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The SWITCH brown roof project, Birmingham UK: rationale and experimental design

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Abstract

Our research investigates a specific type of extensive green roof termed a brown roof, which is designed for the conservation of urban biodiversity from brownfield habitats. Such roofs can play an important role within sustainable urban water management by: (1) reducing storm water runoff intensity by delaying, retaining and removing precipitation, reducing flooding and pressure on drainage infrastructure; (2) improving ecological conditions in streams by reducing hydrological disturbance and the associated influx and re-suspension of pollutants, and removing pollutants from precipitation in the brown roof substrate; and (3) providing water for non-potable uses such as toilet flushing. Nevertheless, green roofs are not a panacea, and the optimisation of one beneficial characteristic may impair another. Our research explores the factors influencing the ecological diversity and function of brown roofs, whilst assessing the water quality and hydrology of the roof through-flow for potential attainment of the SWITCH project objectives. The main area of research involves the creation of a brown roof research facility at The University of Birmingham with 'soils' composed of different recycled aggregates, to test the effects on the development of ecological assemblages, water quality and hydrology. The ecological diversity and functionality of several indicator groups will be studied (e.g. birds, beetles and plants). The hydrology and water quality (e.g. nitrate, heavy metals and *E. coli*) of mesocosm through-flow will be compared with precipitation amount and water quality. A second research thread will investigate the differences between the coloniser pool of roof and ground sites to assess how closely they can replicate ground-based habitats through natural colonisation and assess the relative isolation of roof-top communities. Seed, pan and window traps will capture airborne seeds and invertebrates from several roof and ground sites around the campus and the seed viability will be assessed.

Keywords: brownfield, green roof, green water, novel habitat, sustainable development, urban ecology, urban stormwater management, vegetated roof.

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1 Introduction

A green roof is a broad term for a roof of a building that is covered in a growing medium and has plants growing on it. There are two main types: (1) intensive green roofs, which are heavily landscaped 'gardens' that usually require additional structural support, heavy management and considerable expenditure, and (2) extensive green roofs, which have a shallow substrate layer, can be installed on most low-angle roofs, require minimal management, and are relatively inexpensive; as such their widespread use is more feasible and they are therefore the focus of this research. The design of extensive green roofs is widely variable and is dependent on, for example, the design aims, the spatial location of the roof, and the construction materials used.

Extensive green roof installation increases the construction cost of new buildings and is a significant monetary investment when retro-fitted, however their life cycle costs can be lower than conventional roofs (Wong et al., 2003) and the life cycle environmental benefits are significant (Kosareo and Ries, in press; Saiz et al., 2006). Advantages include: (1) reductions in the need for air conditioning and heating through their effect on building thermal performance (Barrio, 1998; Kumar and Kaushik, 2005; Lazzarin et al., 2005; Niachou et al., 2001); (2) an improvement in air quality through the binding of dust, filtering of air pollution by plants, increased levels of oxygen and humidity, and reduced ozone concentrations due to city temperature reductions (Ngan, 2004; Orwell et al., 2004; Rosenfeld et al., 1998; Wolverton and Wolverton, 1993); (3) a reduction in the urban heat island effect through increased humidity and alteration of the specific heat capacity of roof surfaces (Bass and Krayenhoff, 2002; Onmura et al., 2001); (4) protection of roof waterproof membranes by (a) moderating temperature and thus reducing expansion and shrinkage damage, (b) providing protection from mechanical damage caused by human traffic and hail, and (c) providing protection from ultra-violet radiation (Ngan, 2004; Wong et al., 2003); (5) aesthetic and amenity value, which can potentially enhance emotional wellbeing (Relf and Lohr, 2003; Ulrich, 1984) and raise property value (Ngan, 2004).

