ROOT PENETRATION

1. Executive Summary

With the proliferation of rooftop gardens on modern buildings, our team was pondering over the potential adverse effects of plant roots on facilities, especially the waterproof membrane. True enough, plant roots are known to penetrate the membrane and cause leakages. What is being done in view of this problem is the provision of extra materials in the construction of the garden in anticipation of the problem. This leads to over-specification and increase in construction costs.

Our team aims to suggestion other possible solutions regarding the protection of the waterproofing membrane and to carry out an experiment to determine if soil density would affect the growth of roots such that they grow less deeply and more dispersedly. According to literature review, soil density affects root growth and from the results of our experiment, we concluded that soil bulk density does have a part to play when it comes to root growth with the relationship being soil bulk density proportional to root growth. Higher soil bulk densities promote the number of root tips growing from the plants and the length to which the plant roots grow and vice versa with regards to lower soil bulk densities.

As such, it is probable to employ bulk density of soil as a measure against plant roots penetrating waterproofing membrane. This is a type of active measure to prevent the growth of roots instead of a passive measure like specifying root barriers in the construction of rooftop gardens. It is considered active as it does not wait for the roots to penetrate the membrane while root barriers wait for roots to grow to a certain length before being effective. This method is more cost effective as it does not weigh much and will not need the specification of stronger roof and building structure.

In this report, other than the literature review conducted about the destruction of plant roots, rooftop gardens, plant roots and soil, there is also detailed observations and results gathered from the experiment carried out. In addition, the team has also recommended other active measures that one might carry out to protect the waterproofing membrane and save construction as well as maintenance costs.

Contents

2. Introduction

Background

As buildings are steering towards the direction of energy efficiency, roof gardens are gaining popularity in cities and urban environments nowadays. Plants have the ability to reduce the overall heat absorption of the building which then reduces energy consumption. A roof garden re-establishes the relationship between man and nature that can be lost in urban environments.

There are many advantages of building a roof garden, for instance, increased access to private outdoor green space-at home or at work-within the urban environment as gardening for relaxation is a great stimulus to the mind and body. It also helps to clear one's mind of the competitive thoughts and places. Besides, it can also aid in the insulation of buildings, improve air quality and generally reduce carbon dioxide (CO^2) emissions by catching polluted particulates and absorbing gaseous emissions that arise from the city.

However, there are many issues needed to be taken into consideration when creating a rooftop garden. As actively growing roots tend to grow towards a water source, they can find their way through the smallest of cracks and expand as they grow, which can cause significant damage to the building within a short period of time. For example, water leakage will happen when there is root intrusion; this issue can be problematic as cost of landscaping removal to carry out repair is expensive. As such, current practices are to strengthen the roof in view of these problems. This would result in the over-specification of roof material quantities which would increase upfront cost of the project. This practice is not cost effective as the extra reinforcement might be unnecessary. Hence an active approach to deter the extent of root growth might be the new frontier to protect the roof from damages caused by plant roots.

Purpose

The purpose of this project is to assess the damage brought about by the roots of plants on the waterproof membrane of the roof garden and to propose ways to reduce damages by manipulating type of soil medium.

Aim

This project aims to investigate the possible damages that plants might have on the integrity of the waterproof membrane and to devise methods to reduce depth of root growth such that the damage on the membrane will be minimal.

Objectives

In order to find out the possible damages that could be done by plant roots on waterproofing membranes, the structure of rooftop gardens will be studied. The team will also find literature regarding how plants might affect the waterproof membrane's integrity and quality. The relationship between the different soil types and root growths of plants will be investigated through experimentation too. In conclusion after the experiment, the team will propose active methods to reduce damages caused by plant roots.

Methodology

In this project, the team will employ two types of research, qualitative as well as quantitative.

The qualitative research will be concerned with the collecting and analyzing of literature regarding rooftop gardens, waterproofing membranes, plant roots and soil. The focus would be on the relationship between bulk soil density and the impact on root growth. We will also endeavour to discover literature on the damage done by roots affecting the built environment especially the waterproofing membrane.

The quantitative research will be done through the execution of an experiment where the team strives to find a relationship between the bulk soil density and root growth by cultivating plants in four different types of soils of varying soil densities. More information about this experiment can be found in Chapter 4 of this report.

3. Literature Review

3.1. Destructiveness of Plant Roots

Waterproofing membrane, being the most important component of the roof garden, has to be kept intact at all times. However, the unpredictable behavior of plant roots hidden in the growth medium makes it very difficult to notice the damages done to the waterproofing membrane. Thus, to prevent the potential root damages to the roof of the building, root barriers are set in place to prevent root penetration. However, this might not be required in roof gardens with less destructive plants, hence this would lead to an over-specification and incur unnecessary additional cost, which would instead dissuade the developer from adding a rooftop garden into the scope of the project.

3.1.1 Example of Root Damages in Other Structures

Figure 1: Root Damages to Pavement

Extent of plant roots growth is hard to predict due to the unseen soil condition and the plant's own ability to probe further in all directions in search for more nutrients and water. Hence, plant roots often cause damages in pavements *(Fig 1)*, drainages *(Fig. 2, 3)*, etc. This shows that the plant roots have the strength to crack concrete pavements and penetrate underground water pipes.

The cracks in the pavement seen in *Fig. 1*, is caused by the stress exerted by the root growing under and in between the cracks of the pavement.

Figure 2&3: Root Damage to Drainage and Pipe

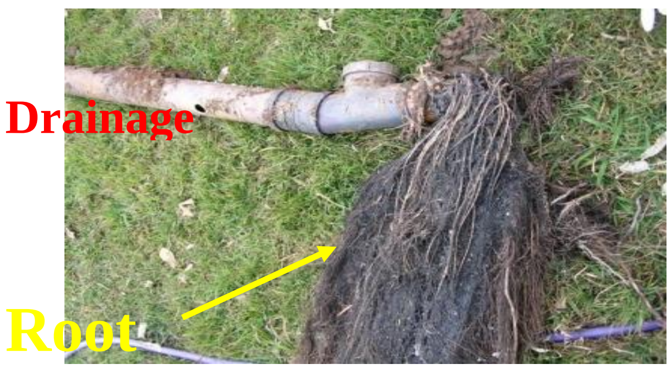

Figure 4: Pipe blockage caused by plant roots

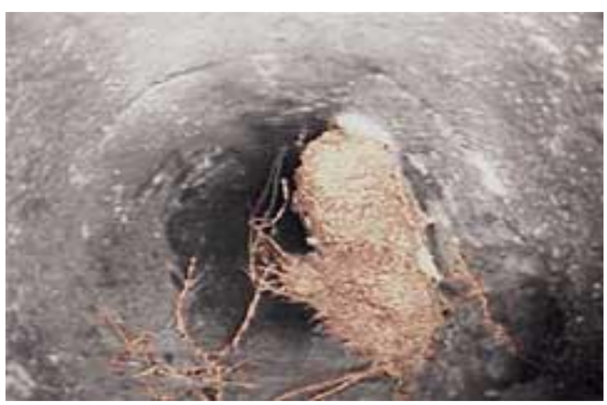

Figure 5: Penetration of root into sewage pipe taken from the inside

Plant roots penetrated the drains and pipes, especially sewage pipes *(see fig.5),* as the sewage carries high amount of organic waste that plants require for growth and survival. Plant roots can generate enough force to damage small structures such as drains and walls. Fine roots can penetrate minute cracks and joints in drains. Once a small root has entered a drain, it can develop a mass of roots, then force open cracks in the pipe's junction and deteriorate the cement junction, eventually leading to blockage *(see fig. 4)* and fracture the drainage pipes. Typical drainage damages are often caused by the Willow, Poplar, Sycamore and Cherry species.

In the 1970s, America's sewer system was threatened by tree roots intrusion, and the roots were interfering with the flow of fluid as the fine hairs on the roots catches on solid particles that flow through the pipes (Premier, 2007). It caused the sewer system to deteriorate as micro-organic activities became rampant and integrity of the pipe was at stake.

These examples show how strong and invasive plant roots are, and how responsive they can be to sources of nutrients. In the rooftop garden, the waterproof membrane is located below the drainage system, which would encourage the roots to grow deeper into the structure, rather than laterally. It would be possible for the plant to damage the drainage system and the waterproof membrane, since it contains organic compounds. Plants like the bamboo has a measured actual penetration force of 9.8N at the tip of it, which can do substantial damages to the waterproof membrane, thus seldom used in roof gardens. However, it is still important for roof garden specialists to not underestimate the destructive strengths of plant roots.

3.1.2 Root Damages to Waterproof Membrane

As the waterproof membrane is made of organic compound for the hydrophobic character, roots are more incline to attach them to it, to extract the nutrients from it. Therefore, plant roots can do substantial damage to the waterproofing membrane as the fine roots would slowly stretch the fibers of the membrane and eventually puncture it *(See Fig.6)* and causing more weak points to occur in the membrane. Leakages would soon follow when the waterproof membrane fails.

This would require maintenance and repair works are to be carried out, but these works are costly and difficult due to the need to remove the plants for assessment of damage and the replacement of both waterproof membrane and root barrier. *(See Fig. 7)*

Figure 6: Root penetration

Figure 7: Exposing membrane for repair

In order to protect or reduce the damages done to the waterproof membrane, retardants are also introduced into the membrane, but it only slows down the damage done by roots on the membrane, and repair works has to take place as soon as possible to prevent further damages (AMI, 2007). The membrane can be also separated from the soil medium by a continuous root barrier. (Ngan, 2003)

3.1.3. Effects of Damages Waterproof Membrane

The damages brought about by the penetration of plant roots into the waterproofing membranes on the green rooftops consist of leaks as well as punctures. In the case of a leak caused by the penetration of the plant roots, the water that is retained by the green roof system will leak into the deck of the roof.

Figure 8: Penetration of the roots into the plastic tray

As can be seen from the picture above, the issue of plant root penetrations into the roof waterproofing membrane must not be overlooked as the roots have penetrated the bottom of the tray in which they were left to grow in. Judging by the penetration of the roots into the bottom of the tray (*see fig. 8*), this issue of roots penetration must not be overlooked when plants such as lupin (Lupinus angustifolius) and medic (Medicago scutelata) are being used for planting at the top of the rooftop gardens which employ the usage of Polyvinyl-Chloride plastic material for waterproofing membrane purposes.

3.1.4. FLL Test Procedure

The FLL (German Landscape Research, Development and Construction Society) test procedure (Procedure for investigating Resistance to root penetration at green-roof sites) is currently used as a standard to test for root resistance of membranes. The purpose of this test procedure is to assess the membrane's ability to resist root penetration and other root related damages. This test procedure is very welcomed and is adapted by various organizations such as the GRHC (Green

Roof for Healthy Cities) and the Architectural Institute of Japan (AIJ). AIJ's method of monitoring root growth is as shown in Figure 9.

Figure 9: AIJ's adaptation of the FLL test procedure

3.1.5. Results from FLL Test Procedure Adapted by Penn State University

Penn State University employed the test procedure to investigate the root resistance of membrane to *Pyracantha* and *Quack* grasses. After two years of growth, there was no penetration in the membrane, yet, fine roots of the grass has adhered to the surface of the membrane, other surface imperfection, and entered air pockets of the membrane. (Penn State Centre for Green Roof Research, 2006) Although, the membrane was not damaged considerably, the experiment lasted only two years, and grass was the only plants used in the experiment. Thus, given more time and a wider variety of plants, the plant roots might cause stretching of the membrane fiber, and eventually the waterproof membrane would fail.

3.1.6. Conclusion

Therefore, maintenance work for the roof garden is made complicated by the potential damage plant roots can do. It is hence, essential to employ a more active approach in dealing with root damage on the membrane, rather than over-specification of root barrier and waterproof membrane. A poorly installed drainage system, susceptible to leakages would also invite plant roots to probe deeper into the growth medium towards the membrane, so it is required to provide adequate drainage system to reduce root penetration into water proofing membrane as plant roots always grow towards the source of water. (Michael, 2007)

3.2. Rooftop Garden

Michael Wong 2006, says that due to the rapid growth in global population, many cities are becoming highly urbanised as buildings and structures are situated in close proximity to each other. This results in an increasingly high concentration of thermal mass, as most modern buildings are made from reinforced concrete. This effect of increase in air temperature within the urbanised areas is further exacerbated with the resultant loss of green areas. This creates serious environmental issues such as the Urban Heat Island effect.

Roof gardens have been used extensively in cities from Europe, North America, South Korea, Japan, and also in Singapore, in a bid to mitigate the adverse effects brought upon by urbanisation. Typically, rooftop gardens are considered to be 'semi-intensive' or 'intensive' green roofs, have a much greater substrate depth, and are more structurally and maintenance demanding (Fassman & Simcock, 2007). The depth of the rooftop garden soil substrate is generally more than 10 centimetres (Natural England, 2007).

The main disadvantage of rooftop gardens is the higher initial cost, around three to six times the initial cost of conventional roofs (Patterson, 1998). Some types of rooftop gardens have more demanding and costly structural standards, especially in seismic regions of the world (Ingrid, 2009). Intensive roof gardens would require regular maintenance such as mowing, fertilising, watering and weeding.

