Maximising CO_2 sequestering in bio-based green roof structures for heavy greenery.

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Abstract

The Netherlands is facing a crisis. Before 2035 1 million homes will need to be built and CO_2 emissions need to be reduced by 49% whilst the main material for housing in the Netherlands is also the most CO_2 emitting material, concrete. Next to this increase in the built environment the existing urban environment is facing issues of the heat island effect, the decrease in population of urban birds, decrease in insect population and the Nitrogen crisis. To deal with these issues, Dutch councils are focussing on nature inclusive buildings. These buildings often require a higher structural capacity increasing material needs and CO_2 emissions. In this paper green roofing solutions are analysed and where possible replaced with bio-based or CO_2 sequestering materials. The result is a system that sequesters up to 759 kg CO_2/m2 compared to the embodied CO_2 emissions of a standard system of 147 kg CO_2e/m2.

Keywords: *Green roof, bio-based, CO_2 Sequestering, vertical forest, nature inclusive,*

I. Introduction

The Netherlands is currently facing a nitrogen crisis. Although only 0,6% (Remkes, 2019 p. 29) of the nitrogen emissions in the Netherlands are caused by the building sector, the government claims there is much potential for profit in this sector by building: modular, energy-neutral, circular and nature inclusive (Remkes, 2019 p. 29).

Climate change is a worldwide problem causing an increase in average temperatures, extreme weather events, melting of ice masses, extreme weather conditions and a shift of ecosystems (Bradford, 2017). Carbon-dioxide is the main greenhouse gas responsible for climate change. According to the Union of Concerned Scientists (USCUSA) CO_2 remains in the air far longer than other greenhouse gasses. Methane, the second biggest contributor to climate change from greenhouse gasses, stays in the air for approximately 10 years and converts to CO_2. It is estimated that 40% of CO_2 will remain in the air for 100 years and the final 10% will stay for 10,000 years (UCSUSA, 2017).

The Dutch government set a target to reduce the CO_2 emissions by 49% in 2030 compared to 1990 (Rijksoverheid, 2019). In the Netherlands there is also a need to build 1 million homes before 2035 to meet the housing demand (ABF Research 2018). The standard building method for housing in the Netherlands is mineral based (concrete / brick and other cement based materials), therefore cement usage is very high in the Dutch building industry. The cement industry is responsible for 8% of the global CO_2 emissions (Andrew, 2018). The aviation industry was responsible for 2% of global anthropologic CO_2 emissions in 2017 (ATAG, 2018). The cement industry emits four times as much of the global anthropologic CO_2 emissions then the aviation industry does. Therefore there is a need for a better building method or material.

During hot summers Dutch cities are facing heat island issues (Klok 2012) due to the high percentage of hardened surface in urban areas. This combined with the heat output of airconditioning and cars in cities increase the heat-stress. This can cause a temperature difference of up to 7 degrees for a city of 200.000 inhabitants compared to outside the city (KNMI 2010). Unhardened surfaces and plants allow evaporation which can lower the air temperature in the city.

The urban bird population is decreasing in the Netherlands. In 2017 only 44% of the urban birds were counted compared to 1990 (CBS 2018). The increase of stone surfaces in the cities and the lack of nesting spaces and food sources are some of the causes of the decrease in urban birds.

Insects serve an important role in our ecosystem. There is a decline of flying insects measured in Germany of 75% over the past 27 years (Hallman, 2017). In the Netherlands there is no data on insect numbers but it is most likely that this is also happening here (Hallman, 2017).

To deal with the problem of insect and urban bird decline, heat stress and the nitrogen crisis local councils in the Netherlands are currently including nature inclusive building in their policies. Nature inclusive building is including space for all parts of nature in the built environment. The Council of Amsterdam published a document including 20 ideas for nature inclusive building (Blokker 2018). The Council of Den Haag is developing a point system to promote nature inclusive building methods (Mulder, 2019).

There are already existing examples of more green and nature inclusive buildings, such as the Vertical Forest in Milan (Boeri 2017). Buildings with roof-gardens and trees on them are usually constructed out of concrete and occasionally out of steel for structural strength purposes. Most of these projects are built by casting concrete on site resulting in inflexible buildings. These buildings result in large quantities of waste when demolished as the concrete can't be reused.

As we are dealing with a growing population and an increase in people moving to the cities we are faced with a housing problem. Building more residential buildings decreases the space for nature in the cities. Cities are growing more horizontally to provide the new inhabitants with housing which includes a private garden or other outside space. The problem which cities are facing is that they can't expand outwards into nature areas yet there is a demand for housing with private outdoor space (Metropoolregio Amsterdam, 2019).

The building industry has been improving the environmental performance of built housing but the building process and methods of the building industry are still lacking sustainable progress. By looking at a building through a lifecycle analysis (LCA) a more clear view on sustainability can be reached where a true circular economy is possible.

To be able to give the citizens of dutch cities a garden within the confines of the existing city, vertical garden cities are needed. To create these vertical garden cities in an environmentally friendly way a new build-up of green roofing is required. Existing green roof structures are highly dependent on fossil resources to provide the necessary build-up of mainly petrochemical components and artificially designed soil compositions. This paper presents a research into designing bio based green roof structures supporting heavy greenery for high-rise mass-timber nature inclusive residential buildings in the form of a vertical forest. The research question will be the following:

How to facilitate maximum roof greenery with bio based and where possible CO_2 sequestering materials?

The research will review a broad variety of green roof types to provide maximum roof greenery.

II. Methods

To answer the research question it is divided in subquestions in which the research results will be organised:

1. *What do different plant groups need to be applied on top of buildings?*
2. *What building materials are currently used to create green on top of buildings and what is their environmental impact?*
3. *Which building materials for green roof structures can be replaced with bio-based materials and sequester the most CO_2 where measurable?*
4. *How do green roof structures built with bio based materials compare to currently used green roof structures based on their CO_2 sequestering capabilities where measurable?*

The first sub question will be answered by gathering information on existing green roof structures available on the market today. This will result in a set of categories of greenery structures. The information will be gathered from suppliers, manufacturers and literature. The materials will be analysed based on their base production material. ZinCo and Bauder are being used as representatives of the market as they use different core materials to produce their products which are representable for most other manufacturers of green roof products.

To answer the second question the materials currently available at ZinCo and Bauder for green roof structures will be categorised based on the information from the previous question. The information will be gathered from suppliers, manufacturers and literature. For structural materials literature research is used for reference. The comparison of insulation materials is based on information from data sheets provided by the manufacturers. This will result in a list of possible materials for each of the layers resulted form the first subquestion.

The third question focuses on alternatives to the standard materials. To answer this question each of the lists will be completed by adding alternative materials for application in these layers. The alternative materials will be judged based on a hierarchy of three methods in quantifying sustainability due to the wide range of materials. The first method is the embodied carbon of the materials including CO_2 sequestering capabilities based on the data from the ICE Database (Jones, 2019). For materials where this information is not available the percentage of bio-based content will be the second method of quantifying sustainability. The third method is based on the recycled content of the materials.

The fourth question focuses on existing green roof structures and how they compare on CO_2 sequestering capabilities to the materials that resulted from question three. The comparison will be made based on the information that resulted from question three.

III. Results

The results of the research are organised according to the research questions. The first paragraph will discuss the build-up of green roof systems. The second paragraph will list the currently used systems for green roofing. The third paragraph will discuss possible alternatives to the currently used materials and the last paragraph will show how the information from the second and third paragraph can be compared.

