognitive development and health. The case study of two rooftops extends existing design guides for outdoor play areas of child-care centres to address the acoustical design and soundscape of outdoor play areas. The findings can generalize the contributions of vegetated roofs to rooftop architecture, and provide instructional guidelines which can be applied to the acoustic design and soundscape planning of rooftop spaces

The contribution of vegetated roofs as a design solution to meet an acoustical program and for soundscape planning is site specific and depends on the overall design of the building and the site context. Urban places such as parks and courtyards have been identified as having opportunity, through soundscape planning, to increase the aural experience and human enjoyment (Ulrich 1991, Kaplan 1998, Brown 2004). Rooftops can now be added to this list.

Discussions required to enable vegetated roofs as solutions to some of the acoustical challenges in current architecture are: first, the development of design guidelines; second, design processes which best incorporate the design guidelines; and, third, an expansion of post-occupancy evaluations to include positive sound, creating a feedback loop from which acoustical design and soundscape planning can be further enhanced. Each of these discussions constitutes an essay on the future research directions in this interdisciplinary field of landscape/architectural acoustics.

Theoretically, the acoustics of rooftop architecture could be evaluated against criteria to address a range of acoustical concerns in architecture; these include: existing criteria for maximum acceptable levels of road and traffic noise in specific outdoor spaces; a criterion for quality of speech communication; and a criterion for reverberation. In addition, a notation system categorizing spectral balance and sound types must be adopted in order to fully understand the site context during the design process and for the evaluation of design during occupancy.

The case study illustrates that in order to reduce road and traffic noise, contextual information about sound and sound type diversity were lost. Alternatively, where the road and transportation noise was constantly audible as background noise, and was not mitigated at the perimeter, the proportional range of informational sounds from the community and natural sounds attributed to rooftop vegetation was significantly higher. Additionally, sound clarity and quality were perceived as high. The single criterion of maximum acceptable levels of road and traffic noise used for private spaces from personal balconies in multi-family housing is not transferable to active rooftop uses. The maximum noise level for programmed outdoor space should be reinvestigated with a goal toward developing activity related sound level criteria. The design team could then respond with activity based acoustical subzones spatially delineated and resolved with material selection.

Noise criteria for mechanical equipment noise in the outdoor environment, let alone for programme rooftop uses, have not been established. In order for criterion to be applied to various environments, the maximum allowable sound level for rooftop mechanical equipment should be set relative to road and transportation noise, at 10 dB less than road and traffic noise (half the sound level).

The ability to communicate without audio or vocal stress and within an acceptable range of privacy and intelligibility is a desirable characteristic of a rooftop place. Speech communication acceptability of a space is acceptable depending on the activities, associated vocal levels and the dimension of the acoustical space. To explore the relationship between activities and acoustical subzones on roofs a rating system for determining comfort levels of communication in a normal voice, communication voice and shouting could be adopted. An existing matrix relates the physical dimensions of space, to a measure of background noise, on the X-axis. (Webster 1969).

In the context of podium and courtyard rooftops, the spaces may be highly reverberant. Acceptable levels of reverberation are based on speech intelligibility, perception and expectation. It is not unreasonable that the expectation of vegetative outdoor space is, for the most part, non-reverberant.

With the surge in sustainable planning practices and the adoption of green building rating systems, programming and design are evolving from a traditional linear process to integrated design processes and, most currently, to parametric design processes. This must be a point of entry for design professionals to address the acoustical quality of outdoor spaces and utilize new knowledge of the acoustical characteristic of vegetated roofs and their potential contribution to the ecological performance of the building envelope and the soundscape. Emerging design methodologies have the inherent capacity to effectively challenge institutional policies, design and construction guidelines and to inform, if not create, the performance criteria.

A growing number of buildings and communities are now being designed in accordance with sustainable building practices (Teed 2007, Williams 2007). Supporting these practices are a number of green building rating systems, such as LEED®, BREEAM and CASBEE (McLennan 2006, Zimmerman 2006, Sakuma 2006) Vegetated roofs as a sustainable building technology have been incorporated into the building rating systems. Acoustics and soundscapes have not been fully integrated into sustainable building practices or green building rating systems in North America (Hodgson 2008). A broader based ambient sound analysis, incorporating empirical acoustical measurement and an interdisciplinary collaboration with the physical sciences of landscape, architecture and engineering can potentially bridge the methodological design gap.

