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Initial insights on the biodiversity potential of biosolar roofs: A London Olympic Park green roof case study

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Abstract

Cities dominated by impervious artificial surfaces can experience myriad negative environmental impacts. Restoration of green infrastructure has been identified as a mechanism for increasing urban resilience, enabling cities to transition towards sustainable futures in the face of climate-driven change. Building rooftops represent a viable space for integrating new green infrastructure into high density urban areas. Urban rooftops also provide prime locations for photovoltaic (PV) systems. There is increasing recognition that these two technologies can be combined to deliver reciprocal benefits in terms of energy efficiency and biodiversity targets. Scarcity of scientific evaluation of the interaction between PVs and green roofs means that the potential benefits are currently poorly understood.

This study documents evidence from a biodiversity monitoring study of a substantial biosolar roof installed in the Queen Elizabeth Olympic Park. Vegetation and invertebrate communities were sampled and habitat structure measured in relation to habitat niches on the roof, including PV panels. Ninety-two plant species were recorded on the roof and variation in vegetation structure associated with proximity to PV panels was identified. Almost 50% of target invertebrate species collected were designated of conservation importance. Arthropod distribution varied in relation to habitat niches on the roof. The overall aim of the MPC green roof design was to create a mosaic of habitats to enhance biodiversity, and the results of the study suggest that PV panels can contribute to niche diversity on a green roof. Further detailed study is required to fully characterise the effects of PV panel density on biodiversity.

Keywords: Green roof, biodiversity, photovoltaic panel, niche, urban ecology, resilience

Introduction

More than half the world's population now reside in urban areas and cities are expected to absorb much of the population growth expected in the future (United Nations 2011). High density urban development is considered an efficient strategy for accommodating increasing urban populations (UN-Habitat 2014), but cities dominated by impervious artificial surfaces can experience myriad negative environmental impacts, including elevated temperatures (urban heat island effect), increased pluvial flood events and pollution, virtual desert conditions for wildlife squeezed between urban expansion and agricultural intensification, and declines in the health and well-being of communities deprived of contact with nature (White 2002; English Nature 2003; Grimm et al. 2008; Fuller & Irvine 2010; Pickett et al. 2011; Cook-Patton & Bauerle 2012).

Reconciling the need for further development to accommodate urban expansion with economic, sustainability and nature conservation policy targets is a major 21st Century challenge (OECD 2012). The Millennium Ecosystem Assessment underlined our dependence on the natural environment for goods and services (ecosystem services) and highlighted the costs of anthropogenic ecosystem degradation (MEA 2005). Research has shown that biodiversity has a positive effect on ecosystem stability and resilience (Balvanera et al. 2006). The need to change patterns of urban development in order to minimise environmental degradation is driving a 'green cities' strategy – an holistic model of sustainable urban growth that seeks to overcome the environmental, social and energy issues related to urban densification (UNEP 2011). Multifunctional green infrastructure is a key tool for alleviating problems associated with urbanisation and can make a positive contribution towards ecosystem services, climate change mitigation and urban resilience (Tzoulas et al. 2007; Ahern 2011; Defra 2011; UK National Ecosystem Assessment 2011; HM Government 2012; Town and Country Planning Association and The Wildlife Trusts (TCPA) 2012; Collier et al. 2013; European Commission 2013).

In high density urban situations where space is at a premium, building rooftops represent a viable space for integrating new green infrastructure. Green (vegetated) roofs are now promoted as valuable components of urban green infrastructure, supporting the restoration of a broad range of ecosystem services to urban areas including stormwater amelioration, pollution uptake, urban heat island mitigation and energy conservation (Takakura et al. 1998; Wong et al. 2003; Lundholm et al. 2010; Schroll et al. 2010; European Union 2011; Nagase & Dunnett 2012; Speak et al. 2012; TCPA 2012). Their potential contribution to increasing green space in cities is considerable, for instance an estimate of potential roof space that could be converted to green roofs in four sample areas of London equated to 3.2 million m^2 of green roof (GLA 2008). However urban rooftops also provide a prime location for photovoltaic (PV) systems, a major renewable solar energy technology that contributes to low carbon cities. Initially viewed as two technologies competing for roof space, research in Germany sought to determine the implications of combining green roofs and PVs together (Kohler et al. 2007). Their study and subsequent research has shown that installing PVs in combination with a green roof (biosolar roofs) can enhance PV performance (Kohler et al. 2007; Perez et al. 2012; Nagengast et al. 2013; Chemisana & Lamnatou 2014).

The study by Kohler et al. (2007) and a study by Bousselot et al. (2013) included limited investigation of the effects of the influence of the PV-green roof arrangement on plant performance. The Kohler et al. (2007) study reported increased species richness and greater variation in plant structure on the PV-green roof and the Bousselot et al. (2013) study reported greater plant survival rate near to PV panels. However, both studies were limited by spatial scale and thus lacked replicate plots. To date these studies appear to be the only research published in English examining the impact of solar panels on green roof biota. Ecologically informed green infrastructure design is essential for resilient sustainable urban development and the present study aims to build on the findings of Kohler et al. (2007). This paper reports on the results of a study examining vegetation and invertebrate community composition on a biosolar roof in London’s Queen Elizabeth Olympic Park. Differences and similarities in vegetation and invertebrate composition in relation to habitat/microhabitat niches created by the biosolar design are explored. Observed trends are used to inform recommendations for future experimental research investigating the influence of PV panels on vegetation and invertebrate communities on an extensive green roof.

Methods

Study site

The London Legacy Development Corporation commissioned an ecological monitoring programme to assess the performance of the Queen Elizabeth Olympic Park living roofs in relation to Olympic Park Biodiversity Action Plan targets (ODA 2008). As part of this process, a comprehensive baseline monitoring survey was undertaken on the most substantial of the Olympic Park living roofs, the Main Press Centre building (MPC) roof (51:32:48N, 0:01:20W) (Figure 1).

The MPC building has a 0.25 ha biodiverse extensive roof (Figure 2) designed using the principles of biomimicry - incorporating habitat features analogous to those found on regionally important Open Mosaic Habitat (brownfield) in the Thames Corridor. The roof was designed to contribute to targets in the Olympic Park Biodiversity Action Plan and featured alternating bands of two different substrates and habitat piles of wood and rubble, creating a mosaic of niches and microhabitats. The roof was seeded with 3.6 kg of a native wildflower mix designed for green roofs, 1.2 kg of a special cornfield annual mixture, and plug planted with 125 each of 8 native wildflower species (Appendix 1 and 2). The seed mix and plug plant selection comprised species characteristic of open mosaic habitat that are suited to green roof conditions and of value to key invertebrates of conservation importance recorded in the Olympic Park. At installation, seeds and plants were distributed evenly across the roof.

In order to meet carbon efficiency targets, the Olympic Delivery Authority (ODA) were required to install solar panels on the MPC roof, and in 2010 an array comprising 317 PV panels were fitted to the roof (ODA 2010). The layout of the array was developed with the living roof designer to create a mixture of exposed and sheltered areas of habitat that would maintain overall habitat quality (ODA, 2010).

[Figure 1 near here]
[Figure 2 near here]

The baseline ecological survey of the roof was designed to provide information on habitat development in relation to Olympic Park biodiversity targets with particular focus on five key habitat features associated with the roof, niche/synusial distribution, vegetation composition, vegetation structure, habitat structure, and invertebrate assemblages.

Monitoring was designed to enable quantification of change in these features seasonally and annually and to quantify the contribution of these features to the overall aim of creating a mosaic of habitats and niches at roof level.

The initial monitoring process comprised:

- a site walkover to identify and spatially reference any location or design features that would create significant habitat/environmental variability across the living roof (e.g. PV panels, outlets, habitat design features);
- a GIS desk-based study to spatially combine and analyse information gathered during the site walkover with an aerial plan of the site to identify the range of habitat niches (synusia) on the living roof (e.g. shaded areas, exposed areas).

The spatial plan was used to design targeted vegetation and invertebrate surveys of the repetitive habitat features across the green roof design.

The green roof comprised four areas separated by footpaths arranged around a central grey infrastructure area (Figure 1.i). The presence of a 2.5 m high barrier dividing the central infrastructure area from the green roof meant that sunlight, shading, wind exposure and rain on these four green roof sides would be different depending upon the time of day and wind direction. This would create some variability in terms of habitat development. Therefore, for the purpose of monitoring, the roof was divided into four areas: north, south, east and west sides and this variable has been termed ‘aspect’.

Within these four roof areas, the next level of synusial variation came from the presence of photovoltaic (PV) panels across the green roof sides (Figure 1.i). Distribution of the PV panels varied between the four green roof sides (west section - 180 panels, east section - 60 panels, south section - 45 panels, north section - 32 panels), but all PV panels were installed at the same orientation, height and angle and thus their individual effect on the underlying habitat would be expected to be relatively uniform . In terms of synusial variation, these effects would create three habitat types: i) open (areas not affected by PV presence); ii) covered (areas immediately beneath the PV panels); iii) transition (areas at the edge of PV panels).

