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Thermal and Acoustical Performance of Green Roofs

SOUND TRANSMISSION LOSS OF GREEN ROOFS

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Abstract

Green roofs have the potential to provide excellent external/internal sound isolation due to their high mass, low stiffness and damping effect, and through surface absorption, reduce noise pollution in the community from aircraft, elevated transit systems, industrial sites and noise build-up in urban areas. This paper reviews the acoustical characteristics and the potential contributions of green roofs to the acoustical environment, investigates applicable literature and sound transmission theory and reports on new empirical findings on the transmission loss of green roofs. The existing infrastructure at the Centre for the Advancement of Green Roof Technology provided an opportunity to evaluate established green roof systems with known system variables, and reference roof systems. A diffuse to free field intensity level measurement methodology was developed to obtain the presented results and for use in a future field test facility.

Green roof technologies may be optimized to increase transmission loss and ameliorate the coincidence effect. Current construction practices, driven in part by sustainable building rating programs, have led to an increased use of lightweight metal roof assemblies and a decreased use of ceilings. Green roofs can provide a higher transmission loss than the additional ceiling element and improve transmission loss throughout the full architectural frequency range, specifically desirable in residential occupancies developed below aircraft flight paths. The field testing conducted on two 33 m^2 low profile extensive green roofs indicated an increase of 5 to 13 dB in transmission loss over the low and mid frequency range (50 Hz to 2000 Hz), and 2 dB to 8 dB increase in transmission loss in the higher frequency range relative to the transmission loss of a reference roof.

Green Roofs – Acoustical Contribution and Benefits

Green roofs have the potential to provide excellent external/internal sound isolation due to their high mass and low stiffness; through surface absorption, green roofs have the potential to reduce noise pollution in the community from elevated transit systems, industrial sites and noise build-up in urban areas. Green roofs can provide mitigation of unacceptable noise levels that affect the health, safety and well-being of the urban population; however, the acoustical benefits of green roof technologies have not yet been investigated. Significant research has determined that green roofs can reduce stormwater runoff and lower a building's energy demand for cooling/heating through improved thermal performance (1). Greening the roof can protect the roof membrane from the elements, thus extending the membrane service life. Strategic coverage of rooftops with vegetation in urban areas can further reduce the impact of buildings in the community, by reducing urban heat island effect, contributing to the region's stormwater and watershed management plan, and enhancing the environment through improved air and water quality. Quite apart from their significant contributions as a sustainable construction technology, green roofs are also recognized for their potential for urban agriculture, recreational and therapeutic benefits, support of biodiversity and habitat, aesthetic attributes, and their overall contribution to increasing the quality of life for those who experience green roofs as part of their everyday lives.

The green roof of a building defines one of the boundaries between the natural exterior environment and a controlled indoor environment. In most instances we are concerned with the transmission of air-borne noise from the urban environment through the building envelope into the habitable areas of a building. The environmental context of highest priority is urban development below aircraft flight paths, exposed to high levels of low-frequency jet noise. It is expected that the greatest benefits will be recognized in lightweight roof assemblies, such as those used in multi-family, commercial and industrial development. Noise from within an industrial building transmits out through the building envelope; in this context a reduction in sound transmission through the building's green roof would provide a community benefit. Although it is not the focus of this report, future research will be considered to investigate the capacity of green roofs, through surface absorption, to reduce noise pollution in the community from elevated transit systems and industrial sites and from noise build-up in urban areas, and to understand the changes the urban soundscape owing to the biodiversity and habitat supported by green roofs.

The sound transmission characteristics of a green roof are governed by the multiple layers of fluid, solid, and poro-elastic materials that comprise the full profile of the vegetated roof system. This research is initially focused on flat, nominally sloped (2% to 4%) extensive green roofs. Extensive green roof systems are comprised of the roof deck, vapour barrier, insulation, waterproofing membrane, root barrier, water reservoir/drainage layer, filter fabric, substrate and drought-tolerant plant species. The extensive green roof has a shallow substrate profile, 40 mm to 150 mm thick, and are installed on both conventional and protected membrane roof systems—often installed on buildings without significant cost for additional structural loading.