A multitude of tools are required to embed acoustical design and soundscape planning into the design process of a vegetated roof. The dissertation research findings, with existing and new design and computational tools, can be used to understand the sonic context of a site and predict the behaviour of sound at the roof level. The design team must make a sound walk of the site and listen in order to understand the sonic context of the site. The subject-centered categorization approach provides landscape/architects with a framework for site analyses, and can be an effective design tool to create improved soundscapes. Sketching tools using such as sound mapping can take clues from the graphic output of the environmental noise maps and create overlays on the schematic site / building layout drawings generating graphic notations of predicted sound fields. This could be done in a manner that is visual for quick interaction and response, assisting all the members of the design team in visualizing the impact on the acoustical environment of each and every design decision including spatial relationships, material selection and building systems.

Vegetated roofs can be used to address some of the dissatisfaction with the acoustical environment. Many of these dissatisfactions have been identified through post-occupancy evaluations (Huizenga 2005, Abbaszadeh 2006). However, the post-occupancy evaluations focus on noise rather than on a neutrality of sounds. Post occupancy evaluations could be expanded into a neutral context to account for noise and informational sounds between the acoustical subzones and from beyond the site, from the block, neighbourhood or community.

Additionally, the discourse on adaptation to design methods and guidelines which will facilitate the realization of the positive attributes of vegetated roofs to roof top architecture, and the breadth of the interdisciplinary nature of vegetated roofs, acoustics, soundscapes, landscape and architectural design, create many more avenues for future research questions which had not been previously formulated.

In consideration of vegetated roofs as a sustainable construction technology, a number of further investigations are required that were not within this scope of research. In the area of sound transmission, the determination of the effective mass of vegetated roofs as a function of the porosity of the substrate and established root mass will benefit the modeling of transmission loss of vegetated roofs. Additionally, the effect on the total absorption and reverberation time of the interior spaces below vegetated roofs can be qualified. The focus has been on air-borne sound propagation, yet it is not unreasonable to assume that vegetated roofs will substantially reduce structural-borne sound generated through impacts on the roof deck. This should be substantiated as an additional benefit of vegetated roofs. High sound reflections from urban surfaces are known to affect communications within bird communities (Roberts 1979, Parris 2009). In cities with a sufficient density of vegetated roofs, the impact on bird populations due to an increased absorption offered by vegetated roofs may be investigated.

Many of the design principles of vegetated roofs may be applied to vegetated façades. Current research has been initiated on modeling the acoustical potential of vegetated façades (Wong 2010, Van Renterghem 2011). Acoustical characteristics and soundscape parameters of vegetated façades will likely follow. Vegetation planted in proximity to the building or elsewhere on the building site is known to have some acoustical benefits (Robinette 1973, Kotzen 2004); interfacing the vegetation directly with the building envelope will provide greater effect on the noise, and a comparative study of cost and effect of the use of resources is in order. Finally, the capacity of vegetated roofs to stimulate and engage human affinity for nature through soundscape enhancement may be revealed through further research.

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Appendix A Physical Properties of Vegetated Roof Materials

As a sustainable construction technology, vegetated roofs have a potentially positive impact on habitable building areas and the sustainable densification of the built environment. The design, construction and ongoing maintenance of vegetated roof systems vary with respect to their design intent and material components. This section provides a summary review of vegetated roof systems and of a system's layered material components.

Systems

Generally, vegetated roofs can be categorized into one of two classifications: intensive or extensive. A vegetated roof can also be a blend of systems, termed a "semi-intensive" vegetated roof. Intensive and extensive vegetated roof systems can be installed on both conventional and protected membrane roof systems by incorporating additional components, such as a root barrier, a water reservoir/drainage layer, a filter fabric, and a substrate to support growth of vegetation. The design intent is a key factor in determining substrate depth and plant selection of any vegetated roof. The intended utilization, substrate depth and plant selection determine the vegetated roof classification.

Intensive vegetated roofs are often referred to as "rooftop gardens" and, with a depth of substrate of over 200 mm, can support diverse plant species and dynamic landscape design, and can facilitate urban agriculture and amenity spaces. Irrigation and maintenance are required over the long term as required by the selected plant species. An intensive vegetated roof is classified as occupied space. Fullcompliance to the building code includes meeting performance requirements for access walkways, railings, lighting and egress.