The next level of synusial variation identified came from the use of two different types of substrate in the construction of the roof (Figure 1.ii). The first substrate (hereafter known as substrate 1) was a general purpose extensive green roof substrate composed predominately of recycled brick of varying diameter, 15% recycled green waste compost and medium clay soil. The second substrate (hereafter known as substrate 2), comprised approximately 80% crushed, recycled ceramics and 20% recycled green waste compost. Aggregate particle size was smaller and organic content higher in substrate 2 compared to substrate 1. Whilst some small areas of substrate were blended, the majority of the roof was covered with alternating substrate bands at a standard depth of 100mm.

The last identified level of synusial variation came from the presence of habitat piles throughout the roof (Figure 1.ii). Habitat piles are small mounds of material thought to benefit a range of organisms by providing refuge, feeding, nesting resources and basking areas. Habitat piles comprised log piles, brick and rubble piles, concrete slab piles, gravel piles and purpose-built bug hotels (a range of materials fixed within a wooden frame). Habitat piles were distributed across the roofs on both types of substrate.

Based on this initial synusial mapping it was determined that the majority of habitat variation across the MPC green roof could be summarised in four variables:

i) Aspect - north, south, east, west.
ii) Proximity to PV panels - open, PV edge effect, underneath PVs.
iii) Substrate type - substrate 1 or substrate 2
iv) Habitat piles - near to habitat pile, no habitat pile.

All monitoring on the roof was designed with these environmental variables in mind and with a view to using sample replication to assess whether variability in green roof habitat design had an effect on the floral and faunal abundance, diversity and structure. All areas were surveyed but most focus was placed on the east and west sides as these provided the greatest scope for replicate sampling. Vegetation and invertebrate surveys were carried out three times during summer 2013 (early, mid and late summer). The repeated survey methodology was used throughout the summer to ensure that detailed information could be provided on the performance of the green roof during the optimal period for assessing invertebrate, habitat/vegetation interest and to capture patterns in relation to seasonal variations in growth and climatic conditions (e.g. drought conditions vs good growing conditions).

Vegetation surveys

The baseline survey contextualised vegetation development and provided spatial information on living roof ecology to characterise patterns in relation to environmental conditions. Surveys included a combination of stratified random quadrat surveys, line transects and available forage inventories designed relative to the living roof synusial map and to represent the different habitat niches on the roof.

Quadrat surveys

Thirty-six fixed-point quadrats were established and monitored (Figure 1.iii). The location of quadrats was planned to capture an accurate assessment of vegetation diversity in relation to three of the four habitat design variables (aspect, proximity to PV panels and substrate type). It was not possible to include the habitat design variable of habitat piles into this survey methodology due to the scale of the habitat piles in relation to the quadrat survey area. Permanent quadrats were established using fixed-point pegs to mark out locations and allow repeated recording of species at the same location over a period of time to assess community composition and change. A 1 x 1 m quadrat was used as this is the optimum sized frame for sampling communities that comprise largely herb layer species (Mueller-Dombois & Ellenberg 1974). The quadrat was subdivided into one hundred 10 x 10 cm squares. A complete list of all plants within the quadrat was recorded and plant frequency data was collected by recording plant presence/absence in each of the 100 subunits within the quadrat, providing a percentage score. This technique is commonly applied to herbaceous communities as it provides an objective measure and gives an accurate indication of vegetation distribution and abundance (Mueller-Dombois & Ellenberg 1974). Species were recorded if any of their above ground parts (shoots) extended into the quadrat. Frequency of moss, deadwood and bare ground was also recorded for each subunit within the quadrat. Dead vegetation was recorded but it was excluded from the data analysis. The records did however support the qualitative evaluation of vegetation performance.

Fixed-point line transects

In total, 12 fixed-point line transects were established and monitored (Figure 1.iii) to investigate the effect of green roof design variation on habitat and vegetation structure. The transects were designed to assess vegetation diversity and structure in relation to all four identified habitat design variables and to measure vegetation dynamics in relation to the structural features on the roof and changes in composition over time. Transects were placed within single substrate bands across the width of the green roof sides and were focused on the east and west sides of the roof to maximise the number of replicates. The orientation and broadly linear pattern of the bands of the two substrate types on these sections meant that a 7 metre transect length could be used. The standard line transect methodology was adapted to incorporate a measure of habitat structure in addition to species abundance. The protocol involved laying a tape measure along the ground between two fixed points covering the width of the green roof side. Six fixed line transects were spaced along the east and west sides respectively, three transects on each substrate type on each side. A vertical 100 cm x 10 cm quadrat-grid divided into 10 x 10 cm vertical sub-units was used to measure vegetation height and diversity at 10 cm intervals above and along the 7 metre line transect. All plant species intercepting the vertical quadrat were recorded. Where any part of a plant intercepted the grid, the height and species was noted on a sheet in the corresponding 10 cm strata to create a structure profile diagram. Both living and dead plants were recorded, but note was made of their status so that they could be separated during data analysis when required. PV panels and habitat piles were measured and recorded within the line transect for analysis of vegetation structure and diversity in relation to structural variables on the roof. In addition to vegetation diversity and height, presence of moss, deadwood and bare ground were also recorded.

Fixed-point line transects - PV 'zones'

PV panels are known to affect the distribution of rainwater and sunlight reaching the surface underlying them (Cook & McCuen, 2013), so to examine the interaction between the vegetation and the PV panels, a series of zones were assigned to sections of the line transects associated with observed variation in habitat conditions around the PV panels. The zones identified were: 'edge (high)' - the area under and adjacent to the raised end of the PV panel; 'under' - the area under the centre of the PV panel; 'edge (low)' - the area under and adjacent to the lower end of the PV panel; 'open' - the area between the panels (Figure 3). An area of 40 cm was used for each of these zones, with a gap between each zone allowing for a transition area.

[Figure 3 near here]

Available forage inventories

Surveys of all floral species in flower at the time of monitoring were carried out on the separate north, south, east and west green roof sides and on the gravel margins at the edge of each of these areas. These surveys were carried out to capture a broad and comparable index of the diversity of species available as a source of nectar and pollen to pollinating insects. Surveys comprised a slow walk over each roof side recording all flowering species observed.

Identification of flora followed Stace (2010) for all vegetation surveys. In addition to generating information on the vegetation performance of the roofs, the fixed-point survey locations provided a context for the invertebrate surveys in relation to the spatial distribution of synusia.

Invertebrate monitoring

Invertebrate survey comprised a combination of general group inventory surveys and surveys targeted toward key species identified within the Olympic Park Biodiversity Action Plan (ODA 2008) as local species of conservation importance for which living roofs might support at least some of their habitat requirements. Targeted surveys were based on the living roof synusial map to incorporate and compare all four habitat design variables (aspect, proximity to PV panels, substrate type and habitat piles) in species distributions.

Invertebrate survey methodology included:

Timed/fixed distance bumblebee

During each of the three survey visits, ten timed bumblebee and butterfly walks were carried out on each of the green roof aspects (north, south, east and west) to assess foraging visits to flora on replicate substrate bands within each aspect. Surveys comprised a modified version of the bee walk transects used by Banaszak (1980) and Saville et al. (1997). Modification of the method was necessary as the forage distribution across the green roofs was too patchy and discontinuous for single straight-line transect walks to be effective. Thus, non-linear walks covering each roof aspect and encompassing the main flowering patches within each area were used. Length and approximate duration of walks was repeated within each green roof survey and throughout all of the surveys. Observations were made approximately 2 m either side of the observer and walking speed was about 10 m per minute. Surveys recorded the number and species of bumblebees observed. Any bumblebee species not easily identified on the wing were caught using a sweep net and/or queen bee marking plunger cage (Kwak 1987) and were identified by species morphology using a field lens. For each individual observed, the behaviour of the individual was recorded (i.e. in flight, or the floral species on which it was foraging/resting). Flower identification followed Stace (2010).

Pitfall trap surveys

In total, 44 pitfall traps were located across the roof sections (Figure 1iv). On the east side of the roof three pitfall traps were situated within each of three bands of substrate 1 and 2 respectively. Within each of these substrate bands one pitfall trap was located in an open area, one next to a habitat pile and one under the PV panels. This pattern was repeated on the west side. As the PV panels on the east side of the roof were not randomised in their location and were situated towards the edge of the green roof, it was impossible to completely rule out the confounding effect of their edge location, but to reduce the potential of this effect the pitfall traps were positioned along the inside edge of the PV panels. This meant the traps were 1.2 m from the roof edge and thus the overriding variable likely to be affecting the microclimate was the proximity to PV panel.