Extensive green roofs can also potentially be used to address several of the SWITCH project objectives. Firstly, extensive green roofs can reduce storm water runoff intensity by delaying, retaining and returning water to the atmosphere via evapotranspiration (Bengtsson, 2005; Bengtsson et al., 2005; Mentens et al., 2006; VanWoert et al., 2005). They can therefore reduce pressure on the urban drainage infrastructure and reduce the incidence of flooding and fluvial erosion, thereby having considerable potential for utilization within Sustainable (Urban) Drainage System's (SUDS) or stormwater Best Management Practices (BMPs) (Carter and Jackson, in press). Secondly, extensive green roofs can potentially improve ecological conditions in urban streams by reducing the influx (e.g. from overland flow and combined sewer overflows) and re-suspension of pollutants during heavy rainfall and high flow events, reducing the level of hydrological disturbance (Carter and Jackson, in press), and by storing or removing pollutants from precipitation as the water travels through the sediment (Köhler et al., 2002). The latter can be due to high pH removing metals from solution, or the uptake of nutrients by plants (Aziz and Smith, 1992; Johnson et al., 1995; Steusloff, 1998). Thirdly, green roof water through-flow could potentially be harvested as green water for non-potable uses such as toilet flushing, cleaning, and garden watering (Saiz et al., 2006).

Extensive green roofs have been specifically designed for the enhancement of urban biodiversity or the conservation of a certain species with some success (Brenneisen, 2003; Gedge, 2003), and they can also potentially play an important role within integrated habitat networks (Kim, 2003). However it is important that extensive green roof habitats replicate the target habitat as closely as possible for them to successfully fulfil these roles (Angold et al., 2006). Roof microclimate does differ from that on the ground, with roofs typically having higher wind speeds, lower maximum air temperatures, and higher minimum air temperatures, which can potentially strongly influence community composition; and the rate of moisture loss, through evapotranspiration and drainage, can be very high from green roofs. Perhaps more importantly however, the height of roofs may act as a substantial barrier to the colonisation and transfer of individuals and propagules between nearby habitat patches, which may prevent the development of a viable community connected by dispersal to other habitat patches and thereby preclude their application within integrated habitat networks (Grant et al., 2003).

Despite the wide range of potential advantages related to green roofs they are not a panacea and designing them to maximise one function is likely to compromise others to some degree. For example, the largest green roof reductions in storm water run-off are achieved with a high vegetation cover (Emilsson and Rolf, 2005; Mentens et al., 2006), and this typically requires the use of specialist xerophilic plants such as species of *Sedum*, and a fertile soil. High soil fertility can lead to nitrate leaching, which can compromise through-flow water quality (Berndtsson et al., 2006; Ngan, 2004), whilst continuous coverage of *Sedum* compromises roof biodiversity (Kadas, 2002). Investigating the factors controlling the balance between the multi-functionality of extensive green roofs is of considerable importance.

This main aim of the project is to investigate the ecology of extensive green roofs designed for biodiversity; specifically, the influence of growing substrate type and ability of plant and invertebrate species to colonise roof-top habitats. However, it will also concurrently investigate the hydrology and water quality of water flowing through these ‘biodiversity’ roofs in order to explore the potential tradeoffs and interactions between the aims of the SWITCH project and the aim of enhancing urban biodiversity.

2 Rationale

2.1 Choice of extensive green roof type

The decline of industry over the last fifty years in Birmingham has created large amounts of brownfield habitat (old demolition sites, typically with a mainly broken brick and concrete substrate) that have become home to diverse ecological communities at a variety of stages of succession (Angold et al., 2006; Small et al., 2003). Brownfield habitats typically provide important centres of biodiversity not only locally within an urban area but also across regional and sometimes national scales, and they are increasingly perceived as a very important conservation resource (Angold et al., 2006; Donovan et al., 2005; Gibson, 1998; Small et al., 2006; Small *et al.*, 2003; Spalding and Haes, 1995). However current development policies consider the redevelopment of brownfield sites of key importance and brownfield sites are disappearing both across Birmingham and the UK due to funding initiatives and tax breaks (Pediaditi et al., 2005; Thornton and Nathanail, 2005) associated with brownfield redevelopment. Sustainable development should aim to mitigate for habitat loss with the creation of habitat as close as possible to that habitat (Donovan et al., 2005), and in the case of urban development, this usually means the recreation of brownfield habitat. For these reasons, examining ways to recreate brownfield type habitat with so called ‘brown roofs’ is the subject of our research.

Ecological surveys of brownfield sites (Donovan et al., 2005; Gibson, 1998; Small et al., 2003), experience from habitat creation and restoration (Gilbert and Anderson, 1998), and exploratory green roof research in several countries (Brenneisen, 2003; Gedge, 2003; Ngan, 2004), have produced useful design critera for recreating brownfield habitat and maximising biodiversity using extensive green roofs. These include the: (a) use of low nutrient growing substrates, to prevent dominance by a few highly competitive species and (b) maximisation of the range of microhabitats, from open bare ground to areas heavily vegetated with ruderal species by varying substrate type and depth. These criteria were used to guide the design of our roof laboratory brown roof mesocosms (see below).