Extensive systems are commonly referred to as "vegetated roofs" or "living roofs" or "eco roofs." An extensive vegetated roof is a vegetative roof system engineered to provide environmental solutions. These roofs are intended to be low-maintenance and to have only temporary irrigation systems for the limited time frame of plant establishment. Limited palettes of drought-tolerant plant species that can withstand extreme and adverse environmental conditions are selected. The extensive vegetated roof is based on a shallow soil profile of up to 150 mm (6 inches). It can often be installed on buildings without significant cost for additional structural loading. Extensive vegetated roofs usually require less maintenance and are less expensive to install than intensive vegetated roofs. Typically, an extensive vegetated roof is not designed for occupancy and is not accessible for purposes outside of maintenance requirements.

Vegetated roofs can be supported on wood frame, steel or concrete building structures; the supporting roof deck may be plywood, corrugated metal roof or concrete. Vegetated roof systems have an additional dead load of the material component, substrate and vegetation and a live load of transient water which must be defined. These loads can be defined through ASTM procedures and are additional to all other loads defined by code, including snow loads and occupancy loads. The use and life cycle of the vegetated roofs may create temporary and/or additional loads over time, such as installation equipment and mature plant weight.

Extensive vegetated roof systems typically have an additional dead load of 65 to 175 kg/m^2, depending on the depth of substrate. The extensive roof is relatively light compared to an intensive system, which may have a minimum load of 450 kg/m^2 due to the substrate and addition of the live load associated with occupancy. The extensive system does not have a significant impact on short-span structures in wood frame, engineered wood, structural steel or concrete. However, the associated loads of extensive systems are considered substantial in long-span structures.

Vegetated roofs can be sloped; the degree of slope determines whether additional construction techniques are required to retain the substrate. Recommendations in the FLL guidelines are: for slopes >3° to use a retention system and substrate with high water storage capacity, and use vegetation with low water demand; for slopes >20° (36%), use specific systems to protect against shear and sliding; for slopes >30° (58%) to a maximum of 45°, advanced engineering design is required.

Roofing has developed as a technology over the past 30 years. Several high quality alternatives for the waterproof membrane exist. The building design and roof form should determine the selection of the waterproof system, as it would without a vegetated roof system. The type of roof deck, location, life cycle and availability of a system applicator impact the decision to use one of the following: hot liquid applied membranes, two-ply Styrene Butadiene Styrene (SBS) modified bituminous membrane, or single-ply systems such as thermal polyolefin (TPO), polyvinyl chloride (PVC), or ethylene-propylene (EPDM).

Root penetration into membrane laps and seams will compromise the integrity of the waterproofing system. Microorganisms in the substrate and plant root system can attack and degrade bituminous and asphalt-based roofing products. A number of approaches have been developed to prevent root penetration into the waterproof membrane: an independent loose layer of thermoplastic such as PVC, polyethylene or TPO which is overlapped and seam welded; a barrier fabric bonded to the drainage layer and overlapped without seal; or a chemical product integral with the waterproof membrane that inhibits root growth.

The basic function of the drainage layer is to maintain the path for discharged run-off from the roof once the substrate is saturated. The most common forms are lightweight polystyrene board (PSB), polyethylene roll-out sheets, or extruded plastic forms with water retention cups for reservoir water storage capacity. A combination reservoir -

drainage layer is typically used for intensive vegetated roofs only, and a non-reservoir drainage layer for extensive vegetated roofs.

The basic function of the filter fabric is to prevent fine sediments from being washed out of the substrate and clogging the drainage system. The filter fabric is a lightweight, non-woven and non-biodegradable sheet made from polyester or polypropylene fibres which are laid independently or may be glued as an integral part of the geocomposite drainage layer.

A water retention mat may or may not be included in a vegetated roof system. Its basic function is to retain water for plant uptake. The retention mat may be fabricated such that the plant roots grow through to the additional water source in a reservoir drainage board, or it may be utilized as a protection fabric to the waterproof membrane, in which case it has an adhered root resistant backing. Typically the mats are made from recycled polypropylene fibres and are loose laid and overlapped at the seams.

Substrates

Vegetated roof substrates have evolved based on principles of soil science and regional experience with the multilayer material assembly and roof level plant survival. The substrate specifications currently used for extensive vegetated roofs in British Columbia are, for the most part, a regionally based modification of specifications developed over the past 30 years from the roof greening experience in Germany. With the growth of the vegetated roof industry throughout Europe and North American, many substrate specifications are based on recommendations in the FLL guidelines. The recently published contributions of North American researchers have been instrumental in translating the FLL guidelines into more regionally specific guidelines. These guidelines provide a basis for the development of the extensive vegetated roof section of the 2007 British Columbia Landscape and Nursery

Association Standards (BCLNA). Testing methods generated by the FLL guidelines were adopted by ASTM in 2005 and 2006 for the evaluation of substrate performance.