3.1 Plant types for vertical and elevated greenery

Green roofs are placed upon standard roof structures, most commonly concrete and steel to bear the heavier loads. Green roofing is typically divided into extensive and intensive green roofs. Extensive green roofs are low maintenance and often non accessible. Intensive green roofs generally require more maintenance but give more opportunities for roof gardening. ZinCo (2019) divides these plant groups into:

1. Wild grassland
2. Perennials, lawn, small shrubs up to 1,5 m
3. Bushes up to 3 m
4. Large bushes up to 6 m
5. Small trees up to 10 m

In Appendix A the structural load, needed maintenance, water supply, water retention and substrate depth are given for the different green roof options. For different intensive green roofing the main difference lies in the substrate layer. For larger plants and shrubs a thicker substrate layer is needed. Only the substrate for small trees is divided in two layers. The top layer consists of standard substrate with a thickness of 350 mm. This top layer contains most of the organic matter needed for plant growth. The bottom layer is the sub-substrate layer which has a higher water permeability and a lower water retention value per m^3 to decrease overall loads on the structure and increase drainage.
From interior to exterior the roof build-up is constructed out of three zones: standard roof structure, drainage and substrate zones. This results in a maximum of nine layers. The layers are:

1. Structural layer
2. Insulation layer
3. Roofing membrane
4. Root barrier
5. Protection layer
6. Drainage layer
7. Filtration layer
8. Sub-substrate
9. Substrate

The first three layers are based on the standard composition of a flat roof. Interior finishings and damp layers have not been taken into account in this research. The top two layers have already been discussed. The middle four layers is the main problem area as these are all made from petrochemicals and therefore rely on a non renewable resource and have relatively high CO_2 emissions. For each of these nine layers specifications have been set out in a table in Appendix B including an image showing how this is built up compared to earth soil build-up.

3.2 Standard materials used for green roof structures

In this paragraph all nine layers will be discussed and which materials are used in standard situations. These materials will be analysed for their environmentally friendly aspects.

Structural Layer
The structural layer is taken into account in this study as intensive green roofs require an increased load bearing capacity. This usually results in an increase in structural materials needed. For most intensive green roofs concrete is chosen as the main structural material because of its high strength and water resistant capabilities. The application of intensive green roofs on top of buildings results in an increase of material required. The same principles apply to steel structured buildings. Appendix C table 1 shows that both steel structured and concrete structured flooring result in a high embodied carbon footprint of approximately 82 kg CO_2e/m^2.

Insulation Layer
For the insulation layer underneath a green roof compression strength and insulation values are the most important. The currently most used high performance insulations are foam panels made from petrochemical basis. Most commonly used insulations are Polyisocyanurate (PIR), Polystyrene (EPS) or Bakelite (Kingspan Kooltherm). These materials are used as they have a high insulation value and have a relatively high compressive strength. They all rely on the petrochemical industry and therefore a finite resource with a high carbon footprint. The embodied CO_2 footprint of PIR and EPS are similar at 16,7 CO_2e/m^2 for PIR and 16,3 for EPS. The thickness of the EPS has been adjusted to create a similar R value based to 120 mm of PIR. (Appendix C table 2)

Roofing Membrane

Flat roofs are most commonly covered in either bitumen based roofing membranes or EPDM roofing membranes. Both are petrochemical based materials. EPDM is a more refined product and bitumen a more raw extract of crude oil. bitumen is not root resistant and therefore will need an additional root membrane when applied. EPDM is root resistant and can be produced with recycled materials and has a longer life span making it the more sustainable option that is readily available. The production of EPDM form new materials however has a much higher embodied carbon footprint than bitumen. bitumen has an embodied carbon footprint of 1,3 CO_2e/m^2 and EPDM 7,9 CO_2e/m^2. Although EPDM lasts about two to three times longer than bitumen, the embodied carbon footprint is still twice as high. (Appendix C table 3)

Root layer

Root resistant layers are mainly used for green roofs on existing structures where a bitumen membrane is present. In newly built situations EPDM is preferred due to it being sustainable and already root resistant leaving the root resistant layer abundant. In Appendix C table 4 three option for the root resistant layer are compared consisting of Polyethylene Polypropylene and polyester. Out of these three materials the polyester has the highest embodied carbon footprint of 3,7 CO_2e/m^2, the polypropylene has the lowest embodied carbon footprint at 0,04 CO_2e/m^2. The polyethylene is made from 100% recycled materials and has the lowest carbon footprint per kg of material. (Appendix C table 4)

Protection layer

The protection layer is there to protect the roofing membrane against the hard edges that the drainage layer can contain. This layer consists generally of polyester fibrous fabric mixed with bitumen to hold it together. Of the studied materials the VLF-100 layer has the lowest embodied carbon footprint per m^2 as this is the lightest and thinnest material studied. (Appendix C table 5)

Drainage Layer

The goal of the drainage layer is to retain some water yet easily release the access water. This is why the standard drainage layers are generally cup shaped polyolefin drainage mat. Water is stored in the cups. When the cups are full the overflow runs through the inverted space underneath between the cups. The standard system that ZinCo provides is called the Floradrain. They are available in different thicknesses for different green roof build-ups. The SDF mat Bauder provides is an all inclusive system for extensive green roof systems that includes the protection layer and filter layer of only 20 mm thick. Permagard also provides two similar systems of 8 mm and 20 mm thick. For intensive green roofs Bauder uses EPS to create their cup shaped drainage and water retention panels. (Appendix C table 6)

Filtration layer

Currently the Filtration layer is most commonly made from recycled man-made fibres from polypropylene and polyester. The layer is there to keep small particles from washing away that could block the drainage system. The reason this material is used is that it doesn’t degrade and keeps its filtration qualities. (Appendix C table 7)

Sub Substrate Layer

The sub-substrate layer is only used in substrate layers of 300mm and thicker. The sub-substrate consists of mineral based materials like: crushed brick, crushed limestone and crushed concrete providing a well drained layer underneath the substrate. (Appendix C table 8)

Substrate Layer

The substrate layer is also called the growing medium. It depends on the type of plants as to what growing medium composition is needed. The growing medium can be divided in inorganic material and organic material. The percentage of organic material in substrates varies between 0 and 20% (Vijayaraghavan 2014). These organic materials can vary from compost, coconut fibre, tree bark and peat (Young, 2014). The organic material provides the nutrients for the plants to

grow. For bigger plants a thicker substrate layer is needed. These plants also need a richer soil with a higher organic matter percentage.
The inorganic materials are mainly mineral based materials like rock wool, perlite, vermiculite, crushed brick, sand, crushed limestone and crushed concrete. These materials are added to provide the minerals needed for the plants and increase the water retention of the substrate. The inorganic materials are mainly chosen based on their low weight compared to their water retention.
There is a lot of research on compositions of substrate to find the best substrate. Thomas Young (2014) gathered a lot of this research and categorised them in a table under: plant growth, drought tolerance, substrate depth and novel substrate materials. The table is available at Appendix four. (Appendix C table 9)

3.3 CO_2 SEQUESTERING MATERIALS FOR GREEN ROOF STRUCTURES

CO_2 sequestering materials are materials that consist partially of carbon retrieved from the atmosphere. Wood is an example of a CO_2 sequestering material. Trees grow by converting CO_2 into Carbon and Oxygen by photosynthesis where the carbon becomes a building stone for the tree. When the tree is burned or decomposed the Carbon is released back into the atmosphere. When we cut the tree down and store the timber in our built environment we sequester the containing CO_2 for the lifetime of the building and after the lifetime of the building it can be recycled or reused as an energy source.
All plants sequester CO2 and release it during decay or burning. For the building industry materials like hemp, cork, hay and many more are sequestering materials that are already in use. Bioplastics like PLA can also be classed as CO2 sequestering materials as they are made from plants.