Pitfall traps were also placed next to habitat piles on the south and north sides of the roof. Pitfall traps were set three times to coincide with the optimal period for surveying terrestrial invertebrates (Drake et al. 2007) and to correspond with the timing of the vegetation surveys. Each pitfall trap was partially filled with a dilute solution of ethylene glycol (antifreeze) and left in position for two weeks. Pitfall traps act as passive traps to capture epigeal invertebrates (those occurring immediately above ground), such as Araneae, Coleoptera and flying insects such as Hymenoptera and Syrphidae. As such, they will give a general index of invertebrates utilising the roof in relation to ecological differences between sample areas related to habitat characteristics such as proximity to habitat piles (Topping and Sunderland 1992). Once collected, samples were transferred to 70% alcohol and stored for later identification. Individuals in traps were identified into different groups at order level such as Orthoptera, Diptera, Hemiptera, Lepidoptera, etc, or higher (e.g. Gastropoda). The exception to this being Araneae, Coleoptera and Hymenoptera which were also identified to species level. These groups were selected for more detailed identification as they have been found to be abundant on London green roofs (including conservation priority species) (Gedge and Kadas 2005; Kadas 2006; Kadas 2010), and are considered to be good indicators of habitat quality (Kremen et al. 1993; Buchholz 2010; Kovács-Hostyánszki et al. 2013).

The invertebrate monitoring was planned with a view to providing an overall inventory of the diversity of the MPC green roof, rather than a specific comparison of the interaction between synusial design features and invertebrate abundance and diversity. Nevertheless, due to the replicated nature of the sampling, it was possible to investigate patterns of distribution in relation to features such as PV panels. Due to the constraints of the experimental design, only data relating to specimens caught in pitfall traps on the east side of the roof could be used to examine the distribution of invertebrates in relation to the PV panels. At 7 metres wide and approximately 100 metres long, the east green roof section provided a substantial area for invertebrate survey. The composition of the habitat variables on this section of roof meant that pitfall traps within a substrate band were separated by a distance of at least 3 metres, and between substrate bands by at least 5 metres, thereby reducing potential for pseudoreplication.

Limitations of experimental design

As the MPC green roof was not originally designed and constructed as a biosolar green roof experiment, there were constraints within this study in terms of the degree of confidence that could be established on the interaction between PVs and the plant and invertebrate communities on the roof. The original design for the monitoring was to assess the overall effect of all of the green roof design variables (aspect, PV panels, substrate type, and presence of habitat piles) on vegetation and invertebrate distributions and diversity, therefore data on the interaction between the PV panels and the roof biodiversity was limited. Nevertheless, several interesting patterns emerged from the monitoring programme that could potentially be associated with the relationship between the green roof and the PV panels and these have been analysed, in addition to the general biodiversity findings, to provide some precursory observations in relation to this emerging area of roof design and scientific research.

The replicated nature of much of the green roof design meant that repetition could be incorporated into the design of the monitoring programme. Whilst it is impossible to control for all environmental variables when moving from laboratory-based study to field-based study, the standardised and repeated design of the roof over such a substantial roof area provided an opportunity to treat sample areas as replicates. Survey of these replicated units of the green roof design enabled investigation of patterns related to the over-arching aim of the roof design: to provide a range of niches for maximising the habitat mosaic and supporting a broad range of biodiversity. Central to this, in relation to the interaction of the green roof and the PV panels, were the fixed-point quadrat and fixed-line transect habitat structure and vegetation community surveys.

For statistical analyses, Mann-Whitney U (1-tailed) Exact tests were used because of the low sample sizes, count nature of the data, no assumption of distribution, and confidence of the direction difference between samples based on initial scoping surveys. For analysis of the effects of PVs on vegetation, vegetation cover and diversity was expected to be greater around PV panels than in more open areas due to the buffering effect of the panels to extremes of heat (shading) and additional irrigation provided at the foot of the sloped surface of the panels from panel condensation and rainfall runoff. Analysis of invertebrate distributions was based on ecological understanding of the habitat preferences of certain groups. Hymenoptera and Diptera would be expected to have a greater association with sunnier more open areas whilst other groups (Araneae) would be expected to be more associated with the increased vegetation and physical structural features associated with the PV panels (Uetz 1991). This ecological understanding was combined with observations from initial scoping surveys to determine expected directions for one-tailed tests. For all tests, the threshold of significance was $P<0.05$.

Results

Vegetation surveys

Total floral species richness recorded during the period of monitoring for all green roof sections was 92 (Appendix 3). Of the 31 species originally seeded and plug planted on the roof, 9 species were not recorded during any of the vegetation surveys in 2013. From the total species recorded, 70 species had naturally colonised the roof. The colonisers comprised 37 species that were perennials, 30 species that were typically annuals, and 3 species that were primarily biennials. The total number of species recorded during the three forage inventory surveys (species in flower) for the west and east green roof sections were very similar; 55 species for the west and 54 species for the east. Whilst the number of flowering species was similar, the species recorded differed. Of the cumulative 66 species recorded flowering on the west and east sides of the green roof, only 43 species were recorded on both roof sides, meaning that a third of flowering species were particular to one roof side.

Differences were also recorded for average floral species richness in quadrats on the east and west sides during the three survey periods (Figure 4). At the beginning of the season species richness was broadly similar, but in August when vegetation cover had declined on the roof during a period of extreme dry weather, average species richness was five times higher on the west side compared to the east. This pattern continued in October but the difference between the two sides was less marked.

[Figure 4 near here]

The effect of PV cover on the proportion of bare ground recorded in quadrats on the west green roof section showed a trend for bare ground to reduce more markedly in open areas on substrate 2 during the survey period (Figure 5). A significant reduction in the proportion of bare ground was recorded in open areas on substrate 2 ($p = 0.02$), but not under PV panels on the same substrate ($p = 0.5$). There was no significant change in recorded bare ground on substrate 1 in relation to PV cover.

[Figure 5 near here]

Horizontal and vertical distribution of living vegetation recorded in six line transects during August 2013 are represented in Figures 6 and 7. These depict three transects from the more PV-covered west side of the green roof and three from the more open east green roof area. These representations illustrate that living vegetation was frequently associated with edges of structural features on the roof - PV panels, habitat piles and roof edges. Large open areas on the green roof, and those directly under the PV panels were typically devoid of vegetation or supported sparse, low-growing plants during the most drought stressed period of the surveys.

[Figure 6 near here]

[Figure 7 near here]

The interaction between vegetation and the PV panels recorded in the line transects was examined further by analysing 'zones' associated with observed variation in habitat conditions around the PV panels (Figure 3) on the west side where the greatest number of PV panels were located. Comparisons were able to be made between twelve of each of these types of zones on the west side of the roof due to the repeated pattern of PV panels across each transect. Comparisons of floral diversity (Figure 8) and vegetation structure (Figure 9) were made. Variation in habitat structure was evaluated for August and October using floral diversity data from the height categories 0-10cm and 10-20cm where the majority of vegetation was recorded. Different height categories were used for the analysis as habitat structure rather than purely sward height is of interest when designing green roofs for invertebrate diversity.

[Figure 8 near here]

[Figure 9 near here]

During the August surveys, diversity was significantly higher in the 'under' PV zone than in the 'open' areas at 10-20cm ($p = 0.03$). No vegetation was recorded in the open areas at this height, and there was no significant difference between the open areas and the edge zones of PVs. No significant difference in diversity was found when zones were compared at 0-10cm height in August.

In contrast, during the October surveys when living vegetation was more abundant and average diversity was higher for all zones, relative patterns had changed, in particular at the edge of PVs. At 0-10cm height, average diversity was highest at the low edge zone, and diversity was significantly higher when low edge and under PV zones were compared ($p = 0.03$). The under PV zone was the least diverse of the zones but there was no significant difference recorded between high edge and under or open zones ($p = 0.06$ and $p = 0.11$ respectively) at this height, and low edge and open areas were not significantly different ($p = 0.06$). At the 10 to 20 cm height significant differences were recorded between the high edge zone and under and low edge zones ($p = 0.02$ and 0.03 respectively), and between the open zone and the under and low edge zones ($p = 0.02$ and 0.03 respectively).

Structural analysis of the zones was also carried out by comparing maximum height of vegetation within each of the 10 cm survey sections within the zones along each of the line transects on the western side of the roof (n = 48 for each zone type). Figure 9 represents the proportion of each of these maximum heights for each zone. The open areas recorded greater proportions of lower vegetation for both August and October. When the roof was at its most stressed, the high and low edge zones recorded the highest proportions of tall vegetation. The under PV zone was the most consistent between the two surveys, falling between the two extremes of the PV edges and open areas.

Invertebrate surveys

A total of 36 species were identified from the target groups caught in pitfall traps across the roof (Appendix 4). This sample included the Red Data Book (RDB3) species the toadflax brocade moth (*Calophasia lunula*), one Notable/Na spider (*Meioneta simplicitarsis,*) one Notable/Nb ant (*Ponera coarctata*), UK Biodiversity Action Plan priority species the brown-banded carder bee (*Bombus humilis*) and 14 other species of Local conservation importance. This equated to almost 50% of the species in the sample being designated of conservation concern.

The average number of individuals from each of the most abundant groups (Araneae, Coleoptera, Hymenoptera and Diptera) for pitfall traps on the east side of the roof associated with the habitat features open, habitat pile, PV panel are shown in Figure 10. The average number of individuals from each of these groups varied in each habitat type, dependent upon the group in question.