A rooftop garden is generally made up of 5 essential layers (Michael Wong, 2006):

1) **Waterproofing / Root barrier layer**

   The waterproofing membrane is used in protecting the building from water seepage, and should be root and rot resistance.

2) **Drainage layer**

   To prevent flooding, a drainage layer such as the incorporation of a layer of gravel or sand, or a proprietary drainage system consisting of polypropylene perforated cells can be installed.

3) Filter layer

To prevent clogging of the drainage layer, a geo-fleece is used to filter out the silt from the planting medium.

4) Planting medium

A heavy layer of soil is used as the planting medium. The recommended minimum thickness of soil for turfing is about 40 cm, while for shrubs and trees ranges between 1 to 1.5 m.

5) Vegetation

Intensive roof garden generally uses plants and vegetation associated with landscaping works. This is because they are constantly maintained, and thus do not need succulent plant types found in extensive roof gardens to prevent drying.

Thus, when building rooftop gardens, one has to take note of the soil and vegetation's potential weight. It is more favourable to use a lower bulk density soil type, as compared to a higher density soil type, when trying to achieve the same outcomes. According to the Housing Development Board (HDB) Structural Engineering Department, the dead load due to the topsoil and planter boxes of a roof garden can amount to 30 kN per m^2. Therefore, the roof deck of roof garden has to be structurally stronger to withstand the additional loads.

The initial cost difference between an intensive roof garden with shrubs and a conventional flat roof is $47.33 per m^2, which is approximately 36% more expensive than a conventional flat roof. Likewise, by planting trees on the rooftop, it would increase initial costs by $65.56 per m^2, thereby creating a cost difference of about 50% from the previous scenario. This option is relatively costlier than the rooftop with shrubs due to the thicker topsoil and higher outlay on trees (Wong et al., 2003).

Rooftop gardens are economically sound, and last longer than conventional roofs, as the vegetation layer protects the roof waterproofing membrane from temperature extremes, punctures, and UV damages (Kortright, 2001). The vegetation layer can shield as much as 87% of solar radiation, while a bare roof receives 100% direct exposure, in which its effects are shown when a London departmental store whose 50-year old roof waterproofing membrane located under a rooftop garden, was still in excellent condition - this achieves a record of more than three times its 10 - 15 year life expectancy (Peck et al., 1999).

Studies have shown that rooftop gardens have been tried in cold, snowy, hot, arid and wet climates (ABRG, 2009). Preserving the rooftop garden in its tip-top condition is thereby crucial in ensuring that the rooftop garden and the water membrane do not develop fissures, biodegrade or erode. The root system of the vegetation may also break through the water proofing membrane, and would cause major inconveniences like leakages; thus needing to replace both waterproofing membrane and the entire garden (Australian Conservation, 2009). Every re-roofing would cost approximately $36 per m^2 - around $72,000 for a 2000 m^2 rooftop (Wong et al., 2003).

Vegetation should be watered in the morning, since there are also dew drops in the atmosphere. They should also be watered in the evening after the sun sets, as the afternoon sun would be too strong. When watering, it is recommended to use either ‘mist’ or ‘drip’ irrigation. A rooftop garden should receive around 380 millilitres of water per square feet (Hemenway, 2001), and the drainage system should be constructed thoughtfully in order to prevent water stagnation.

3.2. Waterproof Membrane

Waterproofing refers to the application of different materials onto the roof structure in order to create a waterproof membrane which allows the structure to be relatively unaffected by water or to resist water passage in wet environments and in situations where it will be totally submerged. It also serves to protect the contents underneath the membrane to protect the structural integrity of the building. Common waterproofing membranes used in the industry range from asphaltic membranes, polymer modified bitumen, clay, polyurethanes, thermoplastics, coal tar, butyl rubber, EPDM or other cementitious products. Our team has chosen 3 most commonly used materials for waterproofing purposes to elaborate on and they are as follow:

1. Modified Bitumen

Bitumen consists of a mixture of organic liquids that are highly viscous, black in colour, sticky and it is entirely soluble in carbon disulfide. The composition of bitumen is as follows:

1) 0.1 to 25% weight of an elastomer
2) 0.1 to 40% weight of a solvent
3) 30 to 99% weight of a bitumen
4) 0.1 to 30% weight of a lithium salt of a fatty acid or hydroxyl fatty acid
5) 0 to 70% weight of a filler.

Base products such as polyester, fibre glass, rag fibre also known as hessian, and paper are used in the production of bitumen. All these products come in the form of roll format and are pulled through the bitumen mixes on huge rollers. The base product becomes saturated in huge tanks by the tar-like bitumen substance leading to the creation of rolls of waterproof material. Minerals are being added to the top of the felt to increase the fireproof capability of the products.

In addition to the base products, modified bitumen consists of various products being mixed together to enhance the characteristics of the original bitumen. Polymers such as atactic polypropylene (APP) are used to give rigidity and tear resistance to the original bitumen. Rubber additives such as styrene butadiene styrene (SBS) are also being used to add elastic benefits to the original bitumen.

Application methods of modified bitumen consist of both hot works and cold works.

For the hot works, there are two types of techniques.

i. The pour and roll technique consists of pouring hot bitumen at 220-240°C in front of the felt as it is unrolled along the roof, The hot and sticky bitumen is poured down the front of the roll in order to provide a continuous bead of molten bitumen across the whole width of the felt. The bitumen fills the voids and when it turns cold, there is a provision of a total contact adhesive bond to the layers and the joints are sealed at the laps.

ii. The torching-on technique uses a specially designed felt that is to be heated with a gas torch. No bonding bitumen is required in this technique. This technique is generally used for small to medium sized roofs; and where the access to the roof is difficult. The torching-on technique is unsuitable for direct bonding to timber and wood-based roofs or lightweight polyester base materials. Since direct heat is applied to the roof in order to seal the felt, precautions must be taken against fire and this method is not suited for use with flammable materials.

For the cold works, there are two techniques used:

i. The cold applied adhesive is applied evenly onto the roof surface as the roofing felts are being unrolled into position. Subsequently the laps are sealed with the cold adhesive. This is a safer alternative as compared to hot bitumen or gas torches.

ii. The use of self-adhesive membranes includes a high-tack adhesive with release paper. Once the self-adhesive membrane is set into the correct position on the roof, the release paper will be peeled off while the membrane will be stuck onto the base. This method is unsuitable for laying over uneven surfaces or in cold conditions. It also requires pressure contact to assist in full adhesion to the roof.

By comparing the cold-works and hot-works application method of modified bitumen, cold-work application is a much safer application method as compared to the hot-works application because of the absence of gas torches which require professional training on the part of the worker otherwise injuries would occur due to mishandling. Based on the specifications given by manufacturers, specific membranes are suited for specific methods only. For example, modified membranes made for torch applications are generally not suitable for cold adhesive applications. Cold works technique such as cold-applied adhesives also take a longer time to set in comparison to hot works technique of modified bitumen application.

Disadvantages linked to the use of modified bitumen as a roof waterproofing technique is linked to the appropriateness of the application technique used. If the application is not done properly, future problems such as defective lap seams, shrinkages, blistering, splitting, ridging and slippage can occur.

Also, the use of modified bitumen as a waterproofing system is not as effective on absolutely flat roofs. This is mainly due to it being of one layer and water can find the smallest opening when the whole area is being totally submerged.

2. Thermoplastics (PVC)

Thermoplastic waterproofing membranes consist of various classes of polymers. They are polyvinyl chloride (PVC), ketone ethylene ester (KEE), thermoplastic polyolefin (TPP) and chlorinated polyethylene (CPE).

The use of PVC as a waterproofing membrane displays many properties such as high tensile strength, elongation degree and allowance of substrate to shift when there are changes in the temperature without any cracks occurring. It is also root-proof, chemical-resistant and ageing-resistant. Being climate-resistant, it is flexible at -20°C. It is also an environmental-friendly product as it doesn’t produce any pollution and it does not have any toxic properties.

Application methods for PVC waterproofing membranes consist of adhesion and hot-air welding methods.

I. Adhesion Application

The adhesion application method consists of a system where the membrane is bonded to the substrate using a proprietary adhesive. There are three generic types of adhesives for single ply membranes.

i. Water-Based Adhesive

The first type is the water-based adhesive, which is an adhesive composing of between 10-70% by weight of a latex emulsion, between 30-80% by weight of an acrylic, between 0.05-5% by weight of a surfactant and between 1-50% by weight of water. It is compatible with a wide range of insulation materials. It may be slower to employ at low temperatures than solvent-based products.

ii. Solvent-Based Adhesive

Solvents such as mineral spirits, toluene and xylene are used as diluents in solvent-based products. These solvents are added to make the product more fluid and easier to apply. When these solvents evaporate, the product dries up, leaving an elastic paste which adheres to the roof surface. The use of solvent-based adhesive is able to achieve suitable tackiness rapidly under normal working conditions.

iii. Polyurethanes

There are significant variations in polyurethane adhesives for the use of many different applications. A typical urethane adhesive may contain aliphatic and aromatic hydrocarbons, esters, ethers, amides, urea and allophanate groups in addition to urethane linkages. The use of polyurethanes is effective in damp conditions as they are water resistant. Adhered membranes may be laid over boards specifically manufactured for adhesive bonding. The taping of the board joints may be required whenever solvents or solvent-based adhesives are employed in the construction of roofs.

II. Hot-Air Welding Method

For the hot-air welding method, the edge of the PVC roll is being fasted through ridged insulation onto the structural deck and later on lapped over by the fasteners by the proceeding roll. The overlap of the PVC roll is then heat-welded using hot air to create a mechanically-fastened thermoplastic roof. The end product is a continuous sheet membrane.

3. Ethylene Propylene Diene Monomer (EPDM)

EPDM rubber is a type of synthetic rubber made from the polymerization of a variety of monomers including isoprene, chloroprene and isobutylene with a small percentage of isoprene for cross-linking. All these monomers are mixed in various proportions to provide a wide range of physical, mechanical and chemical properties in the end product. The addition of impurities and additives to the monomers can give desirable properties to the end result.

The benefits of using EPDM as a waterproofing membrane for roofs are aplenty. It possesses anti-aging properties in the long term under cold usage of the natural environment and has small changes in physical properties. EPDM also provides outstanding ozone resistance, resistance to UV rays as well as atmospheric corrosion of many chemical corrosive substances. It possesses high tensile strength, high elongation, high flexibility and is also capable of withstanding a puncture by hard materials. The material has a long lifetime and thus very durable. It is also non-toxic and by using this as a roof waterproofing membrane, the runoff rainwater will not be polluted and can be collected be recycled.

There are 3 methods of application of waterproofing membrane onto the roof for EPDM membranes. They are loose-laid ballasted method, mechanical attachment method and full adhesion method.

I. Loose-laid Ballasted Method

For the loose-laid ballasted method, insulation is set over the roof deck in a loose manner while a single layer of EPDM rubber sheet is set over the insulation. The membrane is only adhered at the seams and penetrations. Ballast is then applied over the membrane to serve as weight for the roof system. The benefit of using this system consists of the economic savings derived from the low installation costs, fast installation, excellent fire rating and superb weathering resistance. Before the installation of this system, the structural conditions of the building to verify the load bearing capacity. The roof slopes and wind requirements must also be taken into consideration.

II. Mechanical Attachment Method

For the mechanical attachment method, the EPDM panels are loose laid onto the substrate and are fastened mechanically by nailed plates which are placed over the panel and protected by pressure-sensitive strips covering the nailed plates. This method is suitable as a light-installation system for EPDM membranes when the roof is unable to sustain the additional weight of the ballast-installation system and possess a surface which is suitable for mechanical fastening. The roof slope must be assessed to verify if the surface can provide sufficient pull-out resistance for this fastening system to be employed.

III. Full Adhesion Method

For the full adhesion method, the EPDM membrane is adhered directly to the substrates with bonding adhesives or contact cement. This is a light-weight system which is similar to the mechanical attachment method whereby the weight of the ballast is absent. It is more suited for irregular-shaped roofs as well as for steeply-pitched roofs.

3.3. Plant Root

Roots Growth Process

Roots are plants' means of transporting nutrients and water from the soils to the leaves via xylem and phloem to survive. The primary root is the first structure of the plant that occurs during germination, to absorb water for the shooting process to start. Roots growth occurs in 3 phases: the division, elongation and maturity stage. The division stage occurs at the apical meristem located near the root tip, and young cells divide actively via mitosis. When the cells enter the elongation phase, cells would take in water into its vacuole, causing it to be turgid and larger in size. As the cells mature, no further elongation and division would happen. This process can be manipulated by phytohormones, such as auxins and cyctokinins, which would affect the eventual length of root. The primary root continues to grow downwards, while lateral roots grow sideways out of it, to increase anchorage of the plant and to increase uptake of water and nutrient in the soil.

Effect of Soil Compactness on Roots Distribution Pattern

The experiment conducted by Selva Kumar Arunachalam, Christoph Hinz and Graham Aylmore on how soil properties affect roots distribution shows that soil compactness which derives from the soil type itself can affect how the roots grow. Penetration resistance of soil is highly dependable on amount of water present and the bulk density of the soil, and it affects the pore size of the soil (Selva Kumar et al, 2004). The small pore size of soil resulted in roots being thicker and the rate of growth-elongation decreases. More lateral roots will occur as these roots are thinner compared to the primary roots, hence more able to slip through the pores of the soil. Therefore, roots take longer to grow, and roots are less thick as well.