2.2 Choice of study species

A number of target study groups were selected for the assessment of the changing biodiversity and community composition; chosen for their community function, ease of sampling and identification, and their microhabitat dependencies. They thus represent species with wide-ranging dispersal abilities, which rely on many different structural elements of a habitat, which occupy several different roles and levels in the food web. They should therefore provide a good representation of the biodiversity and ecological community composition of the mesocosms and the range of dispersal abilities for the assessment of roof-top colonisation ability. The target study groups are: (1) beetles (Coleoptera), (2) spiders (Araneae), (3) certain groups of aculeate Hymenoptera (the stinging, rather than parasitic Hymenoptera): namely the wasps and bees (4) butterflies (Lepidoptera excluding moths), (5) birds (Aves), and (6) flowering plants, excluding the graminoids (grasses).

3 Experimental design – brown roof laboratory study

A brown roof laboratory is being set up on the roof of the 5 floor Watson building at The University of Birmingham's main Edgbaston campus, composed of 35 brown roof mesocosms comprising seven different growing substrate treatments with five replicates of each. The mesocosms will each be separated by a gap (~50cm) and arranged in a latin square type layout in order to minimise the unwanted effects of small-scale environmental variation. The overall design of all mesocosms will be the same apart from variations in the substrate composition.

Mesocosms will consist of a plywood deck (2.44 x 1.22m) with timber curbs at all sides and a 50mm drainage outlet. A sheet of polyester reinforced PVC will be used as a waterproof and root resistant layer, above which will sit a composite drainage-reservoir board and fleece layer (Figure 1). The drainage-reservoir board will allow free drainage of the substrate and will provide a temporary store of water. The fleece layer will limit the amount of fine sediment that washes through the mesocosms. Each mesocosm will be seeded at a density of 1.6g m^2 with a mix of wild flower species comprising 24 species present on local brownfield sites together with species known to thrive on brown roofs.

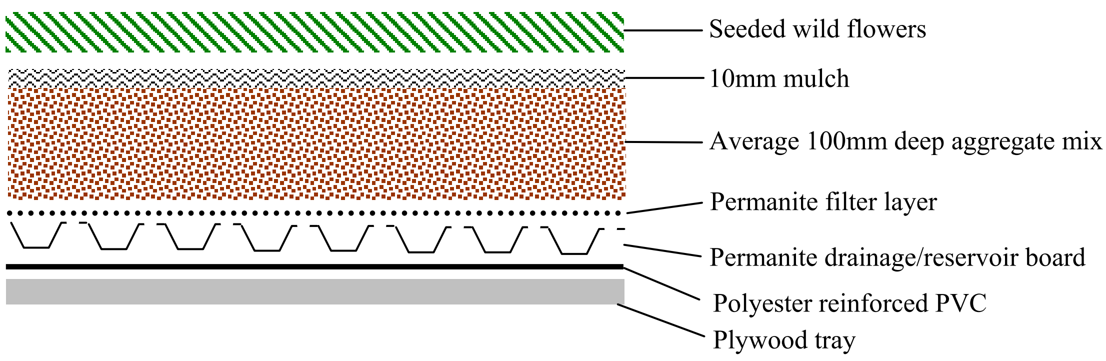

Figure 1. Brown roof tray design used in this investigation

Bengtsson (2005) has shown that altering the size of experimental green roof plots does not alter the hydrological response of the plots as the response is controlled by vertical, rather than horizontal flow characteristics. Brown roof biodiversity experiments in London (Kadas pers comm.) have sampled large numbers of invertebrates from small experimental plots. Therefore the relatively small size of the experimental mesocosms is sufficient for the purposes of the investigation.