Generally, an extensive green roof is not considered occupied space and is not accessible for purposes outside of maintenance requirements.

Literature Review and Empirical Findings

Dr. Ben H. Sharp, a prominent acoustician in the field of sound transmission through structures, not only developed sound transmission theory as it is applied today to building envelope, he also set the framework for this current research. Sharp (1973) proposed a novel approach to the problem of designing roof/ceiling assemblies with high mass and low stiffness. The approach involved the addition of discrete masses to a flexible base panel in such a way that the stiffness of the base panel was not substantially increased at frequencies greater than the critical frequency. The solution was the placement of 1" squares of sand held together by a compound which also provided adhesion of the sand squares to the 1/8" fibre-glass sheet base under investigation. Sharp concluded that due to the mass density and spacing requirements the solution was not satisfactory and proposed that "it is often more efficient to provide complete coverage for the base panel using a limp but massive material such as sand", suggesting that "sand is an almost perfect material for sound-attenuating structures, embodying all the most desirable features—high mass, low stiffness and high damping". Sharp suggested that the only reason that sand was not used more often in building construction is the difficulty of holding it in place and further suggested that it is possible, however, to maintain loose sand in contact with a base panel by means of containers resembling egg cartons.

Sharp's work in the early 1970s came just at the time of an emergence of new European technologies for vegetative roof systems. He did not imagine the potential applications of his assertions. It is apparent that innovation was not lacking in his roof/ceiling designs or in his wall designs. Sharp also constructed an experimental wall prototype which attempted to utilize the beneficial properties of loose sand to provide high mass and low stiffness. The prototype could very well be a current technical solution for living walls (2,3).

Transmission loss (abbreviated TL and measured in decibels[1]) is a measure of how much sound energy is reduced in transmission through a single or multi-layered partition. Review of the scarce empirical findings on the transmission loss (TL) of roofs suggests that the use of green roof technology to mass load the roof may be optimized to eliminate the coincidence effect, and increase transmission loss at all frequencies, of a roof assembly: Friberg, (Sweden, 1973) produced a comparative set of findings of TL for different insulation materials that were applied as an overburden on conventional roofs (4). Cork overburden provided a higher level of performance with respect to sound isolation over the low frequency range up to 550 Hz and elimination of the coincidence effect. Testing completed by *Alexander, O'Conner and Orlowski (1980*), motivated by the European Economic Community legislation for limiting noise at the

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[1] The decibel (dB) scale is logarithmic; 1 dB change is usually not recognized by the human ear, a 3 dB increase represents a two-fold increase in sound energy, a 6 dB increase is a four-fold increase in sound energy. Psycho-acousticians suggest that we perceive an increase of 10 dB as "doubling the loudness" of a signal.

workplace, illustrates the general trend of increased transmission loss with increased frequency and the elimination of a coincidence dip, owing to the damping provided by the additional materials in built-up roofing (5). *Cook (Australia 1979)* measured a higher transmission loss provided by a nominally (2°) flat roof over the 27° sloped roof suggesting that there may be greater benefit with respect to increasing transmission loss to greening sloped roofs than flat roofs (6). Results from the Insulating Buildings against Noise from Aircraft project by the *National Research Council of Canada* confirm that in the context of overhead aircraft noise adding ceiling treatments (added mass, resilient channels and absorptive insulation) to current light-weight roof systems can eliminate the coincidence dip and increase transmission loss significantly at mid and high frequencies (7,8). See Figure1. An increase in transmission loss at low and mid frequencies was measured on a prototype with a pebble overburden - a configuration not unlike a very low organic extensive green roof (without plant establishment) See Figure 2.

A German industry report on the evaluation of the sound insulation of Xero Flor™ sedum vegetation mats was completed by Gerhart and Grundmann in 1992. The mats were tested in combination with three thicknesses of mineral wool as a water retention mat. Sound insulation was dependent on the thickness of the mineral wool, and was between 10 dB in the low frequency range and 30 dB in the high frequency range. It is evident from the two limited studies of pre-cultivated mats that the moisture content of the green roof system is a physical property that affects the acoustical characteristics (9). Ouis and Langstrom, Sweden (2004) utilized a labourer's cabin as a testing facility. The existing roof of the cabin was a 150 mm thick insulated fibre-glass roof with internal pine panelling; the additional green was a pre-cultivated vegetation mat 70 mm thick inclusive of a mineral wool drainage layer. The noise reduction owing to the addition of the vegetation mat to the reference roof is relatively constant over the low (<500 Hz) and high (>2500 Hz) frequencies. In the middle frequencies the additional noise reduction exhibited by the roof with the vegetation mat was generally higher (10).