Structural layer
An alternative to concrete and steel for building structures is mass timber. Mass timber is available in many types. For this research Cross Laminated Timber (CLT) is used for comparison as this is the most commonly used type of mass timber. CLT panels are made out of cross laminated sawn timber. During its lifetime a cubic metre of CLT emits -650 kg of CO2 into the atmosphere including the sequestered CO2 (Hassan, 2019). (Appendix C table 1)

Insulation layer
CO_2 sequestering alternatives to the standard insulation materials could be cork, hemp and wood fibre. Wood fibre and cork have similar insulation values and they both sequester the most CO_2 of all the insulation materials in this study. These materials have a rather low insulation value compared to conventional materials and require a damp proof layer to be added to the structure to prevent condensation inside the insulation. For this research the Visqueen EcoMembrane (Visqueen, 2019) has been added to the carbon footprint alculations. Visqueen polyethylene EcoMembrane is made from 100% recycled materials. There are Polyethylene bio-plastics made by Braskem with a bio-based carbon content of up to 96% (Braskem, 2020). These bio-plastics are however not yet available as a building material. Calostat is a high performance and environmental friendly alternative that is not a CO_2 sequestering material but has a very low environmental impact. Calostat is the only high performance insulation material with a cradle to cradle Gold certification (Evonik 2019). (Appendix C table 2)

Roofing Membrane
There are not many alternatives to bitumen and EPDM yet as the quality level needed to compete with them is very high. Bitumen has been used for over 800 years whilst bio based alternatives have only been explored in the last decade (PowerPoint van Wur). PVC roofing is also an option but this material is very polluting during production and therefore left out of consideration. There are also EPDM membranes available that are partially bio-based and partially made from recycled products. The most bio-based roofing membrane is Derbipure, this material is produced from bio-plastic from the sugar cane industry.(Appendix C table 3)

Root layer
The best alternative to the root resistant layer is to use a root resistant roofing membrane. ZinCo claims that with their bioplastic alternative they can reduce the CO2 footprint of this layer by 20-70% (ZinCo, 2019). This also removes the dependency on finite resources. (Appendix C table 4)

Protection layer
When softer drainage layers are used like the cork modules by Earth Kweek this layer becomes obsolete as the soft cork does not harm the underlying roofing membrane. For the natureline floradrains this layer is still needed and therefore ZinCo has also created a naturline version for the protection layer reducing CO_2 footprint by 20-70%. (Appendix C table 5)

Drainage Layer
To reduce the CO_2 footprint of the Floradrain ZinCo developed their Natureline product line which are the exact same products produced with renewable plastics. This is still a very energy consuming production method but as they use residual streams of the sugarcane production there is some CO_2 sequestering involved. In Portugal cork is being used as a drainage layer for green roofs. In the Netherlands Earth Kweek claims to produce the greenest green roofs. They use cork to create modules for extensive green roofs. The drainage and water storage capabilities of the Floradrain 25 and 50mm are similar to 100mm medium density insulation cork board (Tadeu, 2019). (Appendix C table 6)

Filtration layer
Biodegradable or bio based materials are therefore not an option to replace the current plastic based layer. The cork elements Earth Kweek use do not use a filtration layer as the cork layer provides the filtration. The Natureline series by ZinCo (2019) also holds a filtration layer. The specifications of this material are not available but it is assumed they will be the same as the Filter Sheet SF made of Polypropylene by ZinCo (2018). (Appendix C table 7)

Sub Substrate Layer
Crushed brick has the highest water retention and lowest density compared to the other materials. The crushed brick is available in most urban areas reducing transport CO2 emissions. (Appendix C table 8)

Substrate Layer
In the substrate the organic material is the only material that is 100% bio based and has carbon sequestered. However, growing media like coconut fibre have sequestered carbon yet they also have a high embodied carbon footprint as they are shipped from far creating high transport emissions. Compost from green waste is the most CO_2 negative material that is readily available in all urban areas with a CO_2 sequestering ability of 1,5 kg CO_2/kg.
The inorganic material in not bio based but can be judged based on their embodied Carbon footprint where possible. Crushed brick is available in most urban areas and can therefore be sourced locally which results in low transport emissions.
Biochar is a material that has comparable specifications to the inorganic materials used in substrate. BioChar is made from bio-mass and contains carbon. By replacing 30% of the substrate material with BioChar the substrate becomes lighter, improves water supply to plants, water retention and increases the sequestered CO_2 in the substrate (Cao, 2014). Replacing 40% of the substrate with BioChar gives a further improvement but lowers the growth of the plants (Cao, 2014).
Another alternative to standard substrates is substrate made from sewage waste streams which is currently being developed by Blue Roof (Blue Roof, 2019). There is however no data sheet available on this product as it is currently being tested which is why it isn't be included in this study. (Appendix C table 9)

3.4 CO_2 SEQUESTERING GREEN ROOF STRUCTURES

By calculating the global warming potential of the currently used and the newly proposed build-up for maximum intensive green roofs their environmental performance can be compared. The goal for this research is to maximise CO_2 sequestered per m^2 for highly intensive green roof. The materials are therefore chosen based on their sequestering capabilities.
For both situations the insulation value has been equalised by increasing insulation thickness. The structure thickness has been chosen based on VBI Calculations (VBI, 2020) and Stora Enso standard CLT spans (Stora Enso, 2015). The chosen thickness for the concrete structure is based on VBI structural calculation. The thickness for the CLT slab a six metre single span with a load bearing capacity of 10 kn/m^2 so both build-ups are able to support trees and large bushes.

The newly proposed build-up resulted in an increased structure height of 17% compared to the standard system. The CO_2 sequestering capability of the newly proposed system is 756 kg CO_2/m^2. The way a similar green roof would be constructed currently would have an embodied carbon footprint of 147 kg CO_2e/m^2. This is an improvement of 903 kg CO_2/m^2. If the total thickness is an issue this can be reduced by applying Celostat insulation. This also reduces the amount of sequestered CO_2 per m^2. The total weight of the structure has reduced by almost 60% from 1688 kg/m^2 to 684 kg/m^2 including the structural layers. This is mainly due to the weight of CLT compared to concrete. (Appendix E table 1)

Taking only the green roof layers into account the reduction in weight is 37% from 882 kg/m^2 in the existing structure and 551 kg/m^2 in the proposed green roof build-up. The embodied CO_2 footprint of the existing structure is 40 kg CO_2e/m^2. The newly proposed build-up has a CO_2 sequestering ability of 426 kg CO_2/m^2. (Appendix E table 1)

III. CONCLUSIONS

The results show there is a high potential in improving the existing green roof systems to make them more “green”. For all the layers of currently used standard green roofing systems there are more environmentally friendly alternatives. The CO_2 sequestering capabilities can be achieved in all layers except for the waterproofing membrane. There is however a bioplastic alternative available called Derbipure which reduces emissions and is not dependent on finite resources. It is possible to quantify the CO_2 emissions for the materials by using the ICE Database (Jones, 2019) which provides the embodied CO_2 emissions data of the materials analysed in this research. The result is a system that sequesters up to 759 kg CO_2/m^2 compared to the embodied CO_2 emissions of a standard system of 147 kg CO_2e/m^2 both including the structural layers.

The build-up of the green roof for different plant groups only changes the depth of the substrate layer, the drainage layer and the structural support needed for heavy greenery.

Cork is the main ingredient to increase CO_2 sequestering in green roof structures as cork can replace the protection layer, drainage layer and filter layer. These layers all exist of petrochemical materials in currently used green roof systems. There is research that proves that cork can be used as a drainage layer there is however no research available of the degradation of cork in these circumstances in the long term. There have however been found cork sealed Champagne bottles dating back before 1830 (Tagliabue, 2010). This suggests under certain circumstances a long lifetime.

For extensive green roof systems the system Earth Kweek is providing seems to be the most environmentally friendly material to create extensive green roofs. There is however no data on how these roofs perform on a longer term as the first Cork green roofs were planted in 2016 and there are no reports of problems. The section that was planted in the summer of 2017 that is available on the plantation of Earth Kweek shows no signs of degradation according to Marijn van Rossum owner at Earth Kweek.

There is already a lot of research for improving substrate with the goal of increasing the growth of plants on buildings and increasing water retention. There is a lack of research into using more sustainable materials to create the drainage and green roofs. ZinCo promotes they have a Natureline green roof option yet this product is not currently available. Blue Roof is a potential improvement but there is no data available yet as this is currently being developed and tested.