The substrate layer will be composed of on average 10cm of inorganic substrate, with a 1cm mulch of either sterilised loam or IKO^{TM} extensive soil mix in all treatments. Each mesocosm will include one 20cm mound of inorganic substrate at the up-slope end as a biodiversity enhancement measure. The six treatments will be: (1) 40mm down (to sand) crushed demolition aggregate (mainly concrete and brick, but also ceramics, sand, etc.) with a sterilised loam mulch, (2) 40mm down (to sand) crushed demolition aggregate with an IKO extensive soil mix mulch (3) 40mm down solid municipal waste incinerator bottom ash (glass, ceramics, concrete, fused material, etc) with a sterilised loam mulch, (4) 1:1 40mm down (to sand) crushed demolition aggregate : 40mm down solid municipal waste incinerator bottom ash mix with a sterilised loam mulch, (5) 75mm down crushed brick aggregate with a sterilised loam mulch, (6) 1:1 75mm down crushed brick aggregate : 40mm down (to sand) crushed demolition aggregate mix with a sterilised loam mulch, and (7) crushed demolition sand with a sterilised loam mulch. The substrate production processes do not necessarily preclude the colonisation by plant or invertebrate propagules, but few seeds are typically contained in such aggregates (Hitchmough et al., 2001), and substrates will be used soon after their production to minimise the chance of propagule contamination.

3.1 Ecological monitoring

Sampling methods

Sampling will take place approximately every two weeks between April and September, and less frequently during the winter. The sequence of sampling will be rotated in order to avoid bias due to the diurnal rhythms of the various study groups. Ecological sampling will comprise four elements: (1) vegetation surveys, (2) non-fatal pitfall trapping, (3) bird surveys, and (4) 'general' entomological surveys. Digital photographs of the mesocosms will also be taken as a visual record of their development. Where possible invertebrate species will be identified in the field and released in order to limit potential disturbance.

Vegetation surveys will comprise both floristic and structural components. The cover abundance of flora will be estimated on the semi-quantitative Domin-Krajina scale. Vegetation structural surveys will comprise three main elements: (a) analysis of stratification, (b) analysis of the cover-abundance of different structural elements (e.g. bare ground, plants in seed, etc), and (c) analysis of the richness of nectar, pollen and seed resources. Non-fatal pitfall trapping will be used to sample ground-active beetles and spiders. Two modified pitfall traps (Bates et al., 2005), which help prevent within-trap predation and within trap stress will be set for 24-hours. The number of bird visits will be surveyed over three one-hour periods in the early-morning, around noon, and in the late afternoon, with notes taken on the mesocosms visited and the behaviour of each bird (e.g. foraging for food, perching, singing). General invertebrate surveys are mainly aimed at bees, wasps and orb weaving spiders and will involve general observations, combined with limited sweep netting.

3.2 Hydrological and meteorological monitoring

To adequately quantify and understand the hydrological process within the mesocosms it is necessary to measure the inputs and outputs from the system over time. The local weather conditions determine the amount of water entering the system as well as influencing evaporative losses, soil moisture content and temperature. A weather station will be installed on the roof to monitor air temperature, rainfall, wind speed, wind direction, relative humidity, and direct and indirect solar radiation. The through-flow from mesocosms with the same substrate treatment will be combined and channeled through a ‘V-notch’ weir. The depth of the water behind the weir will be measured using an ultrasonic transducer, the output from which will be used to calculate the water flow. The apparatus will be semi-mobile insofar as it will be possible to move the monitoring hardware between trays containing different substrates until an adequate dataset has been gathered. Soil moisture and temperature probes will also be installed at various depths within the substrate. By comparing inflows and outflows, the hydrological properties of the substrates and the influences upon flow and water balances will be investigated. Both the transducers of the weather station and the roof trays will be continuously monitored and recorded by datalogger.

3.3 Water quality monitoring

A variety of measurements will be made that can be used to assess water quality and interpret the processes that are influencing it. Integrated through-flow water quality will be compared with the water quality of three rainfall samples collected during the same storm event. The number of rainfall events studied will depend upon the frequency of events and the consistency of results.

The collection, preparation and storage of the water samples will follow the recommendations of (Eaton et al., 2005) wherever possible. The pH, conductivity, nitrate, ammonium, sulphate, phosphate and chloride will be measured with a photometer, and total alkalinity will be measured using sulphuric acid titration with indicator solutions. The volume of samples will be measured and the samples filtered on pre-weighed 0.45µm cellulose nitrate filters (acid-washed for metal analysis) as soon as possible to remove any suspended sediments and to allow later determination of the concentration of suspended sediments. The enzyme substrate Colitag™ test will be used to test for the presence or absence of coliform bacteria and, more specifically, *Escherichia coli*, in 100ml samples of through-flow.