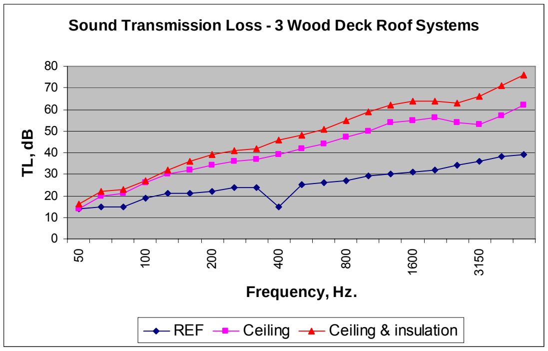

Figure 1
Wood deck roof systems with ceiling treatment

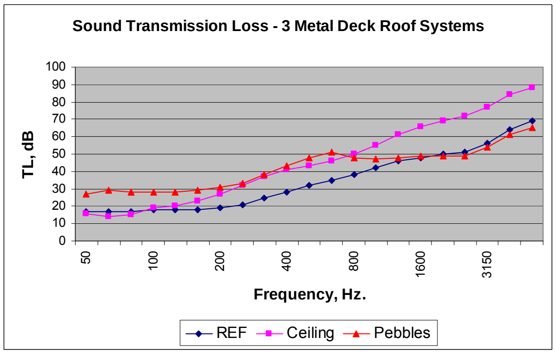

Figure 2
Pebble rock overburden increases low f TL

In the context of green roofs, it is suspected that transmission losses in the layer of the substrate will be of major importance. Acoustical characterization of soils has been investigated primarily to support the development of sub-surface imaging. Findings support the hypothesis that soil texture affects the attenuation of sound as it passes through the depth of the soil (11). The vegetated root interface with the soil has been identified as affecting the normal specific impedance, through the investigation of outdoor sound propagation over ground (12). The findings from the literature support the investigation of sound transmission loss as a function of the plant species on the green roof. The physical properties most prevalent in the research include particle size distribution, bulk density and porosity, flow resistivity, and tortuosity; soil conditions of moisture and compaction are variables affecting the acoustic characteristics (13). The acoustical characteristics include: characteristic impedance, normalized surface impedance, sound absorption coefficient and propagation speed. Current research by the author on soil properties relative to the acoustical characteristics of green roofs is outside the scope of this paper.

The review of empirical findings on the TL of roofs highlights three summarizing concepts. 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 green roof technology, increased TL was achieved by the addition of a ceiling. This addition to the roof assembly increased TL only in the mid and high frequency ranges, not in the low frequency range of potentially disturbing noise from aircraft. Third, although both reports of the pre-cultivated mats provided insufficient findings to allow drawing a broad conclusion on sound transmission of green roof technology, the studies provide evidence that the moisture content of the substrate and the water retention mat is a physical property that affects the acoustical characteristics. The empirical findings lend support to the investigation of how the added mass and low stiffness resulting from the addition of the material components of extensive green roof systems above the membrane can improve the low and high frequency transmission loss of lightweight roof systems.

Sound Transmission

The green roof as a series of finite layers impedes sound energy as it transmits from the exterior environment through each layer of the system to the interior of the building. *Transmission* is defined as the passage of acoustical energy through a material and is dependent on the surface reflection and the process of vibration and absorption of each layer. Multi-layer components which are bonded together permanently, across their entire surface, form one single rigid layer. The roof deck and materials can then be considered as a single massive element (14, 15). The field-incidence transmission loss for diffuse field is expressed as the relationship between the incident intensity and the transmitted intensity with a term quantifying the mass at a given frequency (16). This algorithm is known as the mass-law equation which generates a transmission loss curve with a 6 dB increase in transmission loss per octave and per doubling of mass. Using the mass law algorithm the additional mass of 150 mm of substrate would theoretically increase the transmission loss of an extensive green roof by 15 to 17 dB above that of a non-vegetated roof. The range of 2 dB represents the mass of the % water retained by volume from extremely dry conditions to saturated water holding capacity. This research shows that the mass-law algorithm is not an adequate model to describe lightweight roof systems or green roofs.