The method used for calculating the environmental impact of the proposed green roof structure can be used for whole buildings. The method is limited to materials that are available in the ICE Database. The embodied CO_2 emissions data from the ICE Database is limited in available plastic types but most general building materials and methods are included.

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Appendix A

Table 1: Green Roof Types

	Soil Depth (mm)	Max Weight (kg/m²)	Maintenance	Water supply	Water storage capacity (L/m²)
Extensive green roof	80-120	50-150	1-2 per year	Self-sustaining	25 - 41
Extensive Hybrid roofs	110-150	155	1-2 per year	Self-sustaining	50 - 80
Intensive green roof	120	150	Regular	Need watering in summer months	60
Wild grass	150	240	Regular		40 - 70
Perennials and small shrubs	200	315	Regular	Irrigation	100
Bushes up to 3 m	300	465	Regular	Irrigation	140
Large bushes up to 6 m	400	615	Regular	Irrigation	180
Small trees up to 10m	650-1000	865	Regular	Irrigation	280 - 480

Sources:

1. ZinCo, (2019) Panning guide, *System Solutions for intensive green roofs,* ZinCo GmbH, retrieved from: https://zinco-greenroof.com/downloads
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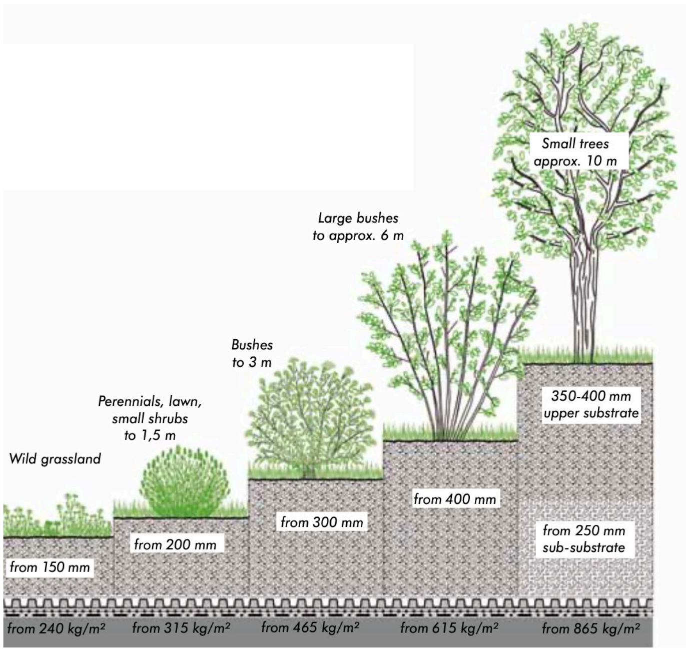


System build-up for different plant types (source: 1. ZinCo, 2019)

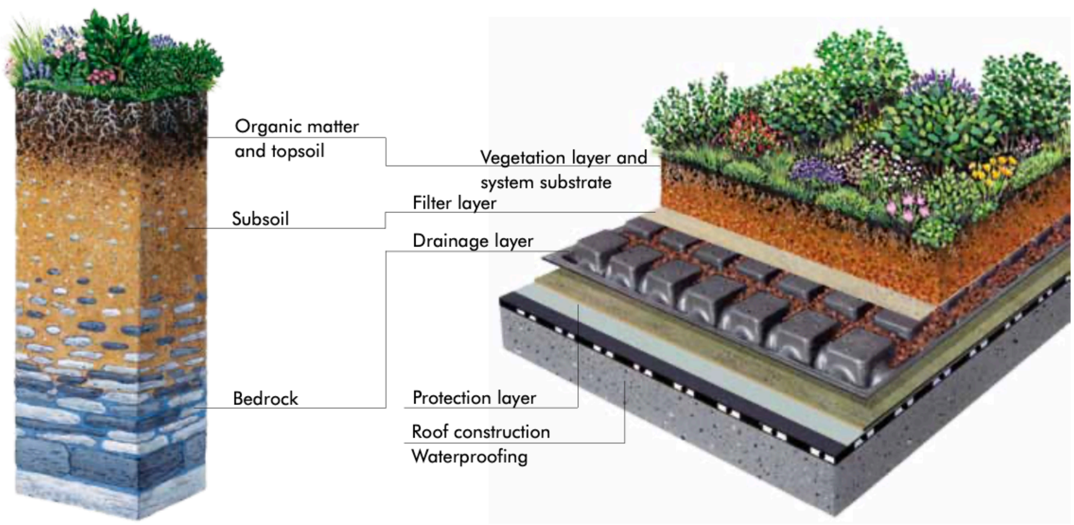
Appendix B

Table 1: Green Roof Layers

	Specifications
Building structure	- Additional load bearing capacity of 65 to 1000 kg/m²
Insulation layer	- Compressive strength of 265 to 1200 kg/m²
Waterproofing membrane	- Waterproof - Root resistant - Long lasting
Root Barrier if waterproofing is not root resistant	- Root resistant - Long lasting
Protection mat	- Protect water barrier against sharp edges - Load spreading
Drainage	- Permeable - Compressive strength of 65 to 1200kg/m²
Filter sheet	- Permeable for water - Hold substrate in place
Sub-Substrate layer	- Lightweight - water permeable - Contain minerals for plant feed
Substrate layer	- Lightweight - Water absorption - Plant feed

Sources:

1. ZinCo, (2019) Panning guide, *System Solutions for intensive green roofs,* ZinCo GmbH, retrieved from: https://zinco-greenroof.com/downloads



Earth soil layers compared to green roof layers (source: 1. ZinCo, 2019)

Appendix C

Table 1: Structural Layer Material Comparison

	Product Base	Density (kg/m³)	Embodied Carbon (kg CO_2 e/kg) 1.	Sequestered Carbon (kg CO_2 e/kg) 1.	Embodied carbon Kg CO_2	Sequestered Carbon Kg CO_2	Amount needed for 1 m² of floor area (kg)	Embodied CO_2 Including sequestered CO_2 (kg)	Sources
Concrete	Mineral based	2400	0,103		236,9	0	800	82,4	2,5
Steel	Mineral based	7850	1,27		9970	0	65	82,55	3,5
CLT	99% Bio based	471	0,437	-1,64	205,8	772,4	94	-113,1	4

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Table 2: Insulation Layer Material Comparison

	Product Base	Insulation Value W/m²K	Compressive strength (Kpa)	Sequestered Carbon Kg CO_2	Embodied Carbon (kg CO_2 e/kg) 1.	Embodied carbon Kg CO_2e/m2 (R=5.46)	Density (kg/m³)	Sources
PIR	Petrochemical	0,022	140	0	4,26	16,7	32,7	2
EPS	Petrochemical	0,034	250	0	4,39	16,3	20	3
Kingspan kooltherm	Petrochemical	0,018	120	0	n.a.		35	10
ISO Hemp blocks*	80% Bio based 20% Mineral	0,07	300	587	n.a.		360	7,8
Wood fibre insulation*	99% Bio based	0,04	200	253	0,98	-221,3	160	4
Cork*	Bio based	0,04	100	198	0,19	-195,5	120	5,6
Cork facade*	Bio based	0,043	220	198	0,19	-192,9	170	6
Calostat	Mineral based	0,019	90	Na	Na		165	11

* Embodied carbon footprint per m2 has been added to the calculation. The chosen material is Visqueen Ecomembrane 0,5mm at 50g/m2. It is made out of 100% recycled Polyethylene. The Embodied Carbon footprint is : 2,5 kg CO_2e/m².