[Figure 10 near here]

Diptera were significantly more abundant in pitfalls next to habitat piles and in open areas, than in pitfalls next to PV panels (*p* = 0.022 and *p* = 0.02 respectively). Significantly greater numbers of Hymenoptera were also recorded in the open and habitat pile pitfall traps than the edge of PV pitfall traps (*p* = 0.04 and 0.01 respectively). For Coleoptera no significant difference was recorded between any of the habitat types (*p* = 0.20, 0.33 and 0.35 respectively). For Araneae, although greater numbers were recorded in the PV panel and habitat pile pitfalls than the open pitfalls, this was not significantly so (*p* = 0.097 and 0.097 respectively for comparison of habitat piles and PVs with open areas for the first survey period). Whilst the differences between open areas and the more structured areas of the PV panels was not shown to be significant in this study, further more focused survey may demonstrate an association between Araneae and PVs and habitat piles, as a preference for habitat structure has been documented for spiders in other habitats (Uetz 1991).

Additional anecdotal evidence on the effect of the PV panels on invertebrate distributions came from the bee walk surveys. Repeated standardised bee walk surveys on the east and west sections of roof recorded substantial differences between the two sides, with greater numbers and diversity of bumblebees being recorded on the more open eastern side than the more PV covered west side (Connop and Nash 2014). This included the UK Biodiversity Action Plan bumblebee species *Bombus humilis* which was only recorded on the more open east and north areas of the roof. Whilst it was impossible to establish the precise reason for this, the greatest likelihood is that it was related to differences in the density of PV panels between the two sides, or aspect, or a combination of both.

During the monitoring, incidental observations of other animals on or near the green roof were recorded. A key objective of the design of the roof was to provide feeding habitat for black redstart *Phoenicurus ochruros* and linnet *Carduelis cannabina*, two species which are listed as Birds of Conservation Concern in the UK and were included as target species in the Olympic Park Biodiversity Action Plan. A pair of black redstart were recorded foraging on the green roof throughout the survey period and were regularly seen perching on and sheltering under PV panels. Pairs and small groups of linnets were also recorded foraging on the roof on a number of occasions. Other bird species recording on the roof included pied wagtail *Motacilla alba*, goldfinch *Carduelis carduelis*, and magpie *Pica pica*.

Discussion

With financial and practical barriers to the establishment of large-scale experimental studies in green roof design for biodiversity, green roof research is frequently restricted to small-scale experimentation or in-situ research on installed green roofs with no experimental process involved in their design and no control over the spatial relationships between roofs. This leads to much green roof research being confounded by problems of pseudoreplication or no replication, with multiple environmental variables between each roof 'treatment' leading to an inability to draw definitive conclusions on the environmental factors affecting change.

Whilst the Olympic Park MPC green roof was not an ideal experimental set-up compared to a large-scale controlled experiment, the design of the green roof and the layout of the PV panels across this design meant that it was possible to incorporate an element of replication over a substantial area into the design of our monitoring programme, which we believe avoided many of the problems of pseudoreplication (Hurlbert 1984; Oksanen 2001; Cottenie and De Meester 2003). As such, the roof made an interesting case study into the effects of incorporating a mosaic of habitats and niches into green roof design using biomimicry of regionally typical habitat of national conservation importance. An overview of the monitoring established on the roof to quantify this value can be found in the baseline report (Connop and Nash 2014).

Records for floral communities, invertebrate assemblages and birds on the MPC green roof provided preliminary insights into the potential value of a biosolar roof for biodiversity. The 92 plant species recorded on the roof during the 2013 surveys represented a floristically diverse example of an extensive green roof when compared to the findings of Bates et al. (2013), who reported a maximum of 59 forb species on a biodiverse 'brownfield' green roof studied over four years. The proportion of faunistically interesting invertebrate species recorded on the MPC biosolar roof was also high compared to previous invertebrate research on London green roofs (Kadas, 2006). These results are a promising indication of the potential for biosolar roofs to provide habitat for a wide range of plant and invertebrate species. Furthermore, the regular sightings of black redstart and linnet on the roof show that a biosolar roof can also provide a valuable foraging resource for conservation priority bird species as well as common birds.

Data on the interaction between PV panels and vegetation derived from the quadrat surveys, transects and flowering inventories showed differences in the plant species composition in relation to proximity to PV panels. Evidence from the vegetation fixed-point transect data and PV 'zone' analysis showed patterns for vegetation to be more species-rich and structurally diverse adjacent to PV panels (and habitat piles). This trend appeared most marked during the period of extreme dry weather that occurred during monitoring. It has been shown that PV panels alter the local climate by providing areas of shade and concentrated patches of moisture from rainfall run-off beneath panel edges (Cook & McCuen 2013). It is therefore possible that the additional microclimates provided by PVs enabled a broader range of plant species to survive the harsh climatic conditions during mid-summer in 2013. Further evidence to support this was provided by differences in floral communities between the more densely PV covered west side and the open east side. This effect seemed strongest during the mid-summer survey when an extended period of drought caused widespread plant dieback on the roof, yet average floral species richness recorded in quadrats on the more PV covered west side was five times higher than on the east. Whilst it was impossible to remove the confounding effect of aspect from the east-west results, these patterns support the findings of two other studies investigating the influence of PV panels on green roof plants (Kohler et al. 2007 and Bousselot et al. 2013).

Our study also found the response of plant cover to the presence of PV panels varied according to substrate type, with the proportion of bare ground recorded in quadrats on substrate 2 reducing significantly in the open, but not significantly under PV panels following the prolonged dry spell. This could be seen as either a positive or negative result, depending on the desired ecological, environmental or aesthetic requirements for a particular green roof. For this study, bare ground was considered a positive feature on the roof as it is an important element of open mosaic habitat, but further more detailed study of the relationship between PV panels, green roof substrates and plant performance is needed to fully understand these interacting effects and advance ecologically informed green roof design.

From the observations in this study it is hypothesised that structural elements such as PV panels and habitat piles could provide refugia for plants, particularly during drought spells, and contribute to the target of creating a mosaic of habitats from bare ground to flower-rich habitats on a green roof. They may also facilitate recolonisation of a roof once environmental conditions improve. Future research should examine these potential refugia effects as a mechanism for increasing resilience in urban green infrastructure to extremes of temperature and drought conditions. The importance of refugia on green roofs has previously been highlighted by Rumble and Gange (2013) in relation to the soil dwelling invertebrate populations critical for soil quality and thus green roof health. Ensuring resilience of green infrastructure through design has been identified as a key mechanism for enabling urban areas to transition towards more sustainable futures in the face of climate driven change (Collier et al. 2013).

With EU and UK policy commitments to halt biodiversity loss (Defra, 2011; European Commission 2012) an ecologically informed approach to GI development is essential, rather than relying on assumptions of the intrinsic benefits of urban greening (Collier et al. 2013). Evidence from this study indicated that biosolar roofs may be a mechanism for expanding the habitat mosaic of green roof systems, thus broadening the niches for biodiversity and increasing resilience. Nonetheless, while PV panel arrays on sections of a green roof can contribute to microclimates and microhabitats on the roof, results from the invertebrate pitfall trap surveys and anecdotal patterns observed during bee walks suggested that comprehensive PV cover could be detrimental to some invertebrate groups like Hymenoptera. In light of this, the effect of density of PV panels on green roof invertebrates should be a focus of future controlled, experimental research.

Whilst this study only represented the pattern of behaviour on a single biosolar green roof system, the replication of sub-units incorporated into the design and construction of the green roof enabled an interesting case study to be carried out. The evidence presented on the potential effect of PV panels on green roof biota and their contribution to the habitat mosaic was sufficient to indicate that further investigation of the interaction between PV panels and green roofs would be of value, with focus on both sides of the reported symbiotic relationship.

Whilst there are restrictions as to what can be evidenced on the MPC green roof due to variation in aspect between heavily PV-covered areas and more open areas, there is still much scope to expand this initial case study in subsequent years and to include investigation of additional aspects of the effects of the PV panels on the underlying habitat. Of particular interest would be a more detailed investigation of the habitat 'zones' associated with the PV panels, perhaps supported by more detailed microclimatic monitoring. This would enable more informed designation of the zones and thus more informative characterisation and analysis of the interaction between the PV panels and the surrounding vegetation. Also of interest would be to expand the number of replicates to investigate whether limited sampling weakened the power of statistical analyses. It is thus intended that further study will be carried out on the MPC roof.

It is also recommended that additional studies on the interaction between PVs and habitat be initiated and/or published to demonstrate whether there is a truly symbiotic relationship between PVs and green roofs and to investigate best practice for multifunctional biosolar roof design. Research of particular relevance would include how density of PV cover affects green roof biodiversity and PV performance. Also, whether the habitat mosaic could be enhanced further by targeted planting of species known to favour habitat niches created by the PV arrays.