Clayey soil generally is prone to cracks due to shrinkage of soil, and the roots of plants favor these root cracks. As shown in the study, where cracks in soil are more evident, root growth is abundant. Also shown in the study is that as the occurrence of cracks decrease with depth of soil, root growth decreases as well. The cracks provide unrestricted growth to the roots, and help to avoid areas of higher mechanical impendence during their growth. Root growth also increase in sandy or silt-like loamy soils. With a composition of more than 18.3% clay and less than 30% sand for soil, may be the factor of limiting root growth as it directs the roots away from cracks.

In another study by C.A. Rosolem, J.S.S. Foloni and C.S. Tiritan, it shows that high compaction in soil not only prevents root traffic; it also interferes with the movement and distribution of water in the profile, that result in low availability of water and nutrients to plants. Thus overtly high compaction in soil would damage the plants.

However, although soil compaction can reduce roots growth substantially and protect the integrity of the roof, we need to consider the health of the plants as well and strike a balance. Soil compaction would result in nutrients deficiency, reduce soil aeration, damage soil structure and decrease moisture available in the soil (Mahdi Al-Kaisi, 2006). As seen in Figure 1, the plant growing in high soil compaction is small and weak, compared to that of the other 2 samples.

Figure 10: Effect of soil compaction on plants (Stephanie Nelson, Honors Program project)

Note: Low soil compaction: $0.7 g/cm^3$, Medium soil compaction: $1.1 g/cm^3$, High soil compaction: $1.6 g/cm^3$

Plants' Response to Fissures in Root Barrier

The experiment conducted by P.N. Jurena, S. Archer showed that plants are able to grow through fissures in root barriers just as easily as plants growing in containers without fissures. The roots were motivated by resources such as water, or nutrients deeper in the container used in the experiment, thus root are able to maneuver through the fissure. Thus, one can deduce that as roots overcrowd the restrictive space of the growth medium overtime, roots tend to dwell deeper into the soil, and it would not be a surprise if roots can penetrate the unfortunate cracks and damage the waterproofing membrane, not to mention the roof structure.

In a statement in Greenroof.com, it warned owners of roof gardens regarding the dangers of taproots that have the ability to damage the integrity of the green roofs and roof gardens, hence the need for a root resistant layer.

Model to Simulate Plants' Growth

The journal article done by A.Chavarr Krauser, U.Schurr used a mathematical approach to simulate root growth and found how the concentrations of phytohormones affect the process. Although overtly simplistic to modal the true root growth of plants in their natural state, it showed correlation in how phytohormones can affect root growth, and that roots growth is exponential. This study might have presented a model for roof garden designers to implement a more active approach to managing root damage to roof layers and to devise a method to manipulate plant hormones to control roots growth.

Dry Mass

Dry mass is the representation of the amount of biomass, which refers to organic materials in the organism. This would indicate the true growth of the organism and researchers can extrapolate the results to study the future potential of growth of the organism.

It requires the organism to be subjected to heat of 110°C and then cooled in a desiccator, before weighing. The procedure is to be repeated until a constant mass is measured. The advantage of measuring dry mass is that the true mass of the organism will be measured and unaffected by the fluctuation of water weight. It is most accurate to calculate the average dry mass from a large number of specimens, in order for the data to be representative of the experiment. However, this would require the killing of many organisms, and future chances of observing the organism would be eliminated.

Dry mass of roots would reflect the growth and health of the roots in the soil, and allow us to observe any effect that environmental conditions exert on the roots. We can also use the data given to extrapolate possible roots distribution, and future root growth.

Conclusion

From the information gathered from the various sources, one can deduce that plants tend to dwell into cracks as cracks provide no resistance to the growth of roots, and as roots grow, they are able to widen the cracks. Hence, roof garden specialists emphasized on the importance of the construction process of the roof garden, as poorly constructed roof garden would result in cracks in the structure, and these weak points would be exploited by the plant roots. However, penetration resistance and manipulation of plant hormones may be one of the methods that can limit the extent of roots growth, such that their destructiveness can reduce. This can be done using the simulation stated as above, and more research can be done as to how penetration resistance can limit roots growth and its distribution. Roof garden specialist might wish to manipulate phytohormones of plants and bulk density of growth medium to regulate the roots growth of plants in the roof garden. Thus, in the next section of this report, the team designed an experiment to test how bulk density of soil (which has a correlation to penetration resistance) affects roots growth and distribution.

3.4. Soil

Soil is a natural entity with layers of mineral constituents of different thicknesses, which differ from the parent materials in their physical, chemical and mineralogical characteristics. Soil is important for plants as it can hold roots that supporting the plants and storing different types of nutrients. Healthy soil has food, air and water to help plants grow. The more nutrients obtainable in the soil, the more the plants it can take up. Most of the plant's nutrients come from the soil; the nutrients are made up of a range of minerals from the earth. Capacity of soils storing water and nutrients increases when their clay in the soil increases as clay has a large surface area/unit volume and they can absorb large amounts of nutrients and water. Meanwhile, a soil with sandy texture is hard to hold water and nutrients and thus growing plants in this kind of soil is very difficult. Clayey soils are poorer in aeration because of stagnation of water and thus weaken the plants growth. Loamy soil, which is a combination of clay and sand, is the best textured soil for crop cultivation since it has all the helpful features that cannot be found in the sandy and clayey soil. Therefore, we can see plants growth can be affected by the texture of soils.

One of the major potential obstacles to robust root growth is high soil strength. Soil strength is the capacity of a soil to withstand forces without experiencing failure, whether by rupture, fragmentation or flow. Excessive soil strength can arise as a result of high soil bulk density, increased friction between soil particles, and increased cohesion between particles or low soil water content (Taylor et al. 1966, Raper and Kirby 2006). Several factors determine soil strength, including water content, bulk density, particle-size distribution etc (Jones 1983). Soil with bulk density greater than 1.5 mg/m^3 reduces root growth, and soil bulk density values of above 1.7mg/m^3 may effectively prevent root growth, particle size distribution in the soil combines with soil density can control root growth (Moenteith and Banath 1965, Gameda et al. 1985, Timlin et al. 1998).

Particle-size distribution in the soil combined with soil density can control root growth. Plant growth can be reduced by using soil bulk density greater than 1.5 Mg/m^3 for most soils and to less than 20% optimum root growth for all soils containing less than 70% sand and having bulk density than 1.6 mg/m^3 (Jones 1983). The figure below shows the limitations of plant root growth imposed by soil bulk density and sand contents.

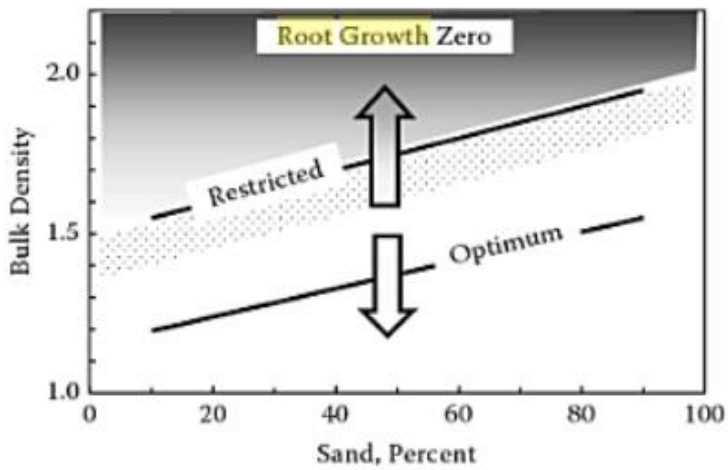

Figure 11: Limits for plant root growth imposed by soil bulk density and sand content.

In addition, the change in bulk density strongly affects permeability, drainage rate and penetration by plant roots in the soil. A change of 5% in the bulk density of a sandy soil may alter the hydraulic conductivity, which means the ease with which water can move through pore spaces or fractures. At low bulk densities and with low moisture contents, compaction may increase the continuity of the liquid phases and hence increase the thickness of the water film around soil particles.

From the point of view of plant growth, the mechanical impedance of soil bulk density has a wide spread influence on root penetration and growth. In sandy soils, growing roots penetrate bulk densities of 1.6-1.8 g/cm3 with difficulty. In clay soils, problems may arise at bulk densities above 1.4 g/cm3 (Australian Soil Resources Information System). For example, cotton root weight and depth of penetration decreases gradually from soil bulk densities of 1.3 to 1.5 g/cm3. There is a sharp decrease in root development with higher bulk densities.

4. Experiment

4.1. Experiment Brief

Soil is essential in the growing of vegetation. It consists of a solid state that contains minerals and organic compounds, as well as liquid and gas states in the pore space. Pore space is the volume of the soil that is not occupied by a solid state but by liquid or gas. There are two types of pore space, the macro pore space and the micro pore space. The macro pore space has a diameter of more than 60mm and stores air, while the micro pore space has a diameter of less than 30mm and stores capillary water. The texture, organic matter in soil, nature of crop cultivated in the soil as well as the soil depth affects the soil pore space. As pore space is created by the interaction between irregular shaped soil particles, more particles in a unit create more contact between the particles and hence have more pore space. Hence, fine textured soil like clay soils has more pore space than coarse textured sandy soils.

According to past botany research, the amount of pore space has an inverse relationship with bulk density. As the amount of pore space is decreased within the soil, the bulk density of the soil is increased.

$$Bulk\ Density, \rho = \frac{Mass\ of\ soil, M_s}{Volume\ of\ Soil, V_s} \propto \frac{1}{Amount\ of\ Pore\ Space}$$

Therefore, it is safe to assume that mineral soils have a higher density than organic and clayey soils.

As the bulk density of a soil is the mass per unit volume of the soil, when the clay content increases, bulk density increases too. The greater the bulk density, the more compact the soil is. Compact soils have low permeability, reduced infiltration, increased runoff and erosion. Since the bulk density affects the growth of the plant, the team is speculating if different types of soils used in growing plants might pose a visible impact on the root growth of the plant without affecting the health and wellbeing of the plant.

The team proposes to carry out an experiment where 4 different types of soil of varying bulk densities will be used to grow the hardy *ficus benjamina* plant. This plant is chosen due to its characteristics to quickly grow strong roots that ensues much damage.

There would be 4 samples for each soil type and the plant cuttings with partially formed roots will be individually grown in separate pots under the same external conditions (water, light, fertilizer). The team will water the plants twice a day at 9am and 6pm with the same amount of water and fertilizer and keep a log of the observations made as well as photos taken.

After 3 weeks, the team will carefully remove the plants from the soil and observe the root growth in terms of wet root mass, dry root mass, root diameter, root length and type of spread so to access if varying bulk densities will affect root growth.

4.2. Aim

As buildings today are steering towards the direction of energy efficiency, rooftop gardens are gaining popularity among developers as it can help reduce the cooling load of the HVAC systems as well as provide recreational space for occupants. However, plant roots are very strong and have the potential to damage the surface of the roof itself. The roots might even penetrate to the waterproofing membrane and cause leakages into the building. As such, current practices are to strengthen the roof in view of these problems. This would result in the over-specification of roof material quantities which would increase upfront cost of the project. This practice is not cost effective as the extra reinforcement might be unnecessary. Hence an active approach to deter the extent of root growth might be the new frontier to protect the roof from damages caused by plant roots.

In this experiment, the team aims to find out if varying soil bulk densities will affect the direction of the growth of root of the *ficus benjamina* plant. The team wants to see if the roots will grow in a dispersal formation or will they penetrate deep down into the soil when the soil bulk density is varied. The team will then see which soil medium is most suitable to be used in the rooftop gardens to minimizing the roots' potentially fast and destructive growths and propose bulk density as an active approach to deter the destructive advances of plant roots on rooftop gardens.

4.3. Assumptions

The experiment is based on the assumptions that the plant cuttings used for the individual pots are the same.