Sources:

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Table 3: Roofing Membranes

	Product Base	Root Resistant	Recyclable	Cradle to Cradle Label	Life span	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m²)	Embodied carbon Kg CO_2e/m²	Sources
Bitumen	Petrochemical	No	Yes		12-20	0,326	4	1,304	2
EPDM	Petrochemical	Yes	Yes		40	3,76	2,1	7,896	3
Eco EPDM	70% bio based	Yes	Yes		40	Na	2,1	Na	3
Protan G membrane	PVC glass fibre	Yes	Yes		30	8,1	1,8	14,58	4
Protan GG membrane	Glass fibre plasticized pvc	Yes	Yes		25	8,1	2,15	17,415	5
Derbipure	100% bio based	Yes	100%	Bronze	30	n.a.	4,1	n.a.	6

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Table 4: Root Resistant Layer

	Product Base	Material	Recyclable	Thickness (mm)	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m²)	Embodied carbon Kg CO_2e/m²	Sources
WSB 100-PO	Petrochemical	Polyester		1,1	3,31	1,13	3,7403	
PermaSEAL	Petrochemical	Polypropylene		0,9	3,43	0,011	0,03773	3
FLW-400	Petrochemical	Polyethylene	100%	0,4	2,54	0,4	1,016	2

Sources:

1. Jones, C. (2019), ICE Database, retrieved from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html
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Table 5: Protection Layer

	Product Base	Material	Recycled content	Thickness (mm)	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m²)	Embodied carbon Kg CO_2e/m²	Permeability (mm/s)	Retention (l/m2)	Sources
VLU-300	Petrochemical	70% PES 30% PP		1,8	3,43*	0,3	1,029	95	1,56	2
VLU-500	Petrochemical	70% PES 30% PP		2,5	3,43*	0,5	1,715	48	2,09	2
VLS-300	Petrochemical	70% PES 30% PP		3	3,43*	0,3	1,029	90	2,7	2
VLS-500	Petrochemical	70% PES 30% PP		4	3,43*	0,5	1,715	50	3,6	2
VLS-800	Petrochemical	70% PES 30% PP		6,2	3,43*	0,8	2,744	Na	5,5	2
FSM 600	Petrochemical	Polyester Polypropylene mix	100%	4	4,5**	0,6	2,7	Na	3	3
FSM 1100	Petrochemical	Polyester Polypropylene mix	100%	8	4,5**	1,1	4,95	Na	6	3
Eco-Mat	Petrochemical	Recycled man made fibres	100%	6	Na	0,6	Na	Na	3,2	4

* as only carbon footprint data is available for PP Polypropylene this will be used to represent the whole product.

** embodied Carbon footprint polyester is 5.56 and of polypropylene 3,43 as the amount of the materials is unknown it is calculated as equal parts of both materials resulting in a embodied carbon footprint of 4,5 kg CO_2 e/kg

Sources:

1. Jones, C. (2019), ICE Database, retrieved from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html
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Table 6: Drainage Layer

	Product Base	Material	Life Span (years)	Thickness (mm)	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m²)	Embodied carbon Kg CO_2e/m²	Drainage (L/s)	Retention (l/m2)	Compressive strength kn/m2	Included filter (Y/N)	Sources
FloraDrain 25	Petrochemical	Polyolefin PE recycled		25	2,54	1,6	4,064	0,85	3	270	N	3
FloraDrain 40	Petrochemical	Polyolefin PE recycled		40	2,54	1,9	4,826	2,1	5	250	N	4
PermaSEAL 8	Petrochemical	HDPE	30	8	1,93	0,55	1,0615	2		250	Y	2
PermaSEAL 20P	Petrochemical	HDPE	30	20	1,93	1	1,93	7,1		150	Y	5
SDF Mat	Petrochemical	Nylon / PP fleece		20	12,7	0,6	7,62	Na	0	20	Y	6
DSE 20	Petrochemical	Recycled HDPE		20	1,93	1,2	2,316	Na	7,4	110	N	7
DSE 60	Petrochemical	Recycled HDPE		60	1,93	2	3,86	Na	10	1000	N	8
PLT 10	Petrochemical	Recycled HDPE		10	1,93	0,75	1,4475	Na	0	400	Y	9
Drainage board	Petrochemical	EPS 15% recycled		50	3,29	0,65	2,1385	Na	0	45	N	10
Reservoir board	Petrochemical	EPS 15% recycled		75	3,29	0,95	3,1255	Na	22,5	35	N	11
Cork	100% bio based	Expanded Cork		100	-1,57*	14	-21,98	0,85	3,3	220	Y	12 13
Drainage Natureline	Bio-Based	20-80% CO2 reduction									N	14

* Cork has a CO_2 sequestering rate of 1,76 kg CO_2 /kg. Cork has an embodied carbon footprint of 0,19 kg CO_2 e/kg. Together this is a embodied carbon footprint including sequestering of -1,57 kg CO_2 e/kg.

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Table 7: Filter layer

	Product Base	Material	Recycled content	Thickness (mm)	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m²)	Embodied carbon Kg CO_2e/m²	Permeability (mm/s)	Sources
Filter Fleece	Petrochemical	Polypropylene		1	3,43	0,125	0,42875		2
VLF-110	Petrochemical	Polypropylene		0,8	3,43	0,105	0,36015	140	3
VLF-150	Petrochemical	Polypropylene		1,2	3,43	0,150	0,5145	105	3
VLF-200	Petrochemical	Polypropylene		1,9	3,43	0,2	0,686	115	3

Sources:

1. Jones, C. (2019), ICE Database, retrieved from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html
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Table 8: Sub-Substrate Layer

	Product Base	Material	Recycled content	Thickness (mm)	Embodied Carbon (kg CO_2 e/kg) 1.	Weight (kg/m³)	Embodied carbon Kg CO_2e/m³	Water retention (l/m³)	Ph value	Sources
Mineral Drain	Mineral	Limestone	90%		0,032	1500	48	100	7-9	2
Crushed brick	Mineral	Brick	100%		0,006	1080	6,48	257	9,4	3
Crushed concrete	Mineral	Concrete	100%		0,006	1600	9,6			
BIO-CHAR	100% bio-based	BIO-CHAR	100%		-3,3	220	-726	690		4
MIX - Y	40% bio-based	40% Biochar 60& Crushed Brik	100%		-1,3164	736	-286,512	430,2		

* BioChar consists for up to 90% out of carbon (5.) 1 kg of carbon is equal to 3,67kg of CO2 in the air. This means 1 kg of BioChar produced from organic waste streams can sequester up to 3,3 kg CO2/kg. Bio char is a byproduct of syngas production and therefore the main embodied carbon footprint is held by syngas as the main product (6.). For this study only the sequestering will be taken into account.

Sources:

1. Jones, C. (2019), ICE Database, retrieved from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html
2. Bauder (2019) Product Data Sheet, *Bauder Mineral Drain,* Bauder Ltd., retrieved from: https://www.bauder.co.uk/getmedia/fd0f573e-5b42-4c84-bea8-b72d431bd90a/Bauder-Mineral-Drain-Product-Data-Sheet.pdf
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Table 9: Substrate Layer

	Product Base	% of total substrate	Recycled content	Dry weight kg/m³	Embodied Carbon (kg CO_2 e/kg) 1.	Saturated Weight (kg/m³)	Embodied carbon Kg CO_2e/m³	Water retention (l/m³)	Ph value	Sources
Perlite	Mineral	20	0%	148	0,52	576	76,96	428	8,3	4
Vermiculite	Mineral	30	0%	279	0,52	978	145,08	699	9,3	4
Crushed brick	Mineral	20	100%	823	0,006	1080	4,938	257	9,5	4
Sand	Mineral	10	0%	1608	0,009	2040	14,472	432	8,1	4
Coco peat	Bio	20	0%	115	-1	597	-115	482	7,1	4
Mix 12	Mineral bio	100	20%	431	0,0621	912	26,7651	481	7,9	4
Scoria		70					0			
BIO-CHAR	100% bio-based	30	100%	220	-3,3**	910	-726	690		5
Extensive	Recycled crushed brick, expanded clay, shale, composted pine bark	100	95%	900	0,101	1200	90,9	350	6-8,5	2
Biodiverse		100	95%	950	0,101	1200	95,95	350	6-8,5	2
Intensive		100	95%	1000	0,101	1200	101	350	6-8,5	2
Seed bed	Crushed brick aggregate and organic material	Top 25mm	90%	1250		1500	0	100	7-9	3
Swellgel	Polyacrylamide	1								
Compost	100% bio-based	15	100%	700	-1,5	1400	-1050	700	7	
Mix X	45% crushed brick 40% biochar 15% compost	100	100%	563	-1,54	1060	-868	497		

* Assuming all parts are divided: 30% Recycled brick (0,006), 30% Shale (0,002), 30% Expanded clay (0,329), 10% Composted pine bark (not available reduced to 0 because of carbon content) the total embodied carbon footprint would be : 0,101 kg CO_2 /kg

** BioChar consists for up to 90% out of carbon (5.) 1 kg of carbon is equal to 3,67kg of CO2 in the air. This means 1 kg of BioChar produced from organic waste streams can sequester up to 3,3 kg CO2/kg. Bio char is a byproduct of syngas production and therefore the main embodied carbon footprint is held by syngas as the main product (6.). For this study only the sequestering will be taken into account.