Acknowledgements

The biodiversity-design led green infrastructure research, incorporating biomimicry of regional habitat of national conservation importance into the design of urban green infrastructure, carried out by the University of East London's Sustainability Research Institute was supported by the EU FP7 funded project TURAS (Transitioning towards Urban Resilience and Sustainability).

This TURAS case study research project would not have been possible without the generous support of the London Legacy Development Corporation, one of the aims of which being to secure a biodiversity legacy for the London 2012 Olympic Games.

Special thanks also go to Peter Harvey for help with species-level identification of invertebrates and to Dusty Gedge, Gary Grant and the Green Roof Consultancy whose passion for biodiversity is fed into every green roof they design and whose designs have been a huge driving force behind London's ever increasing focus on becoming a city that intertwines communities and biodiversity.

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Figure Captions

Figure 1. Plans of the experimental design of the monitoring of the MPC green roof, Queen Elizabeth Olympic Park, London, UK, with aerial photo background. Roof plans comprise: i) layout of green roof areas and PV arrays; ii) location of substrate bands and habitat piles on the green roof; iii) location of fixed point quadrats and line transects; iv) location of pitfall traps relative to habitat piles (Habitat), open areas (Open) and under PV panels (PV). Aerial photo © Getmapping.com

Figure 2. Eastern area of MPC green roof, Queen Elizabeth Olympic Park, London, UK.. Image shows photovoltaic panel area at eastern edge of green roof next to flower-rich green roof area. Photo © Stuart Connop

Figure 3. PV panel vegetation zones. Plan of the four 40 cm vegetation zones that were investigated in relation to vegetation cover, diversity and structure. Designated zones comprise i) under; ii) open; iii) edge (high); iv) edge (low)

Figure 4. Average species richness recorded in quadrats during June, August and October 2013 on the east and west side of the MPC green roof, Queen Elizabeth Park, London, UK. Sample size *n*= 12 on each side. Error bars represent standard error of the mean.

Figure 5. Average frequency of bare ground in quadrats in open areas between PV panels and under PV panels, MPC green roof, Queen Elizabeth Olympic Park, London, UK. Sample size *n* = 6 in each area. Error bars represent standard error of the mean.

Figure 6. Three line transects showing distribution and height of living vegetation in relation to roof edge, photovoltaic panel and habitat pile distribution on the west green roof of the MPC building Olympic Park, following a drought period, August 2013. Vegetation recorded in 10 cm^2 vertical quadrat squares along a 7 metre transect.

Figure 7. Three line transects showing distribution and height of living vegetation in relation to roof edge, photovoltaic panel and habitat pile distribution on the east green roof of the MPC building Olympic Park, following a drought period, August 2013. Vegetation recorded in 10 cm^2 vertical quadrat squares along a 7 metre transect.

Figure 8. Average floral diversity at 0-10 cm and 10-20 cm for zones associated with PV panels (edge (high), under, open and edge (low)) on the MPC green roof, Queen Elizabeth Olympic Park, London, UK. Number of survey squares (*n*) = 48. Error bars represent standard error of the mean.

Figure 9. Distribution of the maximum height of vegetation within the MPC west green roof transects 10 cm survey sections in i) August and ii) October 2013 in each zone associated with the PV panels (edge (high), under, open and edge (low), Queen Elizabeth Olympic Park, London, UK. Number of surveys squares (*n*) = 48.

Figure 10. Average number of individuals of i) Araneae, ii) Coleoptera, iii) Hymenoptera and iv) Diptera in pitfall traps on the east green roof of the MPC building Olympic Park. Six pitfall traps were placed in each of the habitat types: open area, habitat pile and edge of PV panel. Traps were left in place for a two week period, three times throughout the summer 2013 (June, August and September). Averages are for all trapping periods (*n* = 18). Error bars represent standard error of the mean.

Figure 1i

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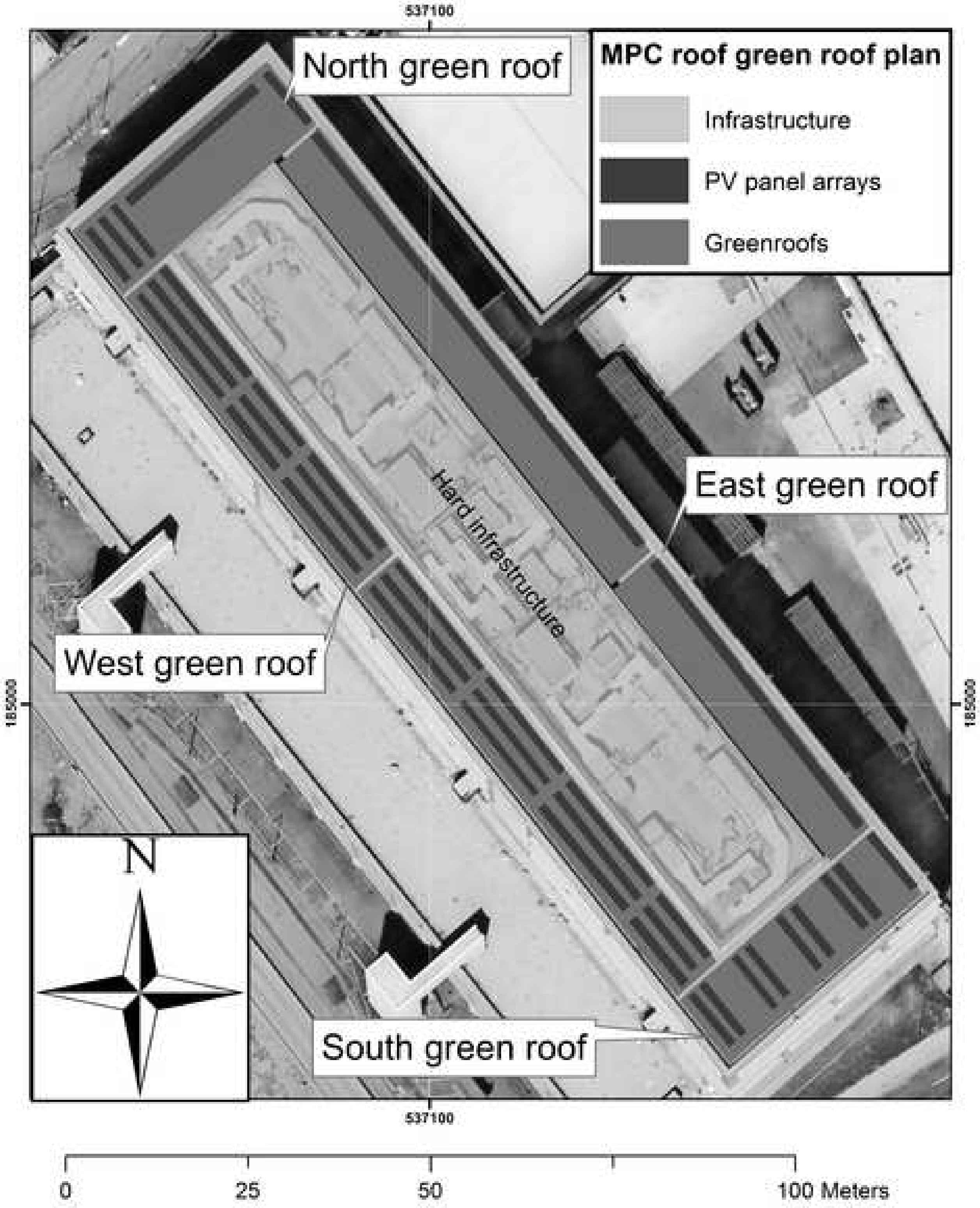
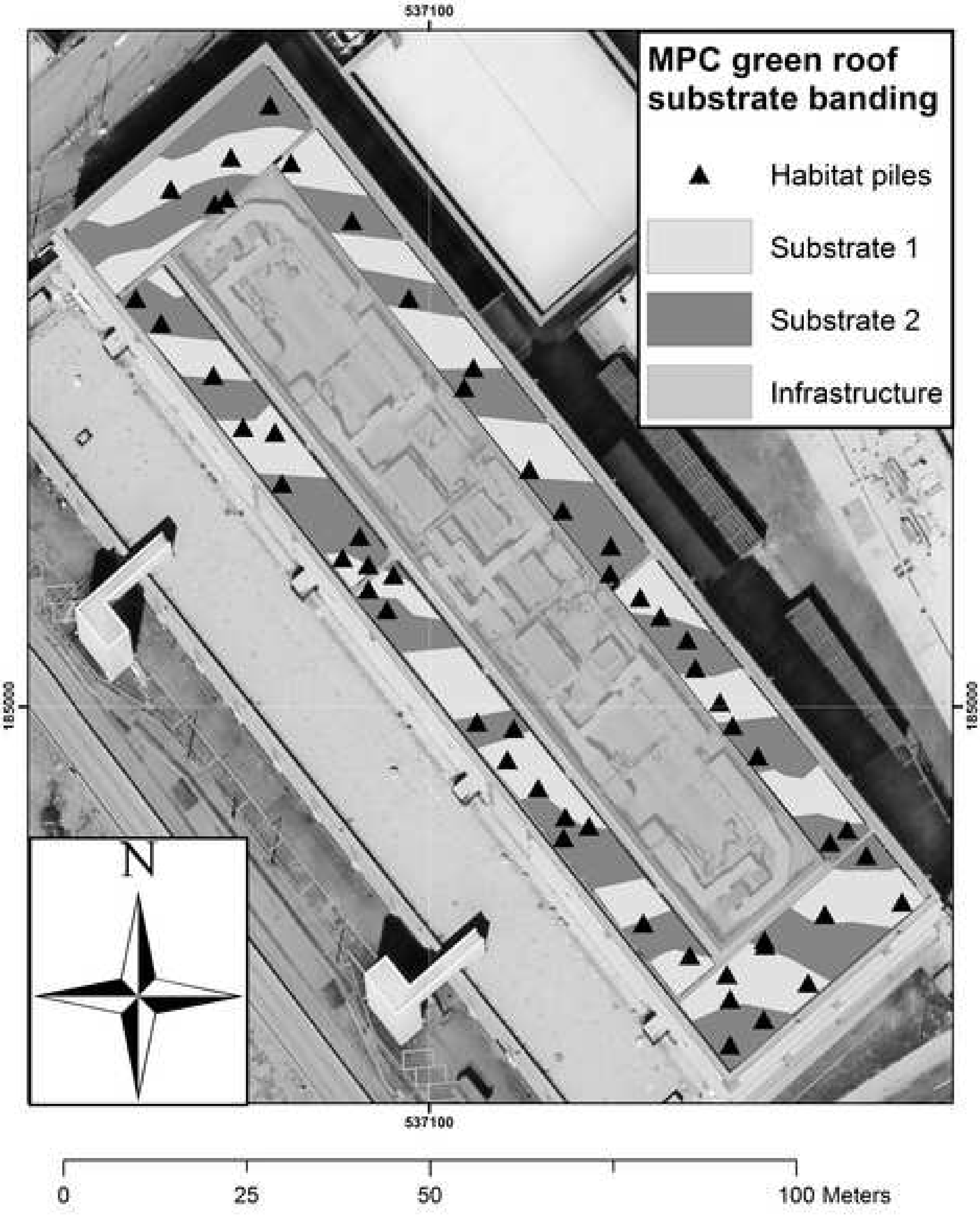