Architectural acoustics is most often concerned with the sound transmission in the frequency range of 125–4000 Hz. It is of importance to identify the lowest value of the frequency-dependent transmission loss of a partition, and the lowest transmission loss attributed to a phenomenon called the coincidence effect. The impact of the coincidence effect is a reduction in transmission loss a specific frequency; this may be significant and create potentially disturbing noise for the building occupant. The roof plane acting as a single panel is large in size compared to the wavelengths in the range of frequencies of concern. 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. Defining the roof plane as such a plate permits the thin panel theory to be investigated for lightweight non-vegetated roof and green roof systems.

In thin panel theory, mass impedance predominates at frequencies below the critical frequency. At high frequencies the resulting plate impedance considers only the mass impedance and the bending impedance in series. The value of the critical frequency increases with increasing material density and decreases with increasing panel thickness and material stiffness (17). Damping can decrease or eliminate the coincidence effect and increase the TL above the critical frequency by an additional factor of 20logŋ over the direct mass law. Although the limp mass of the substrate provides a damping effect, the substrate dissipates sound energy as a primary attenuation mechanism before the sound energy is incident on the plate. Therefore, the thin panel mass algorithm cannot be simply applied. The empirical results of these field measurements are not consistent with this algorithm.

Methodology

The vast majority of both laboratory testing methods and *in situ* field testing methods are focused on interior walls and floors, exterior building facades and facade elements. No testing method published by ISO, ASTM or other standard association exists that has been developed specifically for the measurement of sound transmission through roofs. ATSM and ISO standards define several measurement procedures to evaluate the transmission loss using sound suites. The sound transmission suites provide a high level of control for evaluating transmission loss of single-layer and multi-layer partition wall and floor/ceiling systems under laboratory conditions. The testing methods standardize the sound excitation as a diffuse sound field generated in a highly reverberant room. At first glance this seems counter-intuitive to the research context of aircraft noise, since aircraft generate planar waves on the roof at varying angles of incidence. The empirical findings discussed in this paper, from Sharp to the NRC, have generally been based on the measurement of space-averaged sound pressure and reverberation time in the receiver room (E90 and the IS0 140 series). This is in part due to the state of measurement technology during the time period in which the research took place, which was before the development of instrumentation that allowed for the measurement of sound intensity.

The existing infrastructure at the Centre for the Advancement of Green Roof Technology provided an opportunity to evaluate established green roof systems with known system variables and relevant reference control. A reverse testing method initiated by Mulholand and Sharp (1978), proved to be very useful as a strategy for developing a methodology for this research and a future field test facility(18). The ISO 15186 series Indoor to outdoor method (19), propagating sound from an interior diffuse field to an exterior free field was adopted. The ISO 15186 standard 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:

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

L_{p1} is the average sound pressure level in the source room
S is the area of the separating partition under test
L_{In} is the average normal sound intensity level over the measurement surfaces
S_M is the total area of the measurement surfaces
S_0 $=1\ m^2$

The Green Roof Research Facility at the BCIT Centre for the Advancement of Green Roof Technology illustrated in Photos 1 and 3 has three independent research roofs originally commissioned in 2003 for the evaluation of stormwater runoff characteristics and thermal performance of green roofs. One roof is a conventional system which acts as a reference roof test specimen, the other two roofs (GR1 and GR2) have the same roof system to the top of the membrane as the reference roof, plus identical green roof components, differing only by the depth of substrate. GR1 has 75 mm and GR2 has 150 mm of substrate. The planting was consistent in its establishment at the time of sound transmission evaluation. 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.