4.4. Experimental Procedure

1) Testing of Soil Bulk Density

By allowing the soil sample to go through compaction using a standard test, one can be sure that the amount of soil in the container of known volume is the most condensed. To test for the bulk density of each type of soil, the team subjected the soil sample to compaction by the B.S. Compaction Test and then found out the weight of soil. The density is then calculated by the below formula:

$$Bulk\ Density, \rho = \frac{Mass\ of\ soil, M_s}{Volume\ of\ Soil, V_s}$$

In this experiment, 4 different types of commercially available soil are used. They are:

i. Top soil
ii. Potting soil
iii. Organic soil
iv. Burnt soil

Apparatus:

1. A standard cylindrical metal mould giving a volume of 1/30 ft^3 or 944cm^3 or $9.44\ x\ 10^{-4}$ m^3	

<table>
<tr>
<td>2. ELE Automatic Compactor with a facility to drop a rammer of 2.5kg through a height of 300mm</td>
<td>


</td>
</tr>
<tr>
<td>3. A large metal tray and shovel</td>
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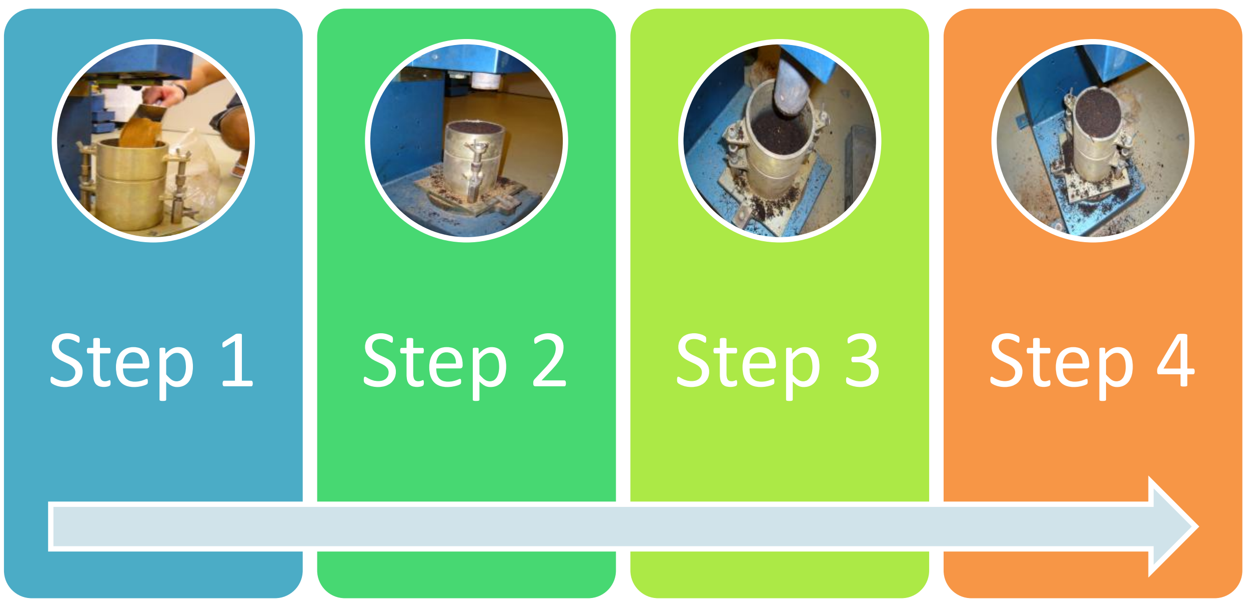
4. A weighing machine	

Procedure:

1. The metal mould is filled with Soil Sample 1 to the brim with the help of a shovel and trowel.
2. The sample shall be compacted into the mould using the ELE Compactor with 15 blows.
3. After 15 blows, more soil sample is added to the mould to fill it up to the brim.
4. Subject the refilled sample to compaction again.
5. Repeat Steps 3 and 4 until the soil sample goes through 4 rounds of compaction.
6. Remove the mould and weigh the soil sample.
7. Repeat Steps 1 through 6 for Soil Samples 2 to 4.



2) Testing the Effect of Varying Soil Bulk Density on Root Growth

The team will attempt to test the effect of varying soil bulk density on root growth by cultivating 12 *ficus benjamina* plant cuttings in 4 different soil samples; top soil, potting soil, organic soil and burnt soil. There will be 4 plant cuttings per soil type to eliminate anomalies.

The plants would be watered twice a day with 200 millilitres of water each at 9am and 6pm with the allowance of 1 hour variance. The plants would also receive 600/ppm or 1ml/l of fertilizer with the water to aid their growth, as per a normal rooftop garden setting.

After 3 weeks of plant growth, we will carefully separate the plants from their root mediums, and measure the growth and the spread of the roots. The wet root mass, dry root mass, root length, root tip and diameter will be recorded for analysis using appropriate software and equipment. Data will be used to extrapolate the potential damage caused by the plants' roots.

Apparatus:

1. 16 plastic pots	
2. 1 bag of top soil	
3. 1 bag of potting soil	
4. 1 bag of organic soil	
5. 1 bag of burnt soil	

6. 16 similar *ficus benjamina* plant cuttings	
7. Watering can	
8. Fertilizer	
9. Root Powder	

10. Digital Calliper	
11. Illuminance Meter – Yokogawa 51001	

Procedure:

1. Many *ficus benjamina* plant cuttings were cultivated in a controlled environment for 3 weeks from 26 February 2010 to 19 March 2010 till there were signs of growth of roots.
2. 16 similar plant cuttings were chosen to be further cultivated in the 4 different soil mediums.
3. The plant cuttings are then labelled and the diameter of the bottom of the stem is measured.

Figure 12: How the measurement of the base of stem is done

4. The bottom of the stem is then coated with root powder to encourage root growth.

Figure 13: Base of stem of plant cutting is covered in root powder

5. The plastic pot is then filled with the relevant soil medium to about 7cm in height and then lightly compacted with hands.
6. A small hole is made in middle of the pot for the plant cutting to enter the soil.
7. More soil is added to the pot to fill it up and to ensure that the plant is stable.
8. Steps 3 to 7 will be repeated for all plant cuttings and soil mediums.
9. Water the plants regularly at 9am and 6pm each day with 200ml of water mixed with fertilizers of the concentration of 600/pm.

10. Records will be logged throughout the experiment duration of 3 weeks from 19th March 2010 to 9 April 2010 with reference to any observations made.
11. A record of the amount of light received per pot of plant at various intervals of the day will also be measured for reference.

4.5. Experimental Precautions

1) Testing of Soil Bulk Density

1. All soil samples undergo the same number of compaction to ensure uniformity in the results.

2. The container is cleaned to remove lingering particles of the previous soil sample before testing.

2) Testing the Effect of Varying Soil Bulk Density on Root Growth

1. When making the plant cuttings of the plant *ficus benjamina*, a standard stature for the plant was observed. The plant cutting would have about 12-15cm of exposed stem with the end cut off at a slant to increase the surface area for the plant to absorb nutrients.

2. When cultivating the *ficus benjamina* plant cuttings in the controlled environment, the cuttings were provided with round the clock light and regular water and fertilizers.

3. The 16 samples of plant cuttings were chosen based on the presence of root growth at the base of the stem as well as the overall healthiness of the plant as can be seen by the growing of new leaves. This is so to ensure that the plants are all healthy and can survive the experiment duration.

4. When measuring the diameter of the base of the stem of the plant cuttings with the digital calliper, the device is cleaned to remove any lingering particles after every measurement.

5. The plant cutting's base of stem is coated with root powder to encourage the survival of the root in a new environment.

6. To ensure that the plants all receive the same amount of water and fertilizer, both substrates will be mixed in a container before distribution to the plants.

7. To ensure that all plants receive the same amount of 200ml of liquid, a container with a 200ml marking is provided for use during daily waterings.

8. When light measurement is carried out, the lux meter should be placed in the same position over each pot.

4.6. Results

1) Testing of Soil Bulk Density

Weight of Container: 5.20kg

Soil Sample 1:

Type of Soil:	Top soil from excavations
Image of Soil:	
Description of Soil:	Soil is very dry and sandy. It contains some concrete pieces as well as plant compound. Its constitution is mainly of large sand granular pieces.
Number of times of compaction:	4
Weight of Soil Sample and Container:	7.45kg
Weight of Soil:	2.25kg
Density of Soil:	$Density = \frac{Mass}{Volume}$ $= \frac{2.25}{9.44\ x\ 10^{-4}}$ $= 2383.47\ kg/m^3$

Soil Sample 2:

Type of Soil:	Potting Soil
Image of Soil:	 
Description of Soil:	Soil is dark brown in colour and moist to the touch. It also feels soft and spongy.
Number of times of compaction:	4
Weight of Soil Sample and Container:	6.60kg
Weight of Soil:	1.40kg
Density of Soil:	$Density = \frac{Mass}{Volume}$ $= \frac{1.40}{9.44\ x\ 10^{-4}}$ $= 1483.05\ kg/m^3$

Soil Sample 3:

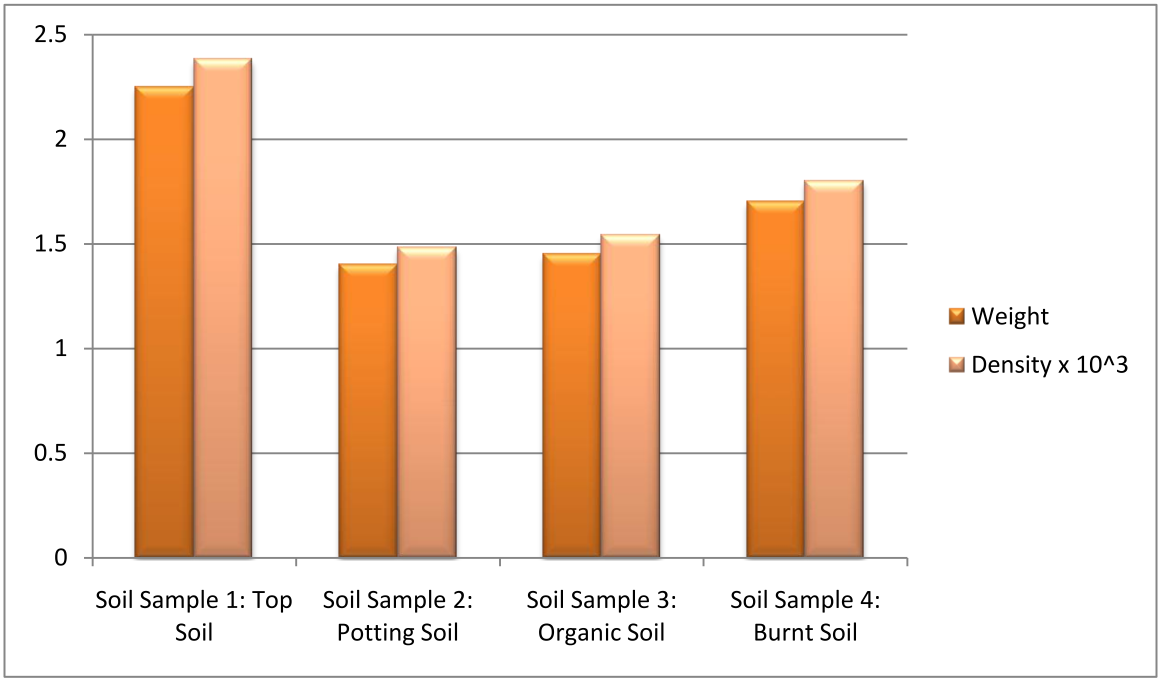
Type of Soil:	Organic Soil
Image of Soil:	 
Description of Soil:	The soil is dark brown in colour and moist to the touch. It consists of many coconut husks' strands and is very soft and fine.
Number of times of compaction:	4
Weight of Soil Sample and Container:	6.65kg
Weight of Soil:	1.45kg
Density of Soil:	$Density = \frac{Mass}{Volume}$ $= \frac{1.45}{9.44\ x\ 10^{-4}}$

	$= 1536.02\ kg/m^3$

Soil Sample 4:

Type of Soil:	Burnt Soil
Image of Soil:	 
Description of Soil:	The soil is almost black in colour and is the moistest out of all 4 samples. It is also the finest.
Number of times of compaction:	4
Weight of Soil Sample and Container:	6.90kg
Weight of Soil:	1.70kg

Density of Soil:	$Density = \frac{Mass}{Volume}$ $= \frac{1.70}{9.44\ x\ 10^{-4}}$ $= 1800.85\ kg/m^3$



2) Testing the Effect of Varying Soil Bulk Density on Root Growth

A logbook regarding the process of the experiment from the planting of cuttings in the relevant soil mediums to the day of extraction to measure the roots will be placed in the appendix for further reference.

The data here are the information gathered from the measurement taken before, during and after the experiment.

i. Diameter of Bottom of Stem of Plant Cuttings
ii. Average Light Measurements in a Typical Day
iii. Wet and Dry Root Mass
iv. Other Measurements
    a. Estimated Number of Tips of Roots
    b. Image Cover Percentage (Percentage of Scanned Image Covered by Roots)
    c. Perimeter in Sample (Overall perimeter of sample)
    d. Sample Area
    e. Average Counts (No. of vertical counts + horizontal counts)/ Sample area)
    f. Average Diameter
    g. Length of Roots in Sample
    h. Standard Counts

i. Diameter of Bottom of Stem of Plant Cuttings

The digital callipers were used to measure the bottom of the stem of plant cuttings. Below are the results of the different cuttings used in the experiment.

Figure 14: Measuring of Stem

Soil Medium 1: Top Soil		**Soil Medium 2: Potting Soil**		**Soil Medium 3: Organic Soil**		**Soil Medium 4: Burnt Soil**	
Plant 1.1	7.8mm	Plant 2.1	5.8mm	Plant 3.1	8.1mm	Plant 4.1	6.9mm
Plant 1.2	6.6mm	Plant 2.2	5.7mm	Plant 3.2	5.0mm	Plant 4.2	5.5mm
Plant 1.3	8.7mm	Plant 2.3	6.8mm	Plant 3.3	5.9mm	Plant 4.3	4.0mm
Plant 1.4	9.6mm	Plant 2.4	8.3mm	Plant 3.4	5.3mm	Plant 4.4	6.6mm
Average 1	**8.2mm**	**Average 2**	**6.7mm**	**Average 3**	**6.1mm**	**Average 4**	**5.8mm**

ii. Light Measurements in a Typical Day

An illuminance meter was used to measure the lux level at each pot of plant during an average day over the span of 9 hours with readings taken 3 hourly.