Figure 1ii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MPC green roof substrate banding
▲ Habitat piles
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Substrate 2
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185000
N
537100
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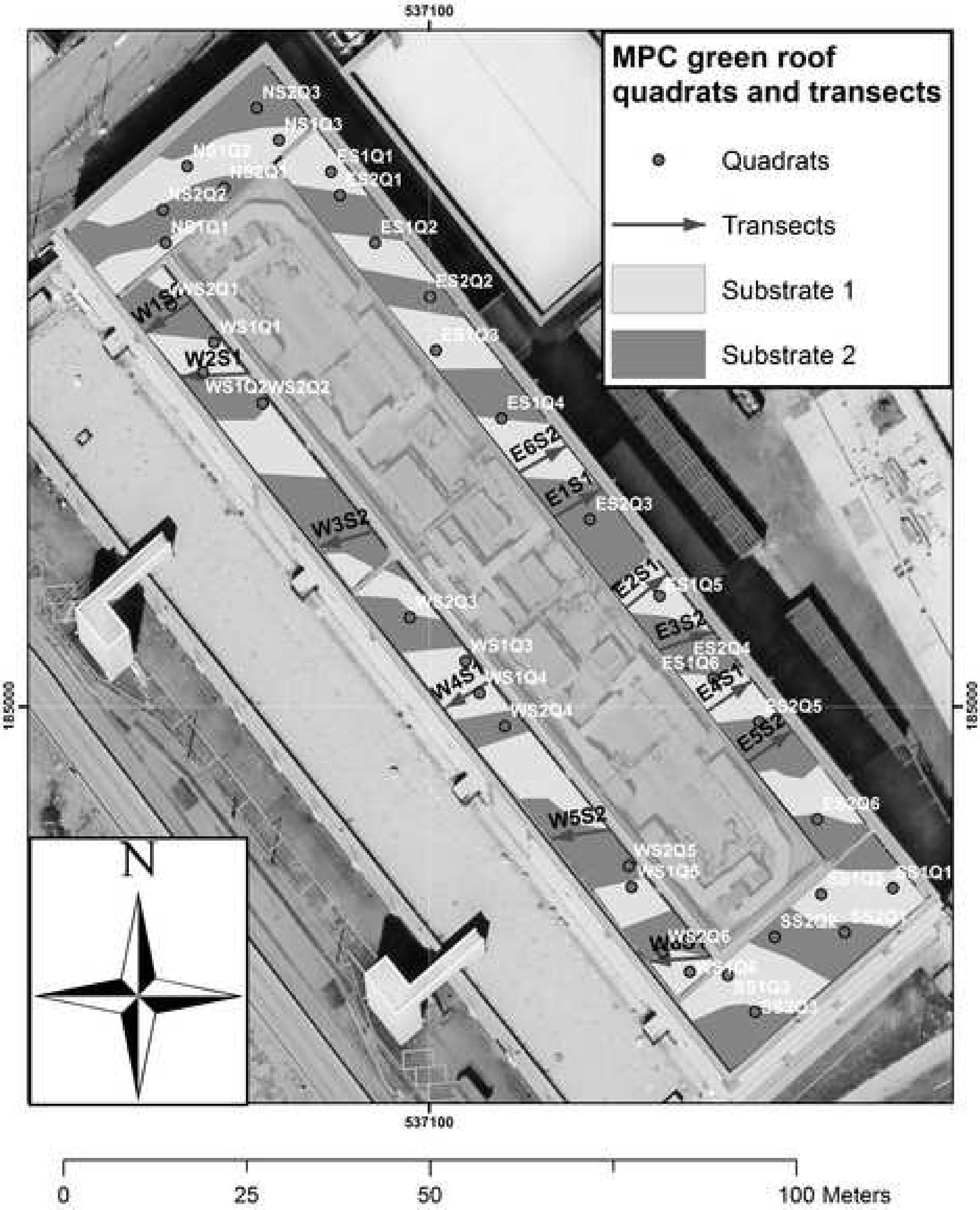
50
100 Meters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MPC green roof quadrats and transects
Quadrats
Transects
Substrate 1
Substrate 2
NS2Q3
NS1Q3
NS1Q2
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ES1Q1
ES2Q1
NS2Q2
NS1Q1
ES1Q2
ES2Q2
W1S2
WS2Q1
WS1Q1
ES1Q3
W2S1
WS1Q2
WS2Q2
ES1Q4
E6S2
E1S1
W3S2
ES2Q3
E2S1
ES1Q5
WS2Q3
E3S2
ES2Q4
ES1Q6
WS1Q3
W4S1
WS1Q4
E4S1
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WS2Q4
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185000
185000
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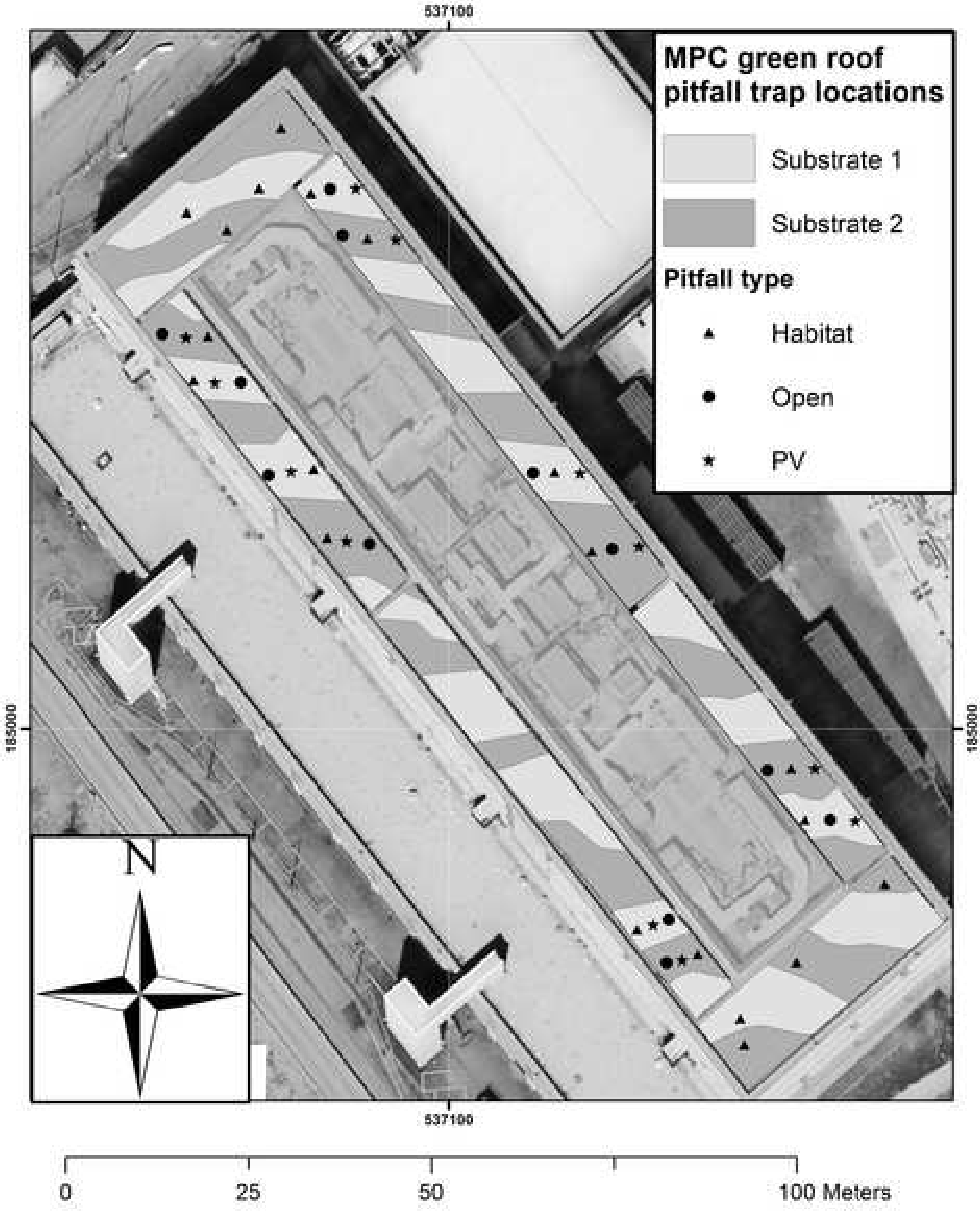
Figure 1iv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MPC green roof pitfall trap locations
Substrate 1
Substrate 2
Pitfall type
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★ PV
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N
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0
25
50
100 Meters