The substrate depth for extensive vegetated roofs is typically less than 150 mm; a minimal depth of 50 mm can support a limited number of plant species on an appropriate site and in select climatic zones. The principal functions of the substrate are to provide water and nutrients and anchorage for the roof top plants. Extensive vegetated roofs are generally not supported with irrigation beyond the plant establishment stage, instead, the substrate is designed to provide sufficient water holding capacity for plant viability.

Most often a goal for extensive roof greening is to minimize the dead load attributed to the additional system layers on the roof deck. The critical dead and live loads to be calculated for structural design are calculated at full saturation levels (as dead load) with water run-off (as live load). This goal towards lighter weight substrates for the purposes of handling and load calculations has driven the inclusion of light weight coarse aggregates.

Vegetated roof substrates contain naturally-occurring and recycled constituents; natural materials include sand, pumice and gravel; artificial materials include Perlite, Vermiculite, light expanded clay granules, expanded shale and recycled or manufactured wasted materials such as crushed clay brick and crushed concrete, and rubber granules. Each of these constituents must be evaluated with respect to density, mass, porosity and water holding capacity, longevity, local availability and embodied energy. The substrate is pre-mixed before delivery to the building site; stratification of sub-layers of soil on the roof is possible but generally not implemented owing to the associated labour cost. The most prevalent constituents used in the Pacific Northwest are pumice, sand and composted organic matter.

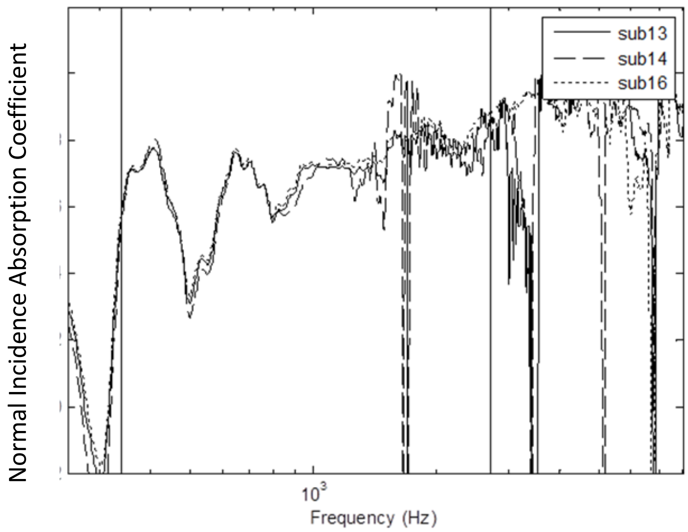
Vegetated roof substrates have a granular structure; the aggregates are separated from each other in a loosely packed arrangement. The substrate must be sufficiently porous to provide internal aeration, and be structurally capable of resisting excessive compaction beyond the mechanical compaction of the substrate on the roof during installation. There is a high percentage of sand in the regional substrates; the void between the sand particles promotes free drainage of water and entry of air into the soil. Sand particles are non-cohesive and hold little water. The coarse sands can be so free-draining that constant irrigation is required for plant survival. Conversely, the fine texture sands can result in a lack of pore space and drainage problems. The appropriate proportion of organic matter provides both a balance of drainage and water retention. The proportion of minerals to organics varies depending on plant requirements, depth and the projected maintenance regime. Clay has good moisture-holding capacity and also provides surfaces that attract and bind nutrients; however clay and silt tend to clog up drainage layers and fabric and subsequently are not as predominant in substrates as in natural soils.

Vegetation

Due to the shallow depth of extensive vegetated roofs, the selection of plant species is limited to plants that thrive in low organic and shallow growing media. The main drivers of plant selection are both the macroclimate and the microclimate conditions (Thuring 2010). The microclimate at the building roof level can be much harsher than at building grade, with conditions of higher wind velocity, including edge/corner wind turbulence and direct solar radiation. Additionally, the lack of ground water, lack of deep thermal mass, and, in some engineered substrate, a lack of natural aeration creates a difficult environment.