*** 45% crushed brick (0,006) 40% BioChar (-3,3) 15% compost (-1,5) equals to: -1,54 kg CO_2 /kg

Sources:

1. Jones, C. (2019), ICE Database, retrieved from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html
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Appendix D

Gathered research on Substrate composition by Thomas Young

Table 6.1: Summary of all the known studies that have looked at the effect of green roof substrate on plant growth and physiological health. Relevant work from this thesis has been included.

Study	Duration	Substrate Composition	Substrate Depth	Other Details	Plant/Substrate Response
Substrate Characteristics-Plant Growth					
(Rowe et al. 2006a) Module experiment	3 years	1. 50-100% heat expanded slate, 0-25% sand, 0-10% peat, 0-5% compost. 2. 60 % heated expanded slate. 0-150g m^{-2} slow release fertilizer.	100mm	Natural rainfall + additional irrigation.	1. Higher levels of slate= lower plant (2 *Sedum* spp. 6 non succulents) growth and visual rating. 2. Lower fertilization=lower growth but greater drought tolerance of non succulent plants.
(Emilsson 2008) Newly installed roof /plot sampling	3 years	1. Commercial substrate (contains soil, lava, organic matter) 2. 60% Crushed roof tiles, 37% sand, 3% organic matter 3. 53% Crushed roof tiles, 37% sand, 10% organic matter Slow release fertilizer 15g m^{-2} added.	40mm		Greater amounts of nutrients available in commercial substrate increased succulent spp. biomass and growth.
(Olszewski et al. 2010) Module experiment	9weeks	30% heated expanded fine slate, 50-70% heat expanded course slate, 0-20% compost. Hydrogel added at 0, 0.75, 1.5 & 3.75lb $yard^{-3}$ and slow release fertilizer at 6lb $yard^{-3}$.	'Shallow'	Watered every 10days	Hydrogel increased porosity and WHC. Higher hydrogel and compost increased shoot biomass and coverage of two *Sedum* spp.
(Olszewski and Young 2011) Plot experiment	12 weeks	Heat expanded clay at 10-60% fine grade, 10-60% medium grade, 10% course grade, 20% compost. Slow release fertilizer at 3.56kg m^{-3}	64mm	Natural rainfall + additional irrigation.	Fine grade particles= higher bulk density, WHC and lower porosity. *Sedum* spp.=greater growth & biomass at intermediate levels of particle sizes *Dianthus* spp. =greater growth & biomass at high fine particle levels.
(Nagase and Dunnett 2011) Module experiment	14weeks	Commercial mix (crushed brick base). Organic matter added at 0%, 10%, 25% & 50%.	80mm	Two watering regimes (every 5 or 15 days)	4 contrasting green roof plant species. Optimal level for growth was 10% 5day watering + high organic=excessive growth.
(Bates et al. 2013) Newly installed roof	4 years	97-100% broken brick, concrete & sand (at a variety of coarseness), 0-3% organic matter. Compost mulch added to some areas.	40-120mm		Plants growing in courser and less fertile substrates showed less growth but greater drought tolerance.
(MacIvor et al. 2013) Module experiment	2 years	Organic media= 25% organic matter FLL media= 70% mineral, 25% organic, 5% sand.	100-150mm	Some modules received additional watering	Grass/forb mix of 16 grasses/forbs. *Sedum* mats contained 28 *Sedum* spp. Plant cover & biomass lower for all species in FLL substrate. Irrigated modules had greater plant diversity.
(Zheng and Clarke 2013) Greenhouse experiment	6 weeks	80% Sphagnum peat, 20% perlite. 4.5-7.5 pH range 0.67g N L^{-1} slow release fertilizer.	Unknown		Species specific response of biomass production to pH levels by *Sedum* spp. Optimum levels varied between 5.91-6.43.
(Graceson et al. 2014a) Module experiment	2 years	Factorial design of 6 substrates composed of 70-80% mineral (crushed brick, tile or Lytag) and 20-30% green waste compost.	150mm		Increased WHC and compost amount increased shoot biomass.
(Razzaghmanesh et al. 2014b) Module experiment	12 months	A= crushed brick, scoria, coir & compost B= scoria, pine bark & Hydrocell® flakes	100mm & 300mm	Additional watering given.	Substrate type had little effect on growth and survival of 4 Australian species.
(Razzaghmanesh et al. 2014a) Module experiment	12 months	A= crushed brick, scoria, coir & compost B= scoria, pine bark & Hydrocell® flakes C= 50% of substrate B, 50% compost	100mm & 300mm	Additional watering given.	Poor plant growth in substrate A but good plant growth in substrates B & C.
(Young et al. 2014a) Young Thesis 2014, Chapter 2 Greenhouse experiment		80% mineral, 20% organic. Factorial design of a) brick size (small vs. large), b) organic matter (green waste vs. bark), c) hydrogel (presence vs. absence).	80 & 120mm	Watering regime given.	*Lolim perenne* used as phytometer species. Large brick=lower WHC& shoot but higher root growth Green waste=greater shoot growth, chlorophyll and N content but lower Root:Shoot ratio Hydrogel=greater WHC, shoot growth and N content
Substrate Components & Amendments- Drought Tolerance					
(Sutton 2008) Plot experiment	4 months	95% mineral, 5% compost. Factorial design of just substrate, AMF inoculum & Hydrogel addition (1.2g l^{-1})	90mm		6 grasses, 1 sedge, 5 forbs. Greater plant growth with hydrogel and AMF. AMF only increased plant growth when present with hydrogel.
(Nektarios et al. 2011) Plot experiment	6 months	1. Pumice 50%, perlite 20%, compost 20%, zeolite 10%. 2. Pumice 40%, perlite 20%, compost 20%, zeolite 50%, soil 15%. Slow release fertilizer 6g m^{-2}	75mm & 150mm	2 x watering regimes (high vs low).	*Dianthus fruticosus* planted. Presence of soil in substrate increased WHC and available water throughout trial. Greater growth and chlorophyll content in 150mm substrate.
(Farrell et al. 2012) Greenhouse experiment	113 days	80% mineral components (scoria, crushed roof tiles, bottom ash from power plants) & 20% coir. Slow release fertiliser added.	160mm	Drought treatment vs. Watered once a week	5 succulent species planted. Substrates with greater WHC showed greater plant survival to drought. Lower biomass production increased drought survival.
(Farrell et al. 2013) Greenhouse experiment	2 months	1. 80% scoria, 20% coir. 2. 80% crushed roof tiles, 20% coir Factorial design with a) hydrogel b) silicon based water retention additive. 53g L^{-1} slow release fertilizer.	120mm	45 days watering then drought	Both additives improved substrate WHC. Silicate additive increased drought tolerance of two plant species whilst hydrogel had no effect. Some effect of substrate type on effectiveness of additive.