Figure 2

Figure 3

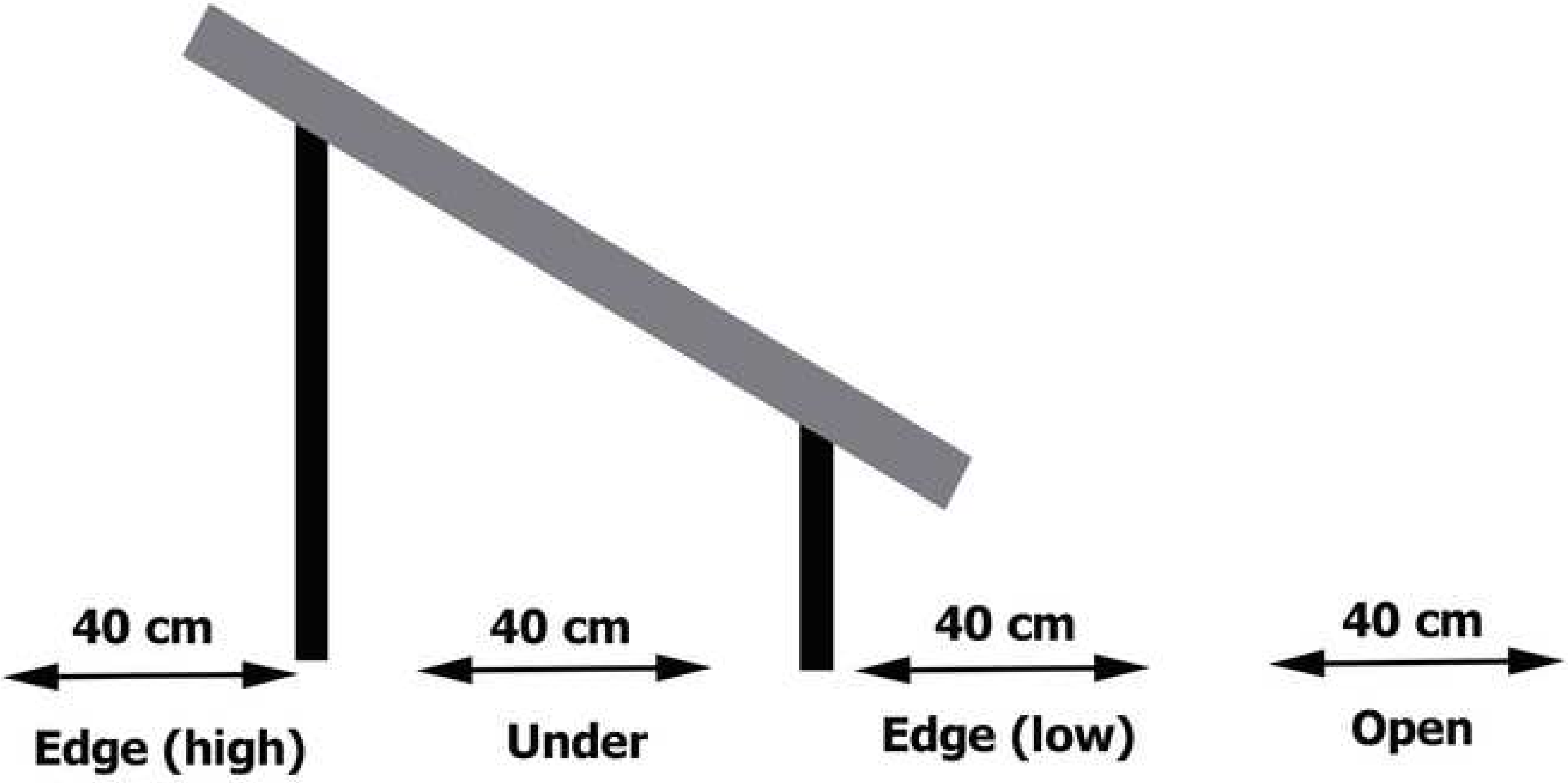

Figure 4

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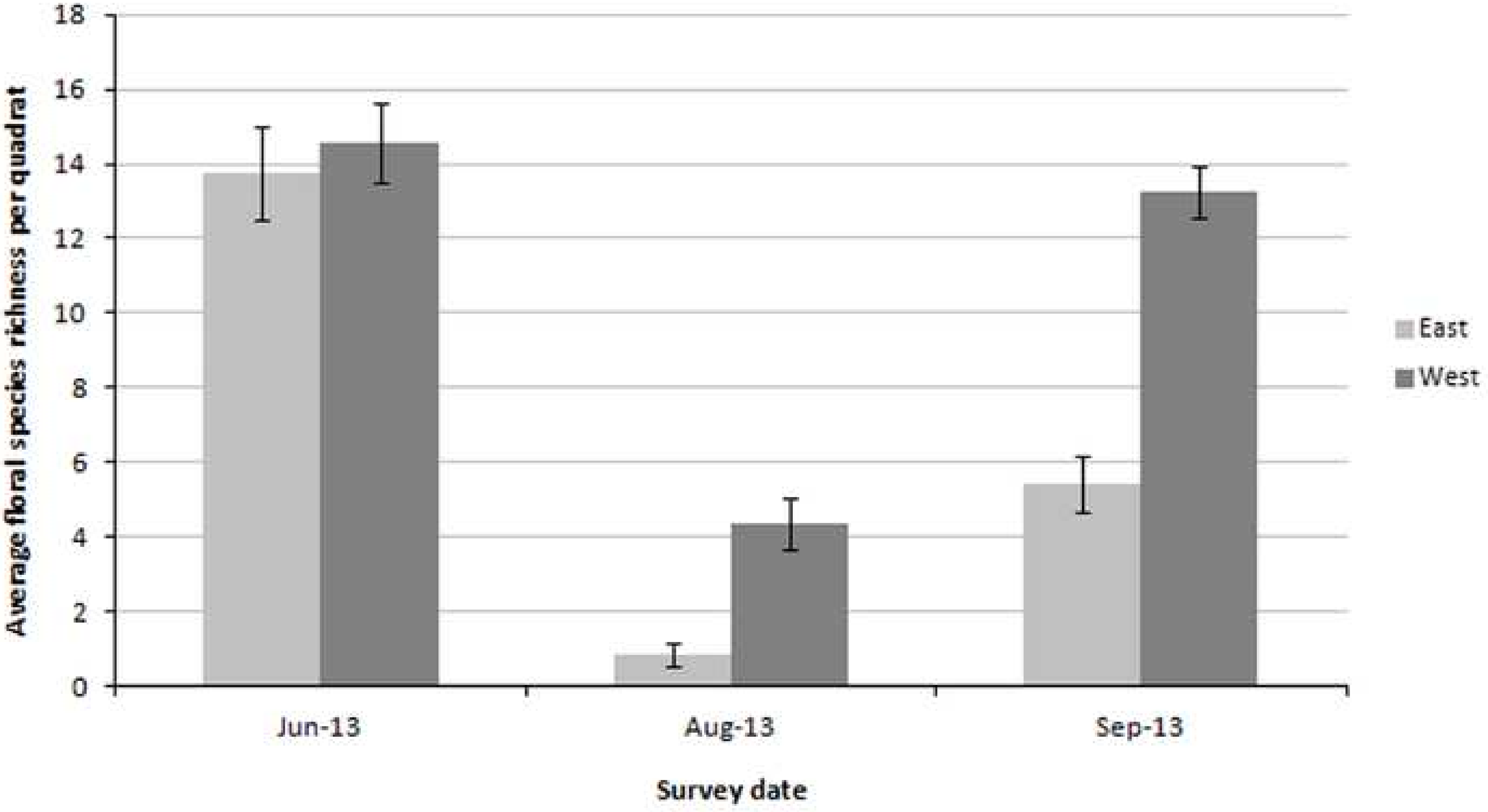