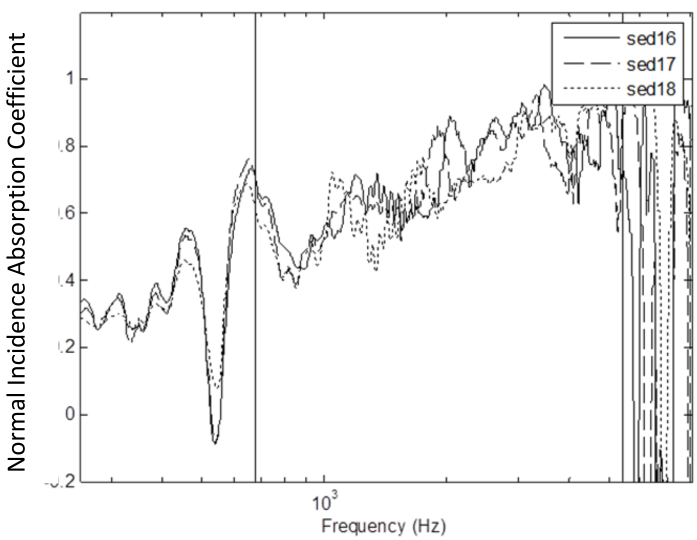
Other drivers in plant selection include aesthetics, native or non-native biodiversity, irrigation capacity for establishment, future maintenance and the implementation issues of cost, supply and scheduling. Most common in our region is the planting of plugs and pots on a set spacing. Planting alternatives include terraseeding, self-propagation and pre-cultivated mats. Pre-cultivated mats can be nominally described as webbed vegetation carriers supporting 25 to 35 mm of substrate. Sedum species are established in the cultivation fields; the mats are rolled and delivered to site for installation above a drainage layer and moisture retention mat.

Appendix B Standardizing the Spherical Decoupling Method



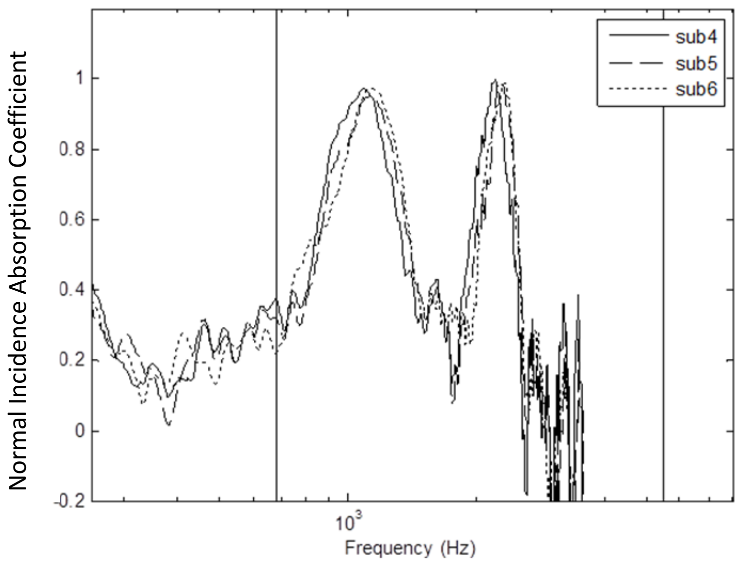
sub 13, hb= 0.122, s= 0.05.vs. sub14, hb=0.122, s=0.10, sub16, hb=0.122, s=.025

Figure B1 Normal Incidence Absorption Coefficient-
Comparison of microphone spacing on substrate



sed16, hb=0.165, s=0.025, sed17, hb=0.122, s=0.025, sed18, hb=0.055, s=0.025

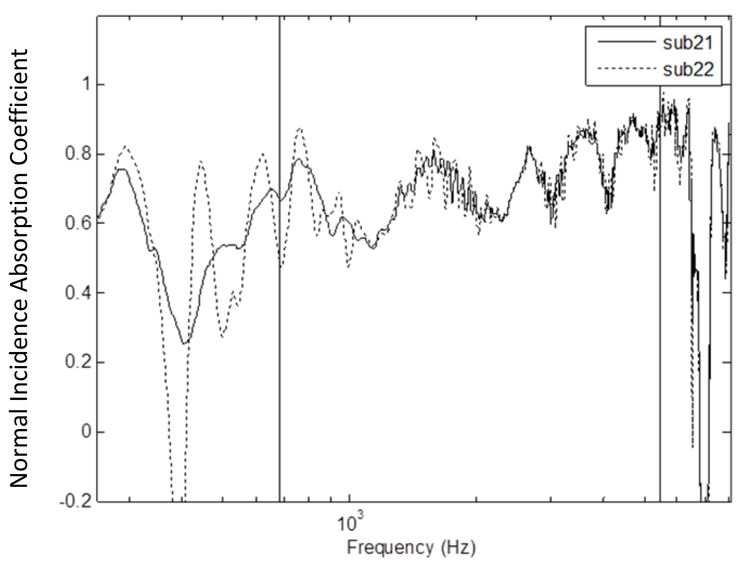
Figure B2 Normal Incidence Absorption Coefficient-
Comparison of spacer and height of base microphone on vegetated plot



sub4- NO baffles, Sub5 - HALF baffles,

- FULL baffles at same location

Figure B3 Normal Incidence Absorption Coefficient- Impact of a reflective surface around the plots



sub21- NONDISRUPTED,

Sub22- DISRUPTED at the same location.