Photo 1 - Green Roof Research Facility

Photo 2 -Roofing Evaluation Modules (REM)

Photo 3 –GRRF, Interior diffuse sound field

Photo 4 - Intensity probe over REM

A number of challenges existed in the execution of the testing. Rainfall events, 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. A virtual measurement surface is required to be within a specified distance from the radiating surface; however, the plant heights were not consistent for all test specimens. The plant foliage was often higher than the virtual surface preventing a time average sweeping method; therefore an averaged discrete point method was use for the positioning of the intensity probe. Figure 4 illustrates that the irradiating intensity measured directly above the fescue is consistent with the intensity measured directly above the exposed substrate. The additional plant foliage did not create an impact beyond the established roots and substrate.

Comparative Data Analysis

An array of five loudspeakers was used in the GRRF interior to create a diffuse sound field. The average sound pressure level was 93 dB generated in each 1/3 octave band. For calculation of the TL the space averaged sound pressure was measured below each of the three roofs. The radiating intensity was measured at 12 discrete points on each of the three roofs. Figure 4 illustrates the resulting transmission loss/frequency curve. All three roofs exhibited an increase in TL with increasing frequency. There is a dip in TL of the reference roof at 125 Hz; however, it is not conclusive whether this is due to the coincidence effect. GR1 (75 mm substrate) exhibited inconsistent increase in TL over the frequency range. The consistent increase in TL of GR2 (150 mm substrate) is illustrated in the TL curve above that of the reference roof. The substrate and green roof materials increased the TL over the low-mid frequency range of 50 Hz to 2000 Hz, by 5 dB to13 dB and in the higher frequency range by 2 dB to 8 dB. This is a significant decrease in low and mid frequency sound level transmission; the green roof then provides the opportunity to eliminate the need for ceiling installations for the purpose of increase sound transmission loss. Comparable sound transmission loss through the addition of a ceiling and insulation may not be attainable at low frequencies up to 125 Hz.

The Roofing Evaluation Modules (REM) were commissioned in 2006 to obtain stormwater and thermal performance data on specific green roof systems (see Photos 2 and 4). The 2 m x 2 m REMs provided an opportunity to evaluate eight different green roof systems as compared to a reference REM and to investigate small sample testing. The interior dimensions of the REM are relatively small compared to the low frequency wave lengths generated in the interior diffuse field. Figure 5 illustrates a comparative difference in sound transmission loss between various REMs. The non-representational dimensions of the REM structure and deck and the low frequency modal interference present a concern. Figure 6 illustrates the difference in results between the field testing evaluation of the GRRF and the small sample testing using the REM test specimens. The field test results of the GRRF roofs decks result in TL values of 10 dB average over the range of frequency higher than the small sample. It is hypothesized that small sample testing requires a modified evaluation; the 4.8 m x 6.8 m roofs are dimensional representational of all materials, framing component and spans of a structurally optimized system, whereas the 2 m x 2 m REM are not dimensionally representational of an optimized roof construction.