Figure 5

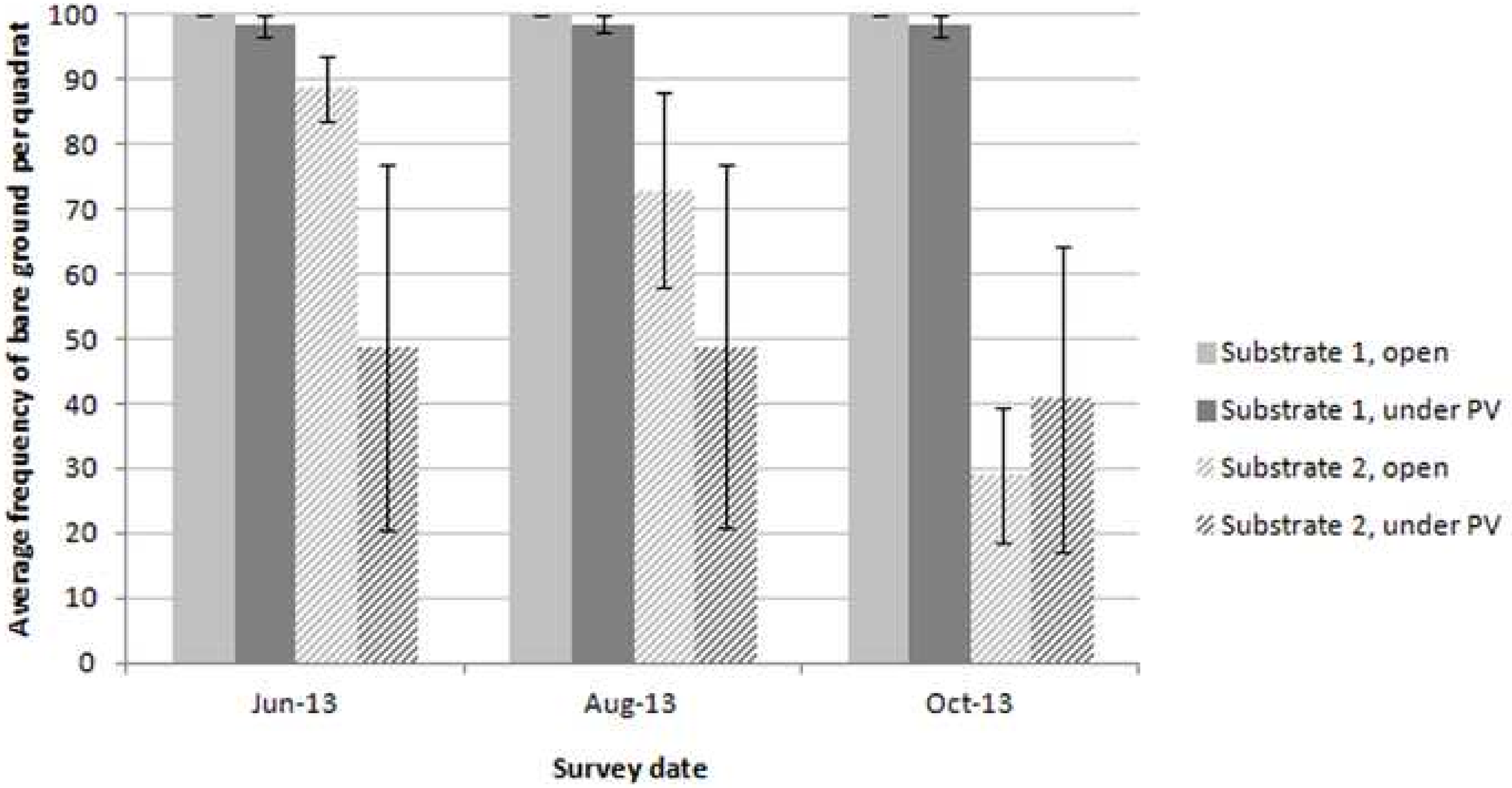
Average frequency of bare ground per quadrat
100
90
80
70
60
50
40
30
20
10
0
Jun-13
Aug-13
Oct-13
Survey date
Substrate 1, open
Substrate 1, under PV
Substrate 2, open
Substrate 2, under PV

Figure 6

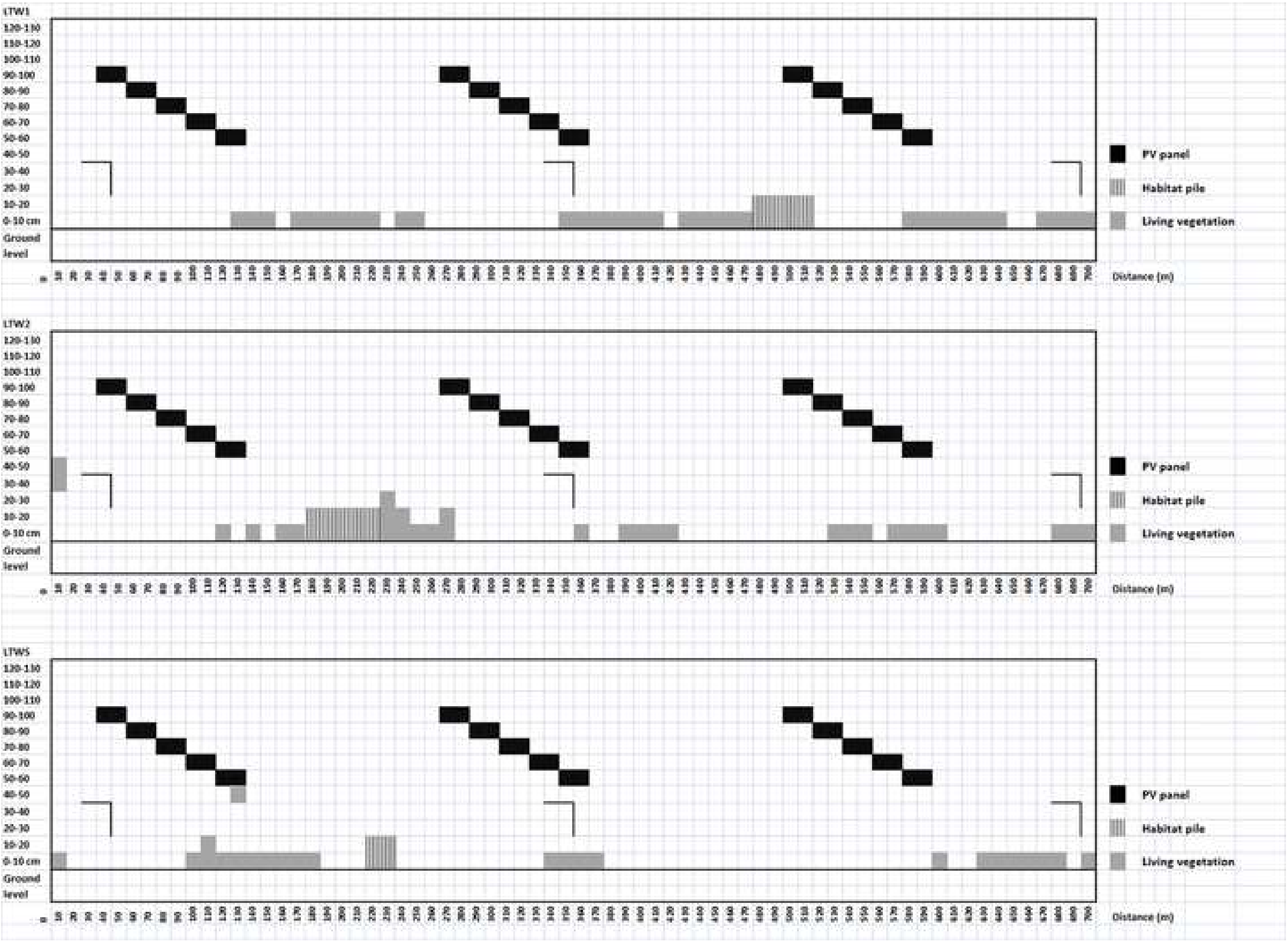
LTW1
LTW2
LTW5
120-130
110-120
100-110
90-100
80-90
70-80
60-70
50-60
40-50
30-40
20-30
10-20
0-10 cm
Ground level
Distance (m)
PV panel
Habitat pile
Living vegetation

Figure 7
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