At 9am:

Soil Medium 1: Top Soil (lux)		**Soil Medium 2: Potting Soil (lux)**		**Soil Medium 3: Organic Soil (lux)**		**Soil Medium 4: Burnt Soil (lux)**	
Plant 1.1	10 200	Plant 2.1	9 700	Plant 3.1	6 980	Plant 4.1	7 050
Plant 1.2	9 400	Plant 2.2	8 020	Plant 3.2	6 520	Plant 4.2	6 170
Plant 1.3	8 560	Plant 2.3	7 960	Plant 3.3	7 350	Plant 4.3	5 270
Plant 1.4	7 980	Plant 2.4	7 450	Plant 3.4	6 320	Plant 4.4	4 750
Average 1	**9 035**	**Average 2**	**8 283**	**Average 3**	**6 793**	**Average 4**	**5 810**

At 12pm:

Soil Medium 1: Top Soil (lux)		**Soil Medium 2: Potting Soil (lux)**		**Soil Medium 3: Organic Soil (lux)**		**Soil Medium 4: Burnt Soil (lux)**	
Plant 1.1	8 390	Plant 2.1	6 700	Plant 3.1	5 350	Plant 4.1	4 290
Plant 1.2	6 670	Plant 2.2	5 670	Plant 3.2	4 260	Plant 4.2	3 730
Plant 1.3	6 190	Plant 2.3	4 970	Plant 3.3	4 000	Plant 4.3	3 070
Plant 1.4	5 530	Plant 2.4	4 540	Plant 3.4	4 030	Plant 4.4	3 160
Average 1	**6 695**	**Average 2**	**5 470**	**Average 3**	**4 410**	**Average 4**	**3 563**

At 3pm:

Soil Medium 1: Top Soil (lux)		**Soil Medium 2: Potting Soil (lux)**		**Soil Medium 3: Organic Soil (lux)**		**Soil Medium 4: Burnt Soil (lux)**	
Plant 1.1	6 630	Plant 2.1	5 560	Plant 3.1	4 310	Plant 4.1	3 420
Plant 1.2	5 570	Plant 2.2	4 830	Plant 3.2	4 420	Plant 4.2	3 370
Plant 1.3	5 450	Plant 2.3	4 470	Plant 3.3	4 320	Plant 4.3	3 280
Plant 1.4	4 890	Plant 2.4	4 540	Plant 3.4	4 100	Plant 4.4	3 040
Average 1	**5 635**	**Average 2**	**4 850**	**Average 3**	**4 288**	**Average 4**	**3 278**

At 6pm:

Soil Medium 1: Top Soil (lux)		**Soil Medium 2: Potting Soil (lux)**		**Soil Medium 3: Organic Soil (lux)**		**Soil Medium 4: Burnt Soil (lux)**	
Plant 1.1	1 260	Plant 2.1	1 230	Plant 3.1	1 040	Plant 4.1	876
Plant 1.2	1 180	Plant 2.2	1 190	Plant 3.2	1 030	Plant 4.2	865
Plant 1.3	1 190	Plant 2.3	1 200	Plant 3.3	970	Plant 4.3	867
Plant 1.4	1 150	Plant 2.4	1 250	Plant 3.4	950	Plant 4.4	795
Average 1	**1 195**	**Average 2**	**1 218**	**Average 3**	**998**	**Average 4**	**851**

Average Illuminance per Type of Soil in the Day

Soil Medium 1: Top Soil (lux)		Soil Medium 2: Potting Soil (lux)		Soil Medium 3: Organic Soil (lux)		Soil Medium 4: Burnt Soil (lux)	
Average 1	**5641**	**Average 2**	**4 955**	**Average 3**	**4 122**	**Average 4**	**3 376**

iii. Wet and Dry Root Mass

Wet root mass is the weight of the roots after removing soil particles.

Dry root mass is the weight of the roots after all moisture has been removed.

The team measured the wet root mass before putting the roots in an oven to bake it at a constant temperature of 80°C over 3 days to get the dry root mass. The results are as shown in the table below.

Plant Number	Wet Root Mass (g)	Dry Root Mass (g)	Difference (g)
1.1	4.2	0.74	3.46
1.2	3.39	0.73	2.66
1.3	4.08	1.18	2.9
1.3	3.91	1.19	2.72
2.1	2.79	0.5	2.29
2.2	-	-	-
2.3	-	-	-
2.4	3.03	0.51	2.52
3.1	2.74	0.7	2.04
3.2	1.78	0.21	1.57
3.3	-	-	-
3.4	1.06	0.47	0.59
4.1	2.42	0.86	1.56
4.2	2.57	0.45	2.12
4.3	-	-	-
4.4	-	-	-

iv. Other Measurements

The team will use a type of scanning software named Silver Fast Ai paired up with a scanner, HP Scanjet 8300, to digitize the images of the roots so that the analysing programme, Delta-T, can examine the images to produce the data below. The plants that do not have values are those that have died and do not have roots.

But before the team can subject the roots to computer analysis, we had to remove all soil particles from the roots. We removed the soil from the roots gently with our fingers and then soaked the roots in water to remove more soil. After which we would tenderly rub the roots with our fingers to remove any stubborn dirt to get a thoroughly clean root system.

Estimated Number of Tips of Roots

Soil Medium 1: Top Soil		Soil Medium 2: Potting Soil		Soil Medium 3: Organic Soil		Soil Medium 4: Burnt Soil	
Plant 1.1	794	Plant 2.1	885	Plant 3.1	607	Plant 4.1	596
Plant 1.2	3334	Plant 2.2	-	Plant 3.2	4023	Plant 4.2	991
Plant 1.3	1076	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	1779	Plant 2.4	1350	Plant 3.4	171	Plant 4.4	-
Average 1	**1745.8**	**Average 2**	**1117.5**	**Average 3**	**1600.3**	**Average 4**	**793.5**

Image Cover Percentage (Percentage of Scanned Image Covered by Roots)

Soil Medium 1: Top Soil		Soil Medium 2: Potting Soil		Soil Medium 3: Organic Soil		Soil Medium 4: Burnt Soil	
Plant 1.1	33.8	Plant 2.1	25.2	Plant 3.1	12.5	Plant 4.1	20.1
Plant 1.2	41.3	Plant 2.2	-	Plant 3.2	29.1	Plant 4.2	24.3
Plant 1.3	26.2	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	23.9	Plant 2.4	48.2	Plant 3.4	35.6	Plant 4.4	-
Average 1	**31.3**	**Average 2**	**36.7**	**Average 3**	**25.7**	**Average 4**	**22.2**

Perimeter in Sample (Overall perimeter of sample)

Soil Medium 1: Top Soil (mm)		**Soil Medium 2: Potting Soil (mm)**		**Soil Medium 3: Organic Soil (mm)**		**Soil Medium 4: Burnt Soil (mm)**	
Plant 1.1	3155.8	Plant 2.1	3393.8	Plant 3.1	2152.5	Plant 4.1	1549.9
Plant 1.2	7278.6	Plant 2.2	-	Plant 3.2	6015.2	Plant 4.2	3224.6
Plant 1.3	2999.6	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	4319.4	Plant 2.4	4587.5	Plant 3.4	703.57	Plant 4.4	-
Average 1	**4438.35**	**Average 2**	**3990.7**	**Average 3**	**2957.1**	**Average 4**	**2387.3**

Sample Area

Soil Medium 1: Top Soil (mm^2)		**Soil Medium 2: Potting Soil**		**Soil Medium 3: Organic Soil**		**Soil Medium 4: Burnt Soil**	
Plant 1.1	1933.9	Plant 2.1	2356.3	Plant 3.1	982.9	Plant 4.1	773.9
Plant 1.2	5892.3	Plant 2.2	-	Plant 3.2	5237.2	Plant 4.2	2143.9
Plant 1.3	3089.7	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	2477.1	Plant 2.4	6849.1	Plant 3.4	670.61	Plant 4.4	-
Average 1	**3348.3**	**Average 2**	**4502.7**	**Average 3**	**2296.9**	**Average 4**	**1458.9**

Average Counts (no. of vertical counts + horizontal counts)/ sample area)

Soil Medium 1: Top Soil		**Soil Medium 2: Potting Soil**		**Soil Medium 3: Organic Soil**		**Soil Medium 4: Burnt Soil**	
Plant 1.1	22 141	Plant 2.1	22 554	Plant 3.1	15 212	Plant 4.1	10 424
Plant 1.2	47 370	Plant 2.2	-	Plant 3.2	48 793	Plant 4.2	22 691
Plant 1.3	22 242	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	30 662	Plant 2.4	30 887	Plant 3.4	4 478	Plant 4.4	-
Average 1	**30 603.8**	**Average 2**	**26720.5**	**Average 3**	**22 827.7**	**Average 4**	**16 557.5**

Average Diameter

Soil Medium 1: Top Soil (mm)		**Soil Medium 2: Potting Soil (mm)**		**Soil Medium 3: Organic Soil (mm)**		**Soil Medium 4: Burnt Soil (mm)**	
Plant 1.1	0.70999	Plant 2.1	1.0656	Plant 3.1	0.85587	Plant 4.1	0.84587
Plant 1.2	0.83958	Plant 2.2	-	Plant 3.2	0.99275	Plant 4.2	0.98159
Plant 1.3	1.3945	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	0.87848	Plant 2.4	1.2665	Plant 3.4	1.1808	Plant 4.4	-
Average 1	**0.955638**	**Average 2**	**1.16605**	**Average 3**	**1.009807**	**Average 4**	**0.91373**

Length of Roots in Sample

Soil Medium 1: Top Soil (mm)		Soil Medium 2: Potting Soil (mm)		Soil Medium 3: Organic Soil (mm)		Soil Medium 4: Burnt Soil (mm)	
Plant 1.1	2723.8	Plant 2.1	2211.2	Plant 3.1	1148.4	Plant 4.1	914.89
Plant 1.2	7018.1	Plant 2.2	-	Plant 3.2	5275.5	Plant 4.2	2184.1
Plant 1.3	2215.5	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	2933.6	Plant 2.4	5408	Plant 3.4	567.92	Plant 4.4	-
Average 1	**3722.75**	**Average 2**	**3809.6**	**Average 3**	**2330.6**	**Average 4**	**1549.5**

Standard Counts

Soil Medium 1: Top Soil		Soil Medium 2: Potting Soil		Soil Medium 3: Organic Soil		Soil Medium 4: Burnt Soil	
Plant 1.1	0.16382	Plant 2.1	0.10213	Plant 3.1	0.081972	Plant 4.1	0.1145
Plant 1.2	0.1053	Plant 2.2	-	Plant 3.2	0.11479	Plant 4.2	0.10901
Plant 1.3	0.079722	Plant 2.3	-	Plant 3.3	-	Plant 4.3	-
Plant 1.4	0.12047	Plant 2.4	0.092018	Plant 3.4	0.10052	Plant 4.4	-
Average 1	**0.117328**	**Average 2**	**0.97074**	**Average 3**	**0.099094**	**Average 4**	**0.11176**

4.8. Analysis

Research student, Mr. Tan Kian Kai has kindly provided our team with information regarding his own experiment with hydroponics. Below are the data gathered:

Plant Number	**1**	**2**	**3**	**4**
Estimated Number of Tips	3253	4287	5362	4239
Image cover percentage	57	45	50	51
Perimeter in sample	5760	7437	8292	9797
Sample Area	7200	7200	7200	7200
Average counts	6873	6432	7148	7301
Average Diameter	0.42	0.686	0.615	0.748
Length in sample	11459	12566	15081	12036
Standard counts	0.13176	0.16985	0.21354	0.20102

Our team has made use of his data to compare to our own and derived the analysis which will be explained in the following pages.

4.8.1. Number of Tips

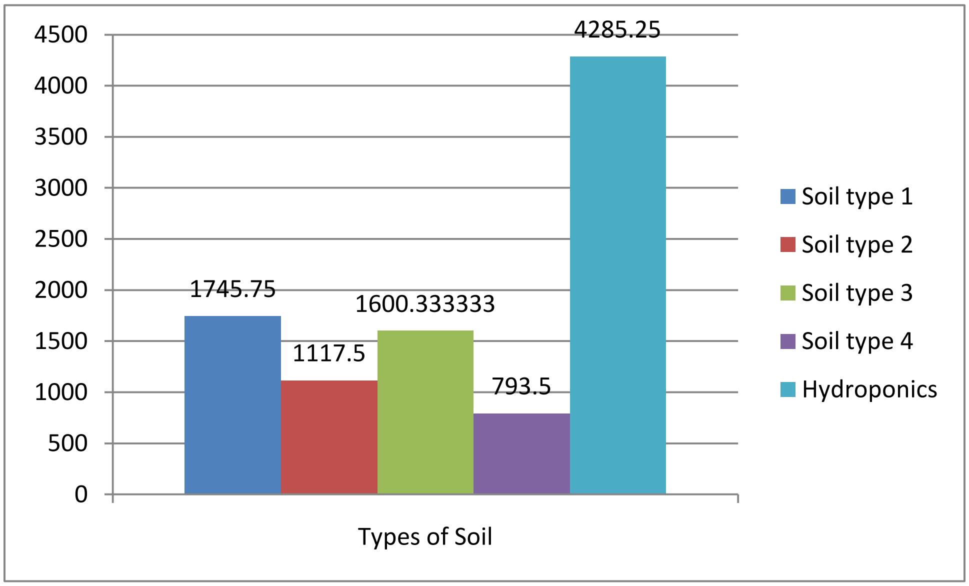


Figure 15: Average Number of Estimated Tips

As can be seen from the different samples of soil which were being used for our experiment, Soil 1 (Top soil from excavations) has the highest bulk density among the 4 different types of soil followed by Soil 4(Burnt Soil), Soil 3(100% Organic Soil) and lastly Soil 2(Garden Formula Potting Soil).