(Savi et al. 2013) Module experiment	6 months	96.2% mineral, 3.8% organic matter. A=Substrate, B=A + drainage layer, C=B+ water retention mat, D=C+ number of drainage holes doubled	140mm	Additional watering given.	Water retention mat improved growth, water status and drought survival of *Salvia officinalis*. Increasing number of drainage holes improved water movement back into substrate.
(Savi and Marin 2014) Module experiment	6 months	97.1% mineral, 2.9% organic matter. Hydrogel (0, 0.3 & 0.6%)	80-120mm	Additional watering given.	Hydrogel increased WHC, available water and water status of *Salvia officinalis*. Greater impact of hydrogel at 80mm.
(Young et al. 2014b) Young Thesis 2014, Chapter 3 Greenhouse experiment	4 months	80% crushed brick (small or large particles), 20% green waste compost. 2 x hydrogel treatments (0 vs. 1%). 2 x *Sedum* treatments (no coverage vs. substrate coverage)	120mm	Control, 10, 15, 25 day droughts. Plant grown for 3.5months before drought.	*Linaria vulgaris* & *Festuca ovina* planted. Hydrogel and large brick increased drought tolerance of both species. hydrogel increased available water without affecting plant growth whilst large brick reduced growth befor e drought.
(Young et al. 2014c) Thesis 2014, Chapter 4 Module experiment	14 months	80% crushed brick (small particle size), 20% green waste compost AMF inoculum treatments a) none, b) with plugs, c) in substrate, d) in plugs & substrate	100mm	Some additional watering given.	All AMF treatments infected *Prunella vulgaris* and increased shoot phosphorus concentrations. Plug only treatment increased flowering length at end of first growing season. No significant effect of AMF on plant growth or biomass.
Substrate Depth					
(Boivin et al. 2001) Module experiment	3 years	60% mineral components, 40% organic matter	50, 100 & 150mm		6 herbaceous perennials. Greater plant damage at 50mm from low temperatures.
(VanWoert et al. 2005b) Module experiment	88 days	40% expanded slate, 40% sand, 10 % peat, 5% dolomite, 3.33% composted yard waste, 1.67% composted poultry litter.	20 & 60mm	Watering regime every 2,7,14,28 & 88 days.	Larger amounts of biomass (*Sedum* spp.) and also transpiration at 60mm. Optimal watering regime at 20mm was every 14 days and at 60mm was every 28 days.
(Getter and Rowe 2008; Getter and Rowe 2009) Module experiment	20 weeks-4 years	86% sand, 10% silt, 4% clay. 100g m^{-2} slow release fertilizer.	40-100mm	Water retention layer used	Greater growth and coverage of *Sedum* spp. at 70 & 100mm.
(Dunnett et al. 2008b) Plot experiment	6 years	50% expanded clay, 15% medium load, 35% green waste compost. 75g m^{-2} slow release fertilizer.	100 & 200mm	Some additional watering given.	15 species initially planted. Greater survival, diversity, size and flowering performance observed at 200m. Greater amounts of bare ground/moss and colonising species at 100mm.
(Thuring et al. 2010) Module experiment	11 weeks	1. 85% expanded shale, 15% organic matter 2. 85% expanded clay, 15% organic matter	30, 60, 120mm	None, early & late drought	3 succulents & 2 herbaceous perennials. Better plant growth and survival in deeper substrates.
(Olly et al. 2011) Module experiment	20 weeks	66% expanded clay, 33% sand. 1cm topsoil (10% organic, 90% mineral).	100-150mm some with access to bare ground		Herbaceous seed mix used. Greater growth, flowering, ground cover and species richness at 150mm, especially in substrates with access to ground
(Rowe et al. 2012) Module experiment	7 years	40% expanded clay, 40% sand, 5% dolomite, 3.33% composted yard waste, 1.67% composted poultry litter.	25, 50 & 75mm		25 succulent species initially planted. Number of species present declined at all depths over time. Rate of decline was faster in shallower substrates. However stable communities still existed at 25mm depth after 7 years.
(Heim and Lundholm 2014b) Module experiment	1.5 years	Commercial mix. 7% organic matter.	50, 100, 150mm.50/150mm mixed depth.		*Sedum acre* and *Festuca rubra*. Mixed depth showed greater overall coverage and less competition.
Novel Substrate Materials					
(Molineux et al. 2009) Greenhouse experiment	2 months	75-85% mineral (crushed brick, clay pellets, paper ash pellets, carbonated quarry waste pellets). 15-25% top dressing compost	80mm	Watering regime given.	Compost amounts had different effects on *Plantago lanceolata* growth depending on mineral type. All mineral types suitable for use in green roof substrate.
(Mickovski et al. 2013) Module experiment	5 weeks	65% loam, 20% demolition waste, 15% compost	75mm	Watering regime given.	Grass mix and *Sedum* spp, planted. Demolition waste can be used as part in green roof substrate.
(Cao et al. 2014) Greenhouse experiment	2 months	1. 80% scoria, 20% coir. 2. 100% scoria. Biochar added at 0, 10, 20, 30, 40% v/v.	100mm	Watered for 50 days then drought	Biochar increased WHC, plant available water and time until permanent wilting. No effect on biomass.

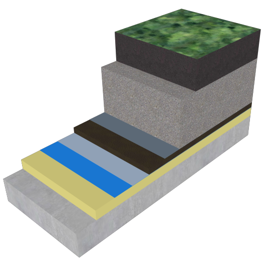
Young, T. (2014) The Influence of Green Roof Substrate Composition on Plant Growth and Physiological Health, Sheffield University, Department of Animal and Plant Science,

Appendix E

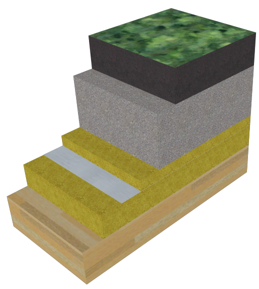
Table 1: Build-up comparison

	Thickness (mm)	Build-up Existing	Weight (kg/m²)	Embodied carbon Kg CO_2e/m^2	Thickness (mm)	Build-up Proposed	Weight (kg/m²)	Embodied carbon Kg CO_2e/m^2
Structural	250	Concrete	800,00	82,4	320	CLT	94	-113
Insulation	120	PIR insulation	3,92	16,7	218	Wood fibre insulation	35	-221
Waterproofing	2	EPDM	2,10	7,9	2	Derbipure	4	1
Root barrier								
Protection layer	2	VLU-500	0,80	2,7				
Drainage layer	60	Floradrain-60	1,90	4,8	100	Cork	14	-22
Filter layer	1	VLF-150	0,15	0,5				
Sub-Substrate	500	Crushed limestone	750,00	24	500	Mix - Y	368	-143
Substrate	300	Mix 12	129,30	8,02953	300	Mix - X	169	-260
Plants	6000	Trees and bushes	Increase over time	Decrease over time	6000	Trees and bushes	Increase over time	Decrease over time
TotaL*:	1235		1688,17	147	1440		684	-759
Total**:	863		882,15	40,0	900		551	-426

* The total does not include the plant layer due to lack of data.
** The total of green roof structure without the structural insulation and waterproofing membrane.