Figure B4 Normal Incidence Absorption Coefficient- Impact of perturbations of the free field

Appendix C Sound Transmission Literature - Empirical Findings

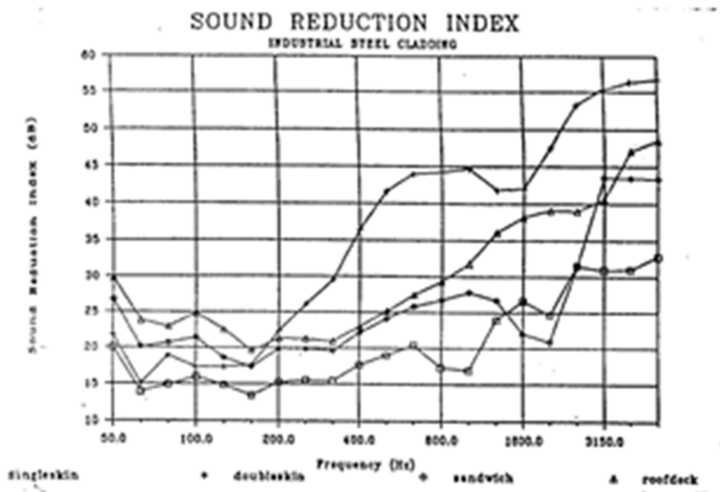


Figure C1 Measured SRI of Industrial cladding samples (Alexander1980)

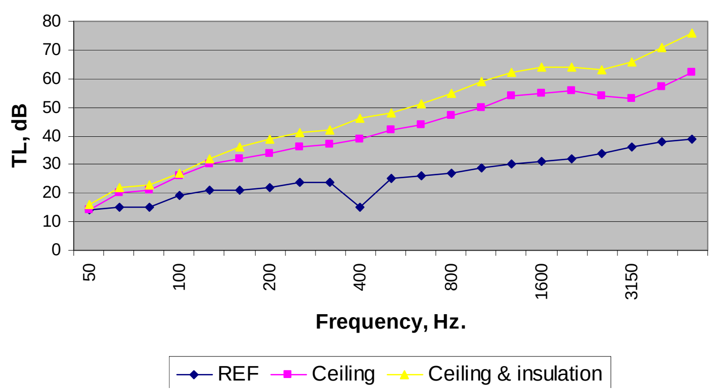
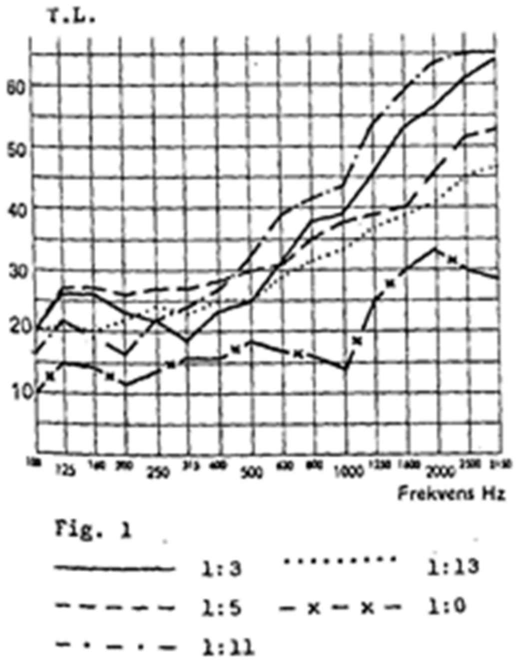


Figure C2 Sound transmission loss (Bradley 2002)



1:0 – Reference Roof, corrugated steel roof, without exterior insulation, without surface layer (REF)
1:3 – REF with 60 mm Rockwool insulation material
1:5 – Same as REF with 60 mm cork
1:11 – Same as REFwith 60 mm glasswool
1:13 – same as REF with 60 mm exterior PVC

Figure C3 Measured TL for Insulation Materials Added to Reference Roof (Friberg 1973)