Based on the figure above stating the average number of estimated tips possessed by the *ficus* plants being planted using the different kinds of soil, it has been observed that the *ficus* plants which use Soil 1 as its soil medium produced the highest average number of estimated tips followed by Soil 3, Soil 2 and lastly Soil 4. The hydroponics method which substitutes soil for water containing dissolved nutrients produced the highest average number of estimated tips. The number of root tips indicates the number of roots that the plants have.

With the exclusion of the hydroponics method and using purely the various kinds of soil for comparison, it can be seen that the Soil 1 and Soil 3 have produced the highest average number of estimated tips for the *ficus* plants.

Through the graph, we can see that Soil 1 produces the plants with the highest average number of root tips followed by Soil 3 and we can draw a conclusion that the bulk density is directly proportional to the average number of estimated tips from the plants. Although Soil 3 has the second lowest bulk density, it has managed to produce the second largest number of estimated tips. However this contradicts our hypothesis that high bulk density would result in a lower number of root tips.

The excessive nutrients in Soil 4 caused it to produce plants with the lowest number of estimated tips. This complies with our hypothesis, but it differs from the results of Soil 1. It might be due to the higher amount of sunlight that plants grown in Soil 1 received compared to Soil 4. As higher amount of sunlight promotes photosynthesis within the plant, so more water is required by the plant to develop, and more roots grew for the process. Hence, future experiments to be conducted for this study should utilize uniform distribution of lighting to clarify this anomaly.

The hydroponics method has displayed the highest average number of estimated tips in comparison to the rest of the types of soil that are being used for the *ficus* plants. The reason for this might be accountable to the different conditions that the *ficus* plants undergo for hydroponics planting. The different conditions are regular intervals of nutrient sprays and artificial day lighting methods throughout the day.

Due to the huge abnormalities in our experimental plant root data, we are unable to conclude on which soil type would desirable for the usage of the rooftop garden. According to our literature review, higher bulk density would be preferred as it does not promote growth of root tips, therefore more preferred to be used on rooftop garden.

4.8.2 Lateral Root Area

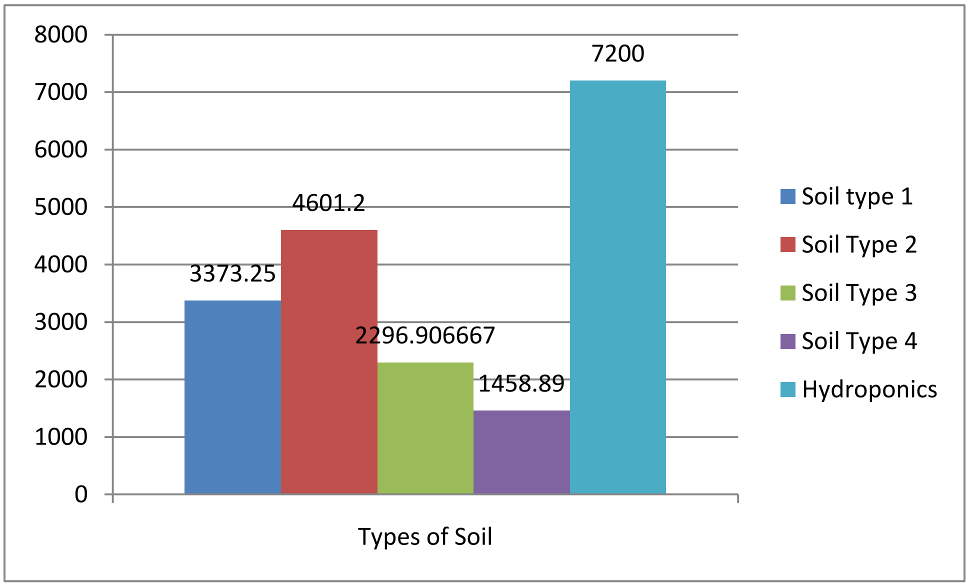


Figure 16: Average Sample Area

Average of sample area means the average area which the plant roots spread on the soil laterally and shows the root distribution pattern. The functions of lateral root are to assist the plant to anchor on the soil properly and to extract moisture and nutrients from the soil .The spreading area of plant roots correlates with the moisture and soil texture of the chosen soil types. Four types of soils were chosen in our experiment, namely top soil from excavation, garden formula potting soil, 100% organic soil and burnt soil. Each soil has different soil textures and bulk densities. The bulk density is lower for soil with high content of organic matter, and higher for soil with high soil content. The higher the sand content in the soil, the lower the native fertility of the soil (Koolen and Kuipers, 1983). However, our team observed that the soils with higher bulk density have higher water retaining capacity, which is top soil and burnt soil respectively.

From the graph we can see that plants grown in hydroponics have the biggest sample root area, which is 7200mm^2, while Soil 2 (Garden Formula Potting Soil) has the second biggest sample root area, which is 4601.2 mm^2. Then follow by Soil 1 (Top

Soil from Excavation), Soil 3 (100% Organic Soil) and Soil 4 (Burnt Soil) at 3373.25mm^2, 2296.90 mm^2 and 1458.90 mm^2 respectively.

Plants grown in hydroponics have the biggest root area because there are regular provisions of water and nutrients provided, by sprays of nutrient solution on the plant roots directly, and the residual water will pool at the bottom of the tank containing the waterproofing membrane, which provides for another source of nutrients. Ample nutrients and water has sped up the growth of the roots, and caused them to grow in a downward fashion towards the excess water on the waterproofing membrane.

There is a paradox that Soil 2 (Garden Formula Potting Soil) has larger root area than Soil 1 (Top soil from excavations). It was mentioned that root area is affected by the moisture content. Soil 1 has the highest bulk density, which has highest water retaining capacity among the rest of the soil types, so it should have the larger root area comparing to Soil 2 (Garden Formula Potting Soil). In the experiment, Soil 1 has a smaller sample root area probably due to the high bulk density which provided for higher anchorage of the root, hence, there is less need for more lateral roots than Soil 2, which has the lowest bulk density of all soil samples.

Moreover, Soil 3 (100% Organic Soil) has the 3rd smallest root area because of its low bulk density. Usually, soils with low bulk density have low capacity of holding nutrient and moisture in the soil. Thus, the plant roots have lesser chance to absorb the water and nutrient from Soil 3 as their low capacity of retaining water and nutrient supplied by our team. Although Soil 3 should have grown more lateral roots due to its low bulk density, there were sufficient nutrients that already existed in the soil, thus less need for more lateral roots.

Soil 4 ought to have one of the highest sample root area according to our hypothesis, our results do not support this claim. It could be due to the over-nutrition that we provided for the plant as the initial nutrition content in the soil was overlooked in this experiment.

In a nutshell, Soil 2 is the most favorable soil type for roof top garden. This is because lower bulk density soil facilitates plants to grow large area of lateral roots that can anchor onto the soil securely, thus reducing the chances of verticals roots reaching the waterproof membrane, and penetrating it. However, more sophisticated research methodology should be carried out to further substantiate this claim as the data did not show the direction of growth.

4.8.3 Diameter of Roots

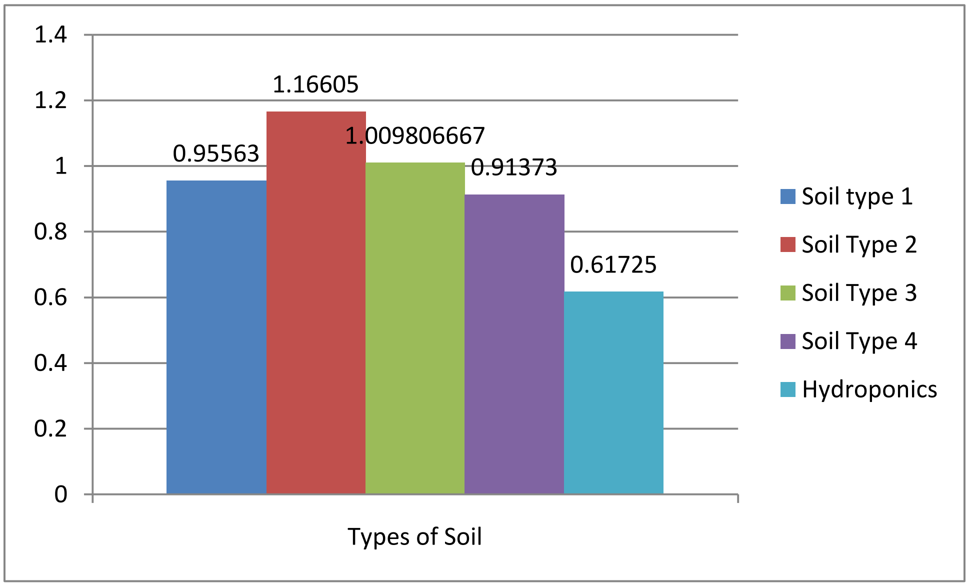


Figure 17: Average Diameter of Roots

The average diameter of roots refers to the average thickness of roots in the plants growing in the soil type. The diameter of roots is affected by the bulk density of soil, as high bulk density of soil would impede root growth thus making roots thinner due to the small pore size of the soil. It would also be an indication on root length in the future, as the thicker the roots the greater chance it has to branch out to finer roots. (Dr Albert L. Smith ET. Al, 2000)

As seen from the graph, plants grown in Soil 2 (Garden Formula Potting Soil) has the thickest roots, 1.16605mm, followed by Soil 3 (Organic Soil) at 1.010mm, Soil 1 (Top Soil from Excavation) at 0.95563mm. Plants grown in Soil Type 4 (Burnt Soil) has the smallest root diameter at 0.91373mm amongst the plants grown in soil. Even so, plants grown via the hydroponics method have very thin roots at 0.61725mm.

Plants grown in the Hydroponics method have the thinnest roots, despite the extremely low bulk density. This is probably due to high availability of nutrients and water as the nutrients solution was directly sprayed onto the roots of the plants, thus, there is little need for the roots to grow thick as it would compromise the surface area it has for absorption of nutrients, rather roots should be longer with greater surface area which can be seen in the following figure.

The average root diameter for each soil types correlates with the bulk density as Soil 2 has the lowest bulk density, followed by Soil 3, then Soil 4, and Soil 1 has the highest bulk density. Hence, we can conclude that the greater the bulk densities of soil, the thinner will the roots of the plants be because of the higher mechanical stress exerted on the roots. Thin roots would reduce the chance of branching of roots, and reduce the chance of the roots to be long as the root often grow in a 'tapering' manner such as that the diameter of roots closer to the plant would be larger than the root diameter away from the plant, as a result, thicker roots allow greater chance for greater elongation of the root.

In conclusion, higher density soil would result in smaller root diameter due to less pore size of the soil. Hence, Soil 1 is most desirable for the rooftop garden as it allows greater survival rate for the plants and root diameter is smaller, which indicates that roots of plants grown in the soil will be thinner and shorter, and less likely to reach the waterproof membrane.

4.8.4 Length of Roots

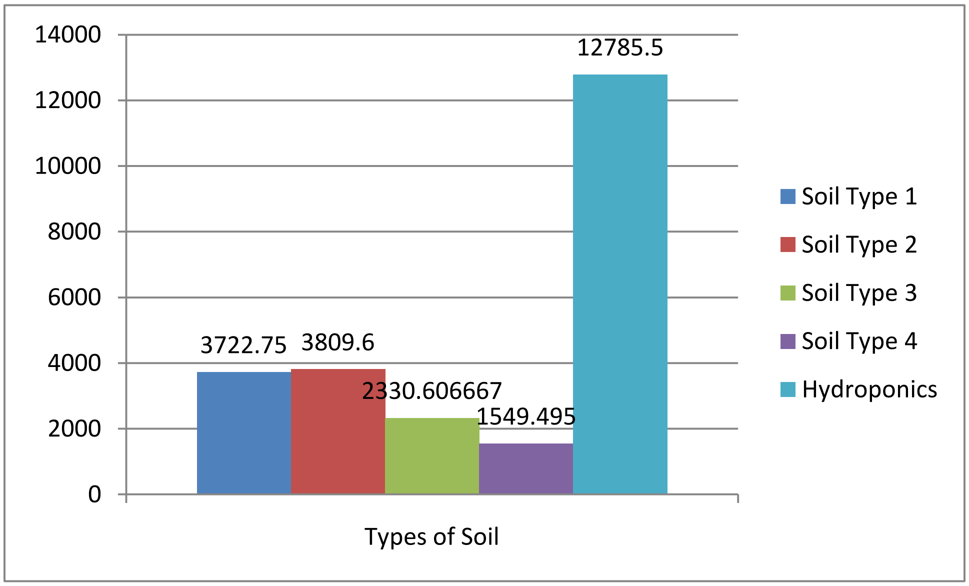


Figure 18: Length of Roots

Our group's first conclusion from various journal articles, which touched briefly on this particular topic of root growth of plants in different soil densities, is that there might be a good chance of plant roots growing differently in different soil densities. Our expectation to come out of this experiment is to prove that greater soil densities would discourage plant root growth, and that lesser soil densities would encourage plant root growth.