Sub-samples will be collected in acid-washed polypropylene or linear polythene sample bottles and acidified to keep metals in solution. They will be analysed using an inductively coupled plasma mass spectrometer (ICPMS) for a range of metals. Initial semi-quantitative analyses on water samples will be run to identify elements in high relative concentration and these elements will be focused on in later element-specific analyses (e.g. aluminium, arsenic, and iron).

3.4 Growing substrate monitoring

The changing conditions within the soil are of fundamental importance for the development of plants, the water quality of through-flow, the water storage capacity, and to a lesser extent, the development of invertebrate assemblages. (Bengtsson, 2005) and (Bengtsson et al., 2005) showed that runoff is not generated until the roof substrate has reached field capacity and that the amount of runoff storage corresponds with the conditions at the permanent wilting point.

Soil samples will be taken from mesocosms every five and three months for measurement of physical and chemical characteristics respectively, and following analysis, returned to the area sampled. The pH will be measured in three sub-samples of 5ml of soil in a calcium chloride solution and electrical conductivity will be measured from three 20g sub-samples of soil suspended in 100ml of water. The sediment size distribution will be determined once after the bedding-in period from three sub-samples by wet sieving for coarse sediments (>2mm) and laser particle sizing for fine sediments (<2mm). The overall density and dry bulk density of soil particles will be determined from three sub-samples by measuring the volume of a known mass and the excavation method respectively, to allow the calculation of soil porosity. The air filled and water filled porosity at the approximate field capacity and permanent wilting point will be measured in three sub-samples of about 10g of soil by measuring the change in mass after heating at 105^{o}C using information on soil porosity. The loss on ignition, which is an approximate measure of organic matter content, will be determined in three oven-dried (105^{o}C) sub-samples of about 10g of soil by measuring the change in mass after heating at 550^{o}C.

4 Experimental design – variation in colonizer ability study

Six ground sites and nine roof sites (1-6 stories) are being sampled around The University of Birmingham's Edgbaston campus. Ground sites vary from brownfield sites with bare ground and ruderal vegetation where there are distinct swards of vegetation to 'rain' into seed traps, to mown grass, where seeds will have to disperse in from elsewhere. Roofs vary widely in both their height and character (e.g. type of parapet, area). All sites are spread over a wide area and vary in their proximity to potential source habitats. At each site 12 seed traps, 3 window traps and 3 pan traps have been installed and are sampled fortnightly for invertebrates and monthly for seeds during the summer months, with sampling suspended once catches become negligible in the winter. Data will be analysed using multivariate ordinations with individual trap returns as samples, and by individual months in order to investigate the seasonal variation in coloniser availability. A range of semi-quantitative and quantitative environmental variables will be measured for each trap on a monthly basis. The distance from the nearest sites that are vegetated or contain ruderal species, and the area of this habitat within 50, 100, 200 and 500m will be measured in ArcView from the university's phase 1 habitat survey. The cover-abundance of forbs, plants in seed, and plants in flower within 1m of the trap will be estimated on the Domin-Krajina scale.

4.1 Invertebrate study

The pool of potential invertebrate colonisers at each site are being investigated using pan and window traps. Pan traps have an area coloured red, yellow, white and blue on the inside and dark green on the outside in order to attract as full a possible range of species to the inside colours, but not draw them in from distance (Laubertie et al., 2006; Leong and Thorp, 1999). Window traps consist of two perpendicular sheets of clear plastic embedded into concrete (for weight) in plastic trays (painted dark green on all surfaces to prevent 'attraction'). Pan and window traps have 3cm deep saturated NaCl solution and a dash of unscented detergent in them to preserve captured arthropods and break up surface tension respectively. The species detected in window and pan traps on roofs will be compared with the species sampled from the brown roof mesocosms in order to assess the difference between those species able to disperse to brown roofs and those species able to colonise brown roofs.

4.2 Seed study

The seed traps used have been designed to intercept and capture wind-blown seeds and still effectively sample gravity seed rain. Seeds will be identified and grown on where necessary to do this, and classified as filled, partially filled, or empty, and classified as plumed, plane winged, rotating winged, or fruited, and a weight range of each seed determined. Seeds will be considered viable when they completely fill their seed cases.

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