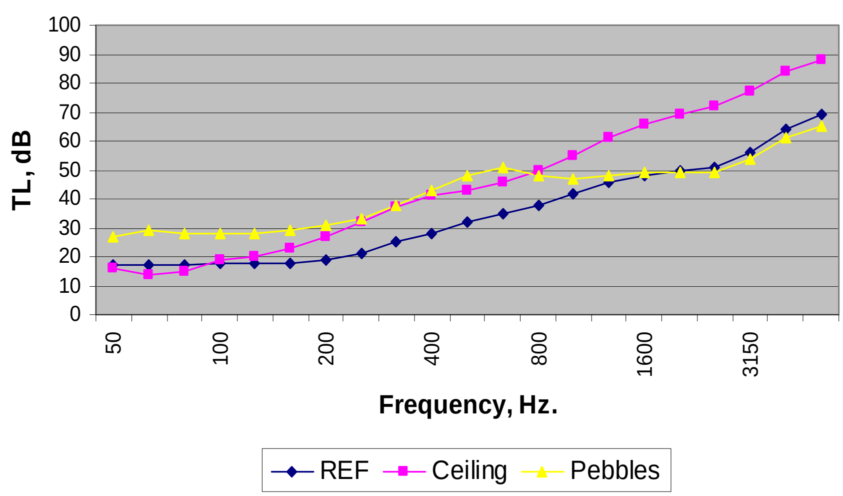


Figure C4 Sound transmission loss three roof systems (Bradley 2002)

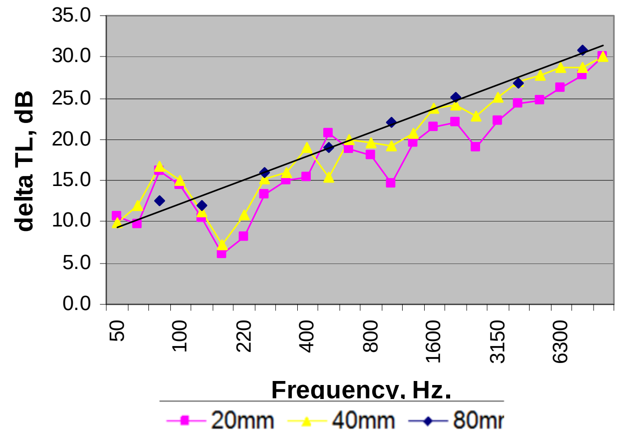


Figure C5 Delta transmission loss Sedum mats (Gerhart and Grundmann 1992)

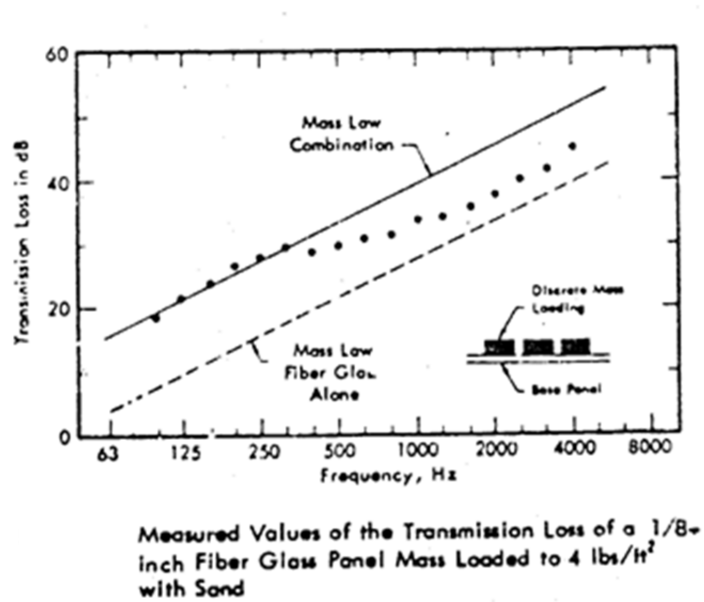


Figure C6 Sand plugging to improve transmission loss (Sharp 1976)

Appendix D CHILD Project – 7 C's criteria.

The CHILD project compiled a set of seven criteria - the 7 Cs – linking the physical conditions of outdoor play area to child development in order to evaluate the quality of outdoor play areas and the extent to which they support child development. The findings were used to develop design guidelines for outdoor play areas associated with child care facilities. The criteria are: character, context, connectivity, change, chance, clarity and challenge and are framed as follows (Herrignton 2006):

Character

The Character criterion indicates the overall character, feel and design intent of outdoor play spaces. Five archetypes have been used to describe the character outdoor play spaces; metaphor, "organic", "late modern", "modular" and "re-use." The archetypes were compiled from a list of outdoor physical factors and characteristics and have been used in numerous studies to code design.