As evident from the density of the soils used, we can gather that the densities of the soils are not a good preventive measure to control the length of the plants.

Soil 2 of lowest density of $1483.05\ kg/m^3$; and Soil 1 with highest density of $2383.47\ kg/m^3$, produced the longest growing plant roots out of the four types of soils. Medium soil densities of both Soil 3 and 4 are $1536.02\ kg/m^3$ and $1800.85\ kg/m^3$ respectively produced the shortest length of roots.

The fact that high density soil would encourage root growth, such as Soil 1, debunks our first theory.

By looking at the graph of root growth, we now can otherwise concur that root growth is hugely affected by different modes of nutrient delivery. Plants grown by using the hydroponics method which transmitted nutrients to the plant roots have proven to grow at an accelerated rate, as compared to plants grown in soils.

However, we have to take into account that the plants grown using the hydroponics method uses a different surrounding condition as compared to soil plants in the open shelter. We have observed that our soil plants are exposed to insects such as spiders, which could have impeded the plant root growth and perhaps even killed the plants that became dead in the span of our 3-weeks experiment. Other unpredictable factors, such as high temperatures during noontime, might have killed the young stem cuttings.

Another difference in situation is that plants using the hydroponics method are exposed to regular intervals of nutrient sprays, as well as constant artificial day lighting. Such variance in conditions might have produced the large discrepancies in the root growths, with hydroponic plants emerging as the obvious success in root length growth.

We can see from the above graph of plant roots, plants that use the hydroponics method grow at a rate of 4-8 times faster than their counterparts which use the traditional medium of soil.

From this observation, we can recommend that rooftop gardens preferably should not use the hydroponics method, even though it saves the rooftop from bearing additional load from soil planting medium, as the hydroponics method greatly encourages root growth which can then translate into more funds spent in the unfortunate event when the plant roots manages to grow strong enough to penetrate through the waterproofing membrane.

The variance in root growth could also be due to the different soil types; being able to retain water, or even have existing good nutrients in them to facilitate the growth of the plant roots. What we have observed is that Soil 1 proved to have the least plant casualties, of only 2 yellowing. Another planting medium that has lesser plant casualties is the Soil 3 in which it had just 1 dead and 1 yellowing.

What we can explain from this finding is that Soil 1, when watered with 200ml of water, takes an unusually long time for water to trickle through the soil medium. This could be because Soil 1 is easily compacted and stays the most compacted. Soil 1 also constantly feels moist to the touch, which is a similar characteristic to that of Soil 3. However, the Soil 3 takes the fastest time to allow water to pass through, which is the complete opposite of the top soil from excavation. The similarity between the 2 types of soils, remain to be only the observation that both remains moist to the touch, as compared to other ‘dry’ soils of Soil 2 and the Soil 4.

4.8.5 Dry Mass of Roots

Dry Mass of Roots	
Plant No.	**Weight (g)**
1.1	0.74
1.2	0.73
1.3	1.18
1.3	1.19
Average	0.96
2.1	0.5
2.2	-
2.3	-
2.4	0.51
Average	0.505
3.1	0.7
3.2	0.21
3.3	-
3.4	0.47
Average	0.46
4.1	0.86
4.2	0.45
4.3	-
4.4	-
Average	0.655

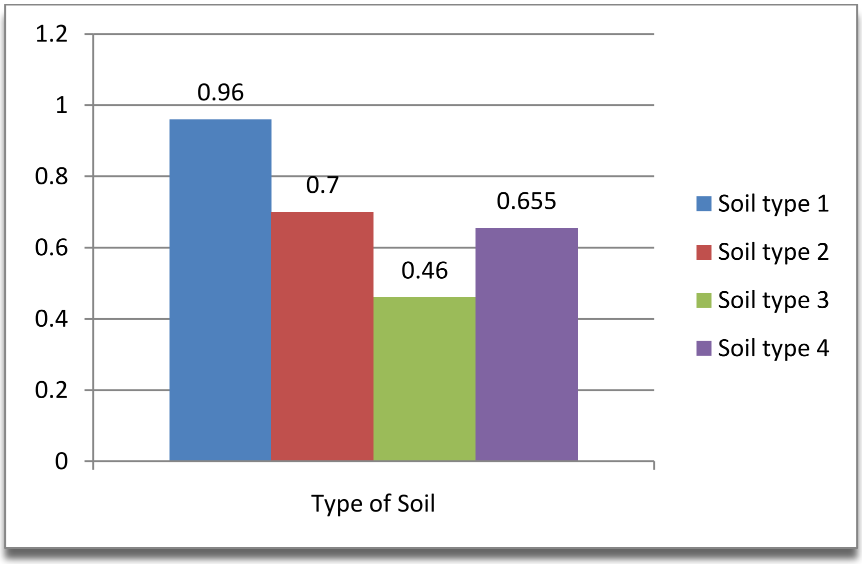


Figure 19: Average Dry Mass of Roots 1

Dry mass of roots indicates the amount organic matter the root contains. The organic matter would be the cell matter that was left behind after all water content was removed from the root section of the plant. The dry mass of the root generally indicates the health of the roots due to the roots' ability to actively generate cell matters.

Soil 1 has the greatest amount of dry matter (0.96 grams) while Soil 3 has the lowest (0.46 grams). Soils 2 and 4 have almost the same amount of dry mass, with 0.7grams and 0.655grams respectively. According to Figure 19, plants grown in Soil 1 are the healthiest, followed by Soil 4 and 2, and plants grown in Soil 3 were the least healthy.

Plants grown in Soil 1 also have the greatest survival rate, which might be brought by the composition of materials in the soil that contributes to the health of the plants. Soil 1 also has high water retention capacity and is able to hold water for the plant's absorption throughout the day. This might be the reason for its good health.

Compared to the other soil types such as 2 and 3, which are very loose and spongy, water retention abilities are not comparable with Soil 1, which probably led to the poor health of the plants as the plants looked dehydrated towards the end of the experiment. Soil 4, has relatively high water retention rate as well, however, it has a much lower dry mass than Soil 1. This could be due to the high amount of nutrients present in the soil as the soil already has high amount of nutrients, and we introduce more nutrients into the soil everyday during watering. Hence, further studies are required to properly assess the true effect of Soil 4 on plant roots, probably by changing the concentration of fertilizers in daily watering solutions to cater to the needs of the plants.

In conclusion, higher soil density produces healthier plants as according to our experiment as plants grown in Soil 1 and 4 resulted in healthier plants compared to the other soil types due to its high water retention abilities.

4.8.6 Difference of Weights between Wet and Dry Root Mass according to Soil Type

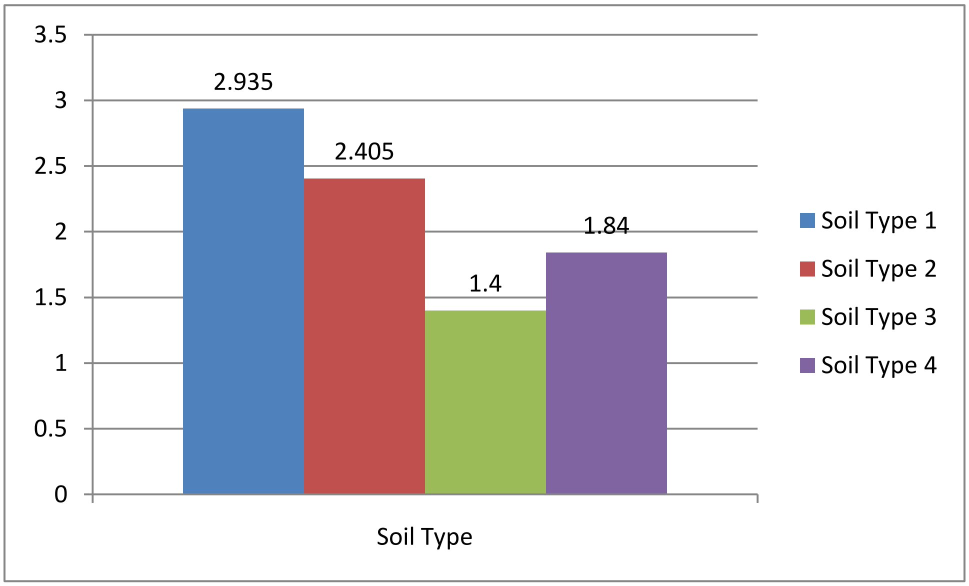


Figure 20: Average Weight (g) of Difference Between Wet and Dry Root Mass according to Soil Type

As we can see from Figure 18 and 20, the Average Weight of Roots correlates strongly to the Length of Roots.

For Soil 1 and 2, which have lengths of between 3722mm to 3809mm, their roots also absorb the most water weighing between 2.4g to 2.9g.

On the other hand, for Soil 3 and 4, which have lengths of between 1549mm to 2331mm, their roots also absorb the least water weighing between 1.4g to 1.84g.

It could be hypothesized that when roots grow longer, they tend to absorb more water mass, which could add to their weight and diameter thus in return, might possess sufficient strength to penetrate through waterproofing membranes.

4.9. Conclusion

Based on the observations made on the studies conducted on the plant roots, our team concluded that soil bulk density plays a part in affecting the relationship of soil and root growth.

Higher soil bulk densities promote lesser root tips growing from the plants, smaller root diameter and healthier plants. Although lower soil bulk density promotes lateral roots, higher soil densities have more benefits with regards to protecting the waterproofing membrane. Therefore, it is preferred to be used on rooftop gardens.

It is also evident from the data supplied that hydroponics is not a suitable method for planting on the rooftop garden, because it strongly encourages the growth of the roots which might in turn result in undesirable damages from the root penetrations, which might lead to substantial costs in restoration works.

In addition to the soil bulk density, other factors such as external surroundings, water retention capabilities of the soil and nutrient delivery method play a part in affecting the root growth of plants, and must be taken into consideration during the planning of construction of a rooftop garden. It is also recommended for more sophisticated experimental studies to be carried out to further establish our claims.

5. Recommendations

5.1. Usage of Plants with Shallow Root Systems

Although almost any plant can be grown on a roof, it would be beneficial if plants chosen to be used have a shallow root system. If the roots are proven not to grow beyond a certain length, and this is factored into when providing for the waterproofing membrane, one can save by eliminating the root barrier layer. This would reduce the material cost. Also, with such short roots, the plant would not be able to penetrate the waterproofing membrane thus also saving on the maintenance costs.

Examples of plants with shallow roots (Drainfield Landscaping, 2009):

Herbaceous Annuals	Herbaceous Perennials	Ground Covers (All Perennial)
Ageratum (*Ageratum housetonianum*)	Amaria, Seathrift (*Amariac maritima*)	Carpet Bugie (*Ajuga raptans*)
Wax Begonia (*Begonia semperflorens*)	Astlibe (*Astlime x arendsu*)	Kennickinnick (*Arctostaphylos uvi-ursa*)
Coleus (*Coleus species*)	Campanuia (*Campanuis species*)	Irish Moss (*Arenaria verns*)
Lobella (*Lobella ertinus*)	Snow in Summer (*Cerastium tomentosum*)	Bunchberry (*Comus canadansis*)
Sween Alysum (*Lobularia maritima*)	Lily of the Valley (*Convailaris majalis*)	Blue Fescue (*Fastuca ovina glauca*)
Geranium (*Pelargonium x hortorum*)	Sweet William (*Dianthus barbatus*)	Wintergreen (*Gauitheria procumbens*)
Penunia (*Petunia x hybrida*)	Cottage (and other) Pinks (*Dianthus species*)	Salal (*Gaultheria shallon*)
Salvia (*Salvia species*)	Coral Bell (*Haucheria sanguinia*)	Lydia Broom (*Genista lydia*)
Marigold (*Tagetes patula*)	Candytuft (*Iberis sempervirens*)	Sword Fern (*Polystichum munitum*)
Zinnia (*Zinnia alegans*)		Stone Crop (*Sedum species*)

5.2. Treated Root Barriers that Stunt Growth of Plant Roots

A recommendation would be to invest in treated/physical root barriers to minimize/prevent root penetration of plants. Treated Root Barriers come in the form of chemically treated soil types to stunt the growth of the plant roots. Physical Root Barriers can be lightweight plastic shields of 2-3 layers, or just solid concrete, to form a protection against plant roots. (Coulton, 2001) Plants such as the Euonymus japonica, Raphiolepis indica, could be used as they have less invasive roots, and are less likely to penetrate through the waterproofing membrane. Also depending on the client’s needs for the rooftop garden, the outlook could be tuned by an experienced arborist who can advise the client on plants that look appealing and have also less invasive roots to reduce maintainability problems.