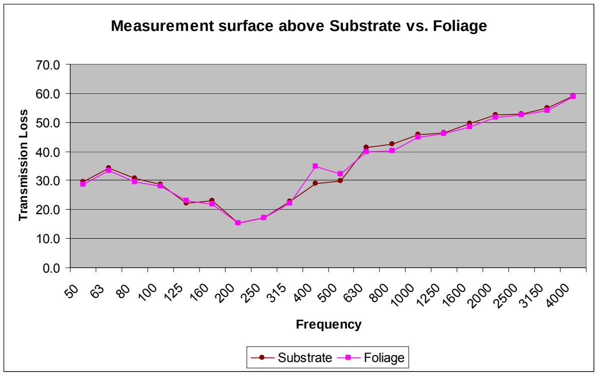

Figure 3
Wood deck roof systems with ceiling treatment

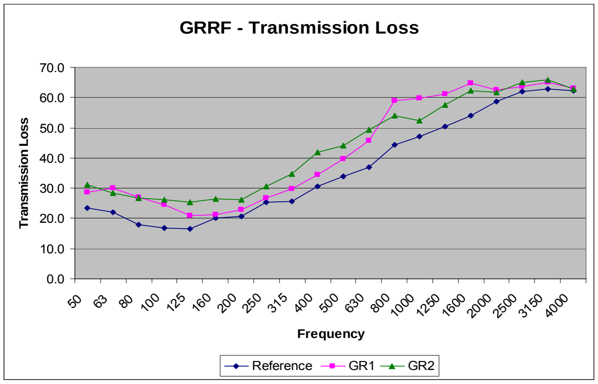

Figure 4
Pebble rock overburden increases low ƒ TL

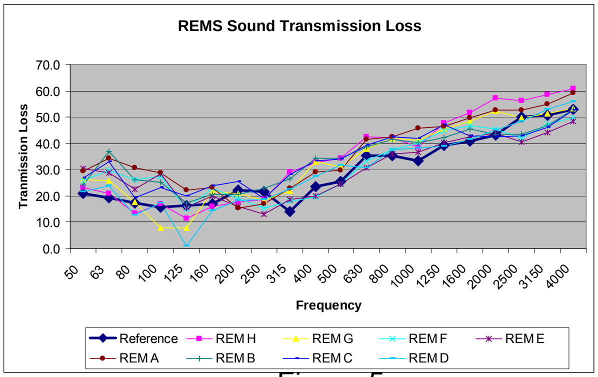

Figure 5
TL of REM green roof prototype

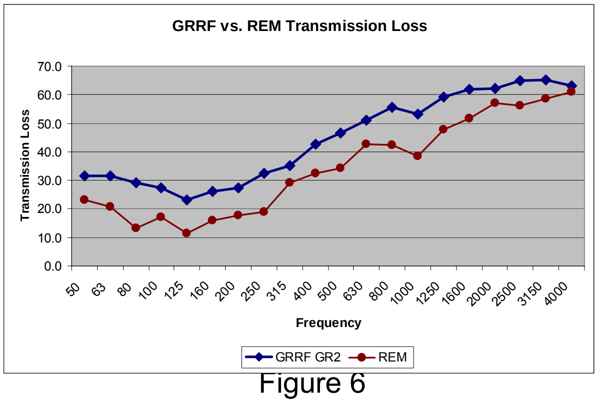

Figure 6
Compare TL results: field to small sample

Conclusion

The empirical findings on the sound transmission loss of green roofs suggest that the use of green roof technologies may be optimized to increase transmission loss and ameliorate the coincidence effect. The field testing conducted on two 33 m^2 extensive green roofs indicated an increase of 5 to 13 dB in TL over the low and mid frequency range, 50 Hz to 2000 Hz, and 2 dB to 8 dB increase in TL in the higher frequency range above the reference.

Current construction practices, driven in part by sustainable building rating programs, have led to an increased use of lightweight metal roof assemblies and a decreased use of ceilings. Green roofs will provide a higher TL than the additional ceiling element and improve TL throughout the full architectural frequency range, specifically desirable in residential occupancies developed below aircraft flight paths.

Existing sound transmission algorithms do not adequately predict TL of light-weight roof system or green roofs, nor describe the potential effect of % water content of the substrate. The sound energy is dissipated in the substrate and provides a mass loading and damping effect on to the light-weight roof deck. Evaluating roof specimens which are representational of all material and structural framing dimensions with a diffuse to free field intensity level measurement method will provide comparative data over the range of architectural frequencies.

Recommendations for Further Research

Research is required to define the relationship between the substrate properties and plant root interface to the acoustical characteristics of green roofs. The contribution of each material layer as a function of its properties to the acoustical characteristics of the green roof is not independent of the other layers and boundaries in the multi-layer system. Each green roof material layer should be evaluated at a field-test facility individually and in permutations of fully functioning green roof systems. Empirical measurements will support the development and validation of an empirically-based prediction model of sound transmission loss, facilitating the design optimization and cost-benefit analysis of green roofs.

An investigation of the specific impedance of green roofs is required to identify the absorption and reflective properties which will potentially alter the urban soundscape by decreasing noise pollution and supporting bird habitat, ultimately changing our habitation patterns at the roof top levels of the city. Ecological impact investigations of the soundscape are required to identify further acoustical relationships of green roofs to the sonic environment and provide feedback which we can apply towards a more ecologically interface with our biosphere.

Acknowledgements

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