Context

The context is defined by three factors. First, the context is defined by the centre's location within the urban fabric and the degree of transparency between the outdoor play area and surrounding context; and the relationship of the play area to the ground plane. Second, the context is internally shaped by the number of children in the play area relative to size and the presence of adults, other than the child care providers. The municipal recommendation for area per child is 10.6 m2-14 m2, Third, the context is also defined in part by the micro- climatic condition of the play area; wind, rain, sun and shadows.

Connectivity

Connectivity is evaluated at two levels; the first is the physical, visual and cognitive connection between the indoor area and the outdoor areas of the child-care centre and the second connection is the between places and elements within the outdoor play area. The connectivity with the areas beyond the child-care centre is encapsulated in the Context criterion.

Change

The concept of change encompasses both spatial and temporal variations of the outdoor play area. The Change criterion evaluates the design for subspaces of different sizes within the outdoor play area and evaluates how the outdoor play area changes dynamically over time. The design of different size subspaces allows for a single child to find privacy, and for variability in group size and play activities. This criterion evaluates the inclusion of vegetation and its bio-cycles to provide a temporal aspect of change to the outdoor play area.

Chance

Chance as a criterion involves the opportunity for the child to simply create and manipulate space with material found within it. Chance is the closest approximation, within designed and constructed environment, to '*just go outdoors and do something,*" synthesizing spontaneous exploration and expression.

Clarity

Clarity evaluates the design of the play area in terms of its physical legibility and perceptual imageability from a child-centric view. Without compromising the concepts of change and chance, the play area needs to have sufficient structure to allow the children to have a spatial understanding of their environment.

Challenge

The challenge criterion refers to the available physical and cognitive challenges that a play space provides.

Appendix E Summary of NRC Values

Date	Plant Species	Depth (mm)	Coverage%		Temperature² °C	Summary of NRC Values NRC	Min	Max	Mean
5-Sep	Sub	50	-	-	16.42	0.57	0.56	0.70	0.62
		75	-	-	15.77	0.56			
		100	-	-	15.8	0.61			
		125	-	-	16.48	0.67			
		150	-	-	16.73	0.65			
		175	-	-	16.72	0.70			
		200	-	-	15.56	0.61			
29-Sep	P1	50	52.6	25.4	18.21	0.46	0.24	0.46	0.39
		75	54.2	25.4	17.46	-			
		100	72.6	27.0	19.91	0.37			
		125	56.6	45.4	16.97	0.24			
		150	82.6	31.8	20.57	0.44			
		175	75.4	35.4	19.28	0.43			
		200	43.0	13.4	16.48	0.39			
4-Nov	P2	125	63.0	51.0	15.30	0.27	0.20	0.31	0.26
		150	63.8	60.6	15.04	0.31			
		175	64.2	58.2	15.01	-			
		200	63.0	62.2	15.55	0.20			
4-Nov	P3	125	95.0	5.8	15.12	0.41	0.29	0.41	0.35
		150	95.0	3.4	15.44	-			
		175	95.0	6.6	15.02	0.29			
		200	95.0	0.2	15.56	0.33			
22-Jun	P1	50	81.8	51.0	20.99	-	0.32	0.56	0.47
		75	75.0	50.6	20.42	0.48			
		100	81.4	61.8	18.26	0.56			
		125	91.0	85.4	20.45	0.39			
		150	95.0	73.8	17.89	0.52			
		175	93.8	55.4	17.71	0.32			
		200	86.6	65.8	21.10	0.52			
5-Jul	P1	100	81.4	61.8	23.67	0.57	0.50	0.57	0.53
		150	95.0	73.8	23.40	0.51			
		175	93.8	73.8	23.08	0.50			
6-Jul	P2	75	65.8	6.6	21.99	0.49	0.46	0.63	0.55
		100	77.4	18.2	22.17	0.62			
		125	76.6	13.6	23.17	0.63			
		150	83.4	9.8	23.23	0.59			
		175	81.6	13.5	23.36	0.46			
		200	80.2	8.0	22.31	0.50			
6-Jul	P3	125	86.6	50.2	21.26	0.50	0.39	0.51	0.46
		150	94.6	47.4	23.02	0.43			
		175	94.6	70.2	21.26	0.39			
		200	94.6	32.2	22.06	0.51			