With this system, future maintenance cost will be saved as the plant roots have lesser chances of penetrating the waterproofing membrane.

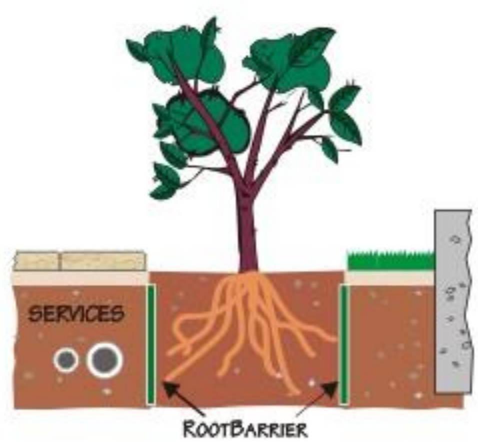


Figure 21: Root Barrier to contain the plant roots

5.3. Sub Base Protection Layer

American Wick 2006, recommends investing in an additional sub-base protection layer, made from unbound granular materials, to evenly spread the load of the paving to avoid differential settlement, and in addition also provide ready protection to the waterproofing membrane from the plant roots. This sub-base protection layer should be placed above the water membrane. The layer is used to be an added protection over the waterproofing membrane, so that the roots have to pass through the tough sub-base protection layer in order to reach for the waterproofing membrane. The unbound granular materials have natural interlocking capabilities, and can be loosened to remove easily. These unbound granular materials should be inorganic to avoid decomposition over time.

Although this layer is an additional layer over what is specified and may cause over-specification, it is to protect the waterproofing membrane. This extra upfront construction cost would be much lesser than if the roots penetrate the membrane and the whole membrane needs to be replaced.

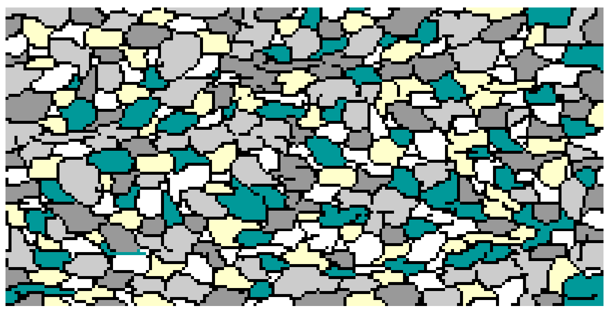


Figure 22: Interlocking Inorganic Granular Materials

5.4. Copper Threading Network to Detect Leakages

In the event of weakening of the waterproofing membrane due to UV ageing of the membrane, uneven medium loads, via destructive chemical exposures or even penetration due to plant roots, it will inadvertently cause water leakages. Thus a system of electrical copper threading network could be installed under the waterproofing membrane, as this helps in pin-pointing leakages for repair. The system gets activated when water enters the copper threading network, thus short-circuiting it, and would give an exact location of the leak. Once the leak shorts the copper network, the owner will be notified accordingly to do repair works to the waterproofing membrane. Subsequently when leakages are located by the owner with the help from the copper network, the vegetation and any material under it would be easy to lift aside for repair and to replace afterwards. (ABRG, 2009)

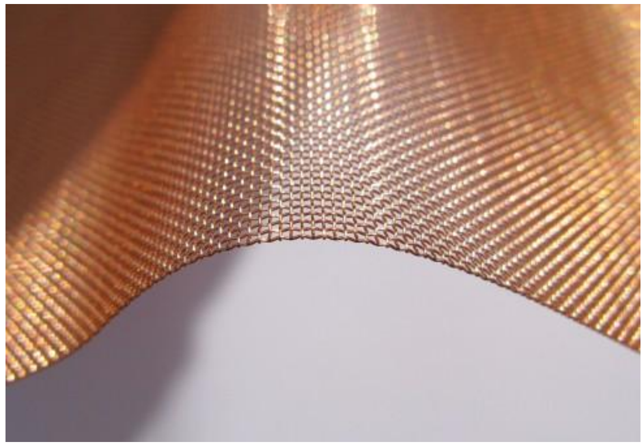


Figure 23: Electrical Copper Threading Network

5.5. Maintenance & Replanting

Since rooftop gardens do require regular care and maintenance, also for functionality and aesthetic appearance, large roots can be removed and plants can be replanted at intervals, to avoid potential damage to the waterproofing membrane which can cause leakages. (Perth, 2009)

By replanting, we can also introduce newer more appealing hybrids which can prevent from damaging the waterproofing membrane, and revitalize the surroundings. However, this renewal method poses a significant amount of money to be sunk every couple of years, and the waterproofing membrane might be inadvertently damaged by renewal of the garden. But on the plus side, the garden will have a new change periodically which will attract visitors to visit regularly.

Figure 24: Replanting the Rooftop Garden

5.6. Alternative Membranes

5.6.1. New Waterproofing Systems

With the growing popularity of rooftop gardens and green roofs, manufacturers are inventing new materials to solve problems relating to these gardens. Some suppliers like Delta Membrane Systems have come up with waterproofing systems that are root resistant. One example of such a product from them is the Delta-FM. It features a studded sheet made from virgin high-performance, high-density polyethylene. It has good chemical resistance, zero root penetration, rot resistance, and the ability to operate in temperatures ranging from -30°C to +80°C. It is endorsed by BBA, British Board of Agreement: Assessment of Products for Construction. With the waterproofing membrane being root resistant, it prevents roots from penetrating it to compromise on waterproofing capabilities. (Delta Membrane Inc., 2009)

By using this system, future maintenance cost will be saved as the membrane has less chances of being penetrated by plant roots.

Figure 25: Delta-FM Membrane

5.6.2. Single-Ply Membranes

Single-ply membranes like ethylene propylene diene monomer, commonly known as EPDM or butyl rubber are inorganic, and do not need a root-protection barrier as the material will remain stoic against root penetration. Single ply roof membranes are rolled sheets of inorganic plastic rubber material sealed with heat of solvents. They can be very effective if applied properly and are generally root-resistant. These types of membranes have a long proven track record in the industry but only if it was installed properly. (Townshend, 2007)

Similarly, using this system will eliminate future maintenance cost as the membrane has less chance of being penetrated by plant roots.

5.7. Plant Hormones

The growth of the root tip uses a one-dimensional string of cells and each cell is characterized by three distinct phases: division, elongation and maturity. Two phytohormones, produced at the root tip and the other at the shoot, determines the performance of the cell and consequently the growth of the whole root tip. (A.Chavarria-Krauser & Schurr, 2004)

The cells undergo certain processes, which impacts root growth as a whole. This implies that the behavior of the ‘‘system’’ root tip is related to the behavior of its individual components (Kaplan, 1992). It is recognized that growth is regulated by phytohormones (Steward & Bidwell, 1991). Organ production is known to be controlled by the ratio of auxins and cytokinins (Ray, 1963).

In the experiment carried out by Chavarria-Krauser and Schurr, they assumed that the two hormones produced at the shoot and root control root growth by changing the ratio of the phytohormones (A.Chavarria-Krauser & Schurr, 2004). From the numerical results and observations taken, an exponential relationship between root tip growth and level of phytohormones was established.

This usage of plant hormones to influence the growth of roots can be adapted for a different usage in the case for this project. Plant hormones can be introduced to the plants used on roof gardens so that their roots can be influenced to grow in a dispersed fashion instead of the more destructive vertically downwards type. This way, the threat of roots to penetrate the waterproofing membrane is mitigated.

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7. Appendix

7.1. Logbook for Watering Plants for the Experiment

Date	Time	Weather	General Description	Special Comments
19-Mar	2pm	Sunny	Plants look good	Just planted them today
20-Mar	10.30am	Raining	Plants look lethargic before watering them	
20-Mar	5pm	Cloudy	Plants look normal	Area around the pots is very wet
21-Mar	10.30am	Sunny	Plants look normal	
21-Mar	6.30pm	Cloudy	Plants look normal	
22-Mar	8.40am	Sunny	Plants look healthy	Before watering, I noticed that there were water marks on the soil below most pots indicating that the plants are sufficiently hydrated. Furthermore, when watered with 200ml, it took quite a bit of time for the soil to absorb the 200ml of water (esp. soil sample 1: top soil).
22-Mar	5pm	Drizzling	Plants look healthy	Samples Soil 1 (Top Soil) always took the longest to drain the added water out.
23-Mar	9.30am	Raining	Plants look generally healthy	Slight withering of leaves have been noticed
23-Mar	5.15pm	Sunny	Plants look generally healthy	Slight withering of leaves similar from the morning exists
24-Mar	8.35am	Sunny	Plants look relatively healthy. Some plants' leaves are curled but there are water stains at the bottom of the pot. New leaves found previously seemed to have withered.	There were water stains below most pots. Some plants' leaves are curled but there are water stains at the bottom of the pot. New leaves found previously seemed to have withered. Some plants' leaves also seem to be mottled with yellow spots.
24-Mar	5.05pm	Drizzling	The plants look healthy with no signs of any major withering.	
25-Mar	8.55am	Sunny	Some plants look healthy while others are becoming leaf-less.	There are water stains below most pots before watering. Some plants have fallen leaves and are spotted.
25-Mar	6pm	Cloudy	While plants growing on soil type one looks healthy, the some other plants growing in other soils are beginning to wither.	
26-Mar	8.35am	Sunny	Plants seem fine although mottled with	Some pots look to be falling ill?

			yellow spots	
26-Mar	6.44pm	Cloudy	Leaves of the plants look dry and wrinkle. Some of the leaves of pot 2.3 and 4.3 have withered. Pot 3.3 becomes leaf less soon.	All the plants look weak
27-Mar	9.12am	Sunny	Looks better and fresher than Friday evening	Most of the plants look OK, except, pot 2.3-4.3
27-Mar	5.45pm	Sunny	Most of the plants look OK, except, pot 2.3-4.3	There are water stains below most pots before watering
28-Mar	9.10am	Sunny	Plants look normal	
28-Mar	6.15pm	Cloudy	Plants look normal	
29-Mar	8.30am	Sunny	Most pots look ok. Except Pot 3.3 which has lost all its leaves.	Pot 3.3 has lost all its leaves but watering will continue just in case the plant is surviving without leaves.
29-Mar	6pm	Sunny	Plants look generally ok	No new leaves have been found to grow from withered pot 3.3.
30-Mar	1045am	Fair	A few plants are beginning to shed a lot of leaves. While the most healthy plants belong mainly to soil type one, and some from soil type 4	
30-Mar	5.50pm	Cloudy	More pots are wilting	Pot 3.3 has lost all its leaves. Pot 2.3 has many wilting leaves. Pot 4.4 has only a few leaves left. Pot 4.3 has only 4 leaves left.
31-Mar	8.40am	Sunny	Plants look like it was the day before	
31-Mar	5.15pm	Cloudy	More pots of plants have wilted leaving behind plants with lower survivability rate.	
1-Apr	8.30am	Sunny	Plants look like it was the day before	
1-Apr	6pm	Sunny	3.3, 2.2, 4.3, 4.4 and 2.3 looks weak and dehydrated.	
2-Apr	8.50am	Cloudy	Plants look less dehydrated.	
2-Apr	5.50pm	Raining	Plants look like it was previously.	
3-Apr	9.40am	Cloudy	Plants look like it was the day before.	
3-Apr	6.30pm	Raining	Plants look like it was previously.	

4-Apr	9.15am	Cloudy	Some pots look to have lost leaves.	
4-Apr	5.40pm	Raining	More leaves dropped.	
5-Apr	8.30am	Sunny	More plants look to have withered over the Easter weekend.	Pot 4.3 has 1 withered leaf left. Pot 4.4 has a few withered leaves left. Pot 2.3's leaves look to be withering.
5-Apr	5.15pm	Wet	Plants are withering quickly	About 5 pots (4.4, 2.3, 3.3, 4.3, 2.2) looks to be withering/withered.
6-Apr	9.30am	Sunny	Plants are withering still	About 5 pots (4.4, 2.3, 3.3, 4.3, 2.2) looks to be withering/withered. 4 pots (1.1, 1.3, 3.4, 4.1) have yellow spots on them
6-Apr	5pm	Humid	Plants are withering	About 5 pots (4.4, 2.3, 3.3, 4.3, 2.2) looks to be withering/withered. 4 pots (1.1, 1.3, 3.4, 4.1) have yellow spots on them
7-Apr	8.40am	Cloudy	Plants look the same as before	
7-Apr	5.15pm	Drizzling	Plants look weak with lesser potential survivors	
8-Apr	8.30am	Cloudy	Plants look limp due to maybe lack of water	
8-Apr	6pm	Drizzling	Plants look the same as before	
9-Apr	8.30am	Sunny	Plants look the same as before	

7.2. Photos of Plants before Uprooting at End of Experiment

Plant Number		
1.1		
1.2		

1.3		
1.4		
2.1		

2.2		
2.3		
2.4		

3.1		
3.2		

3.3		
3.4		

4.1		
4.2		

4.3		
4.4		

7.3. Photos of Roots

Plant No.	Photo of Roots
1.1	
1.2	

1.3	
1.4	

2.1	
2.2	
2.3	

2.4	
3.1	

3.2	
3.3	
3.4	

4.1	
4.2	
4.3	**-**

4.4