- 300mm Mix -12
- 500mm Crushed limestone
- 1mm VLF-150
- 60mm Floradrain
- 2mm VLU-500
- 2mm EPDM
- 218mm PIR Insulation
- 250 mm Concrete

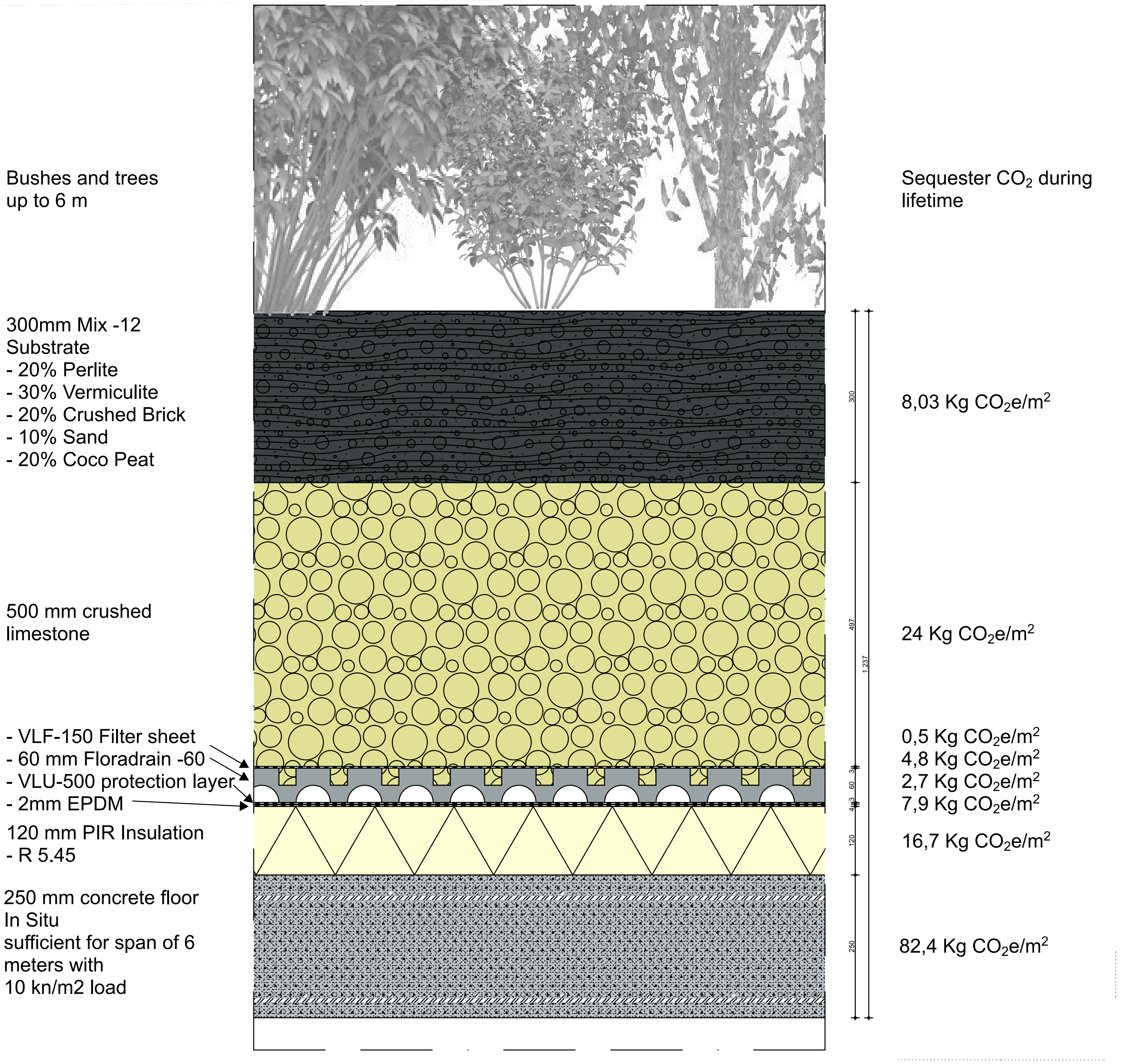


- 300mm Mix -X
- 500mm Mix-Y
- 100mm Cork
- 2mm Derbipure
- 218mm wood fibre insulation
- 320mm CLT

Build-up existing

Build-up Proposed

Standard Green Roof build-up



Proposed intensive green roof build-up

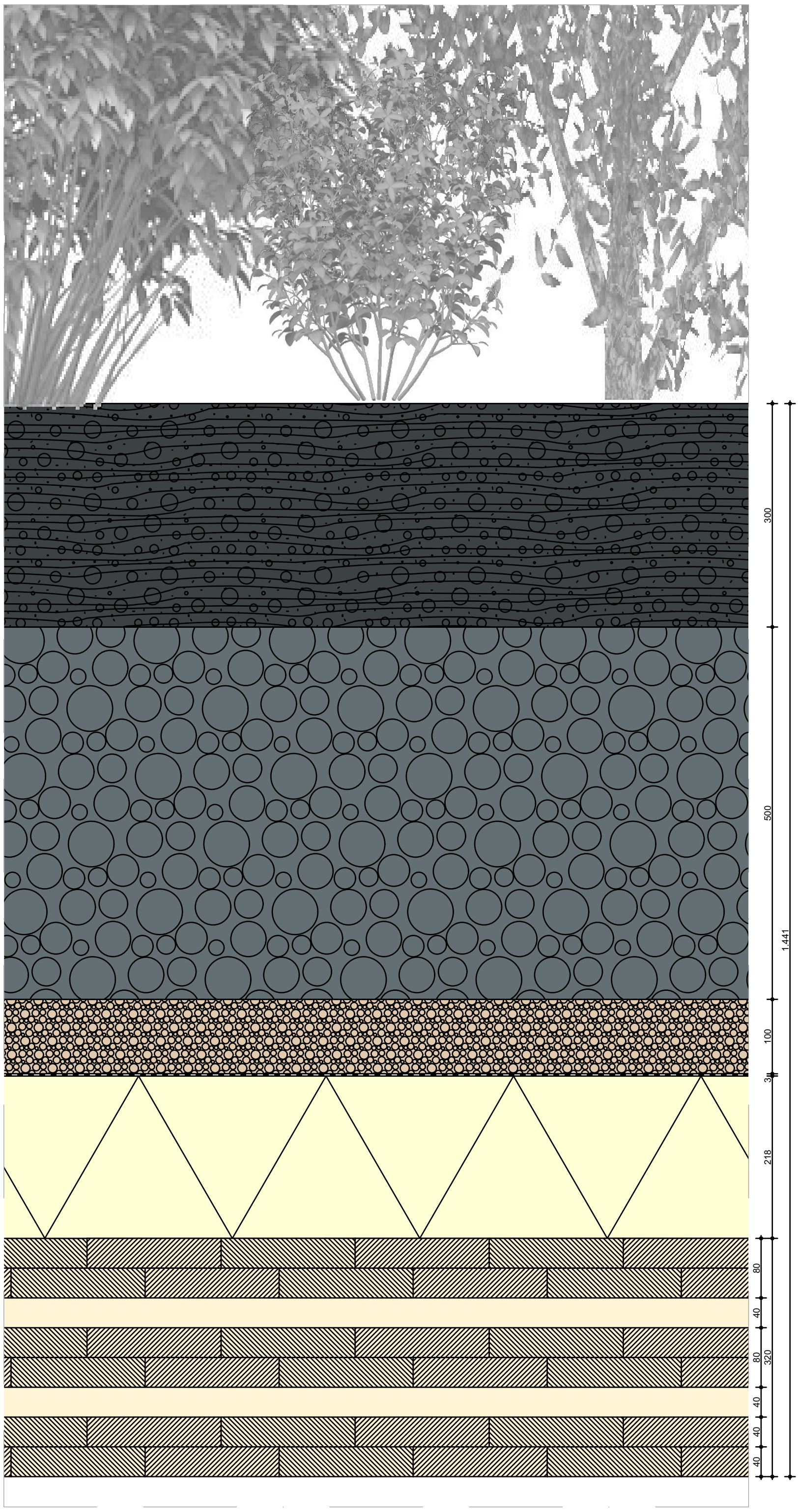


Table 2: Build-up comparison results

	Standard Build-up	**Proposed build-up**	**Difference**
Including structure:			
Weight in kg/m^2	1688	684	-1004
Thickness in mm	1235	1440	205
Embodied carbon footprint In: Kg CO_2e/m^2	1688	-759	-2447
Excluding structure:			
Weight in kg/m^2	882	551	-331
Thickness in mm	863	900	37
Embodied carbon footprint in: Kg CO_2e/m^2	40	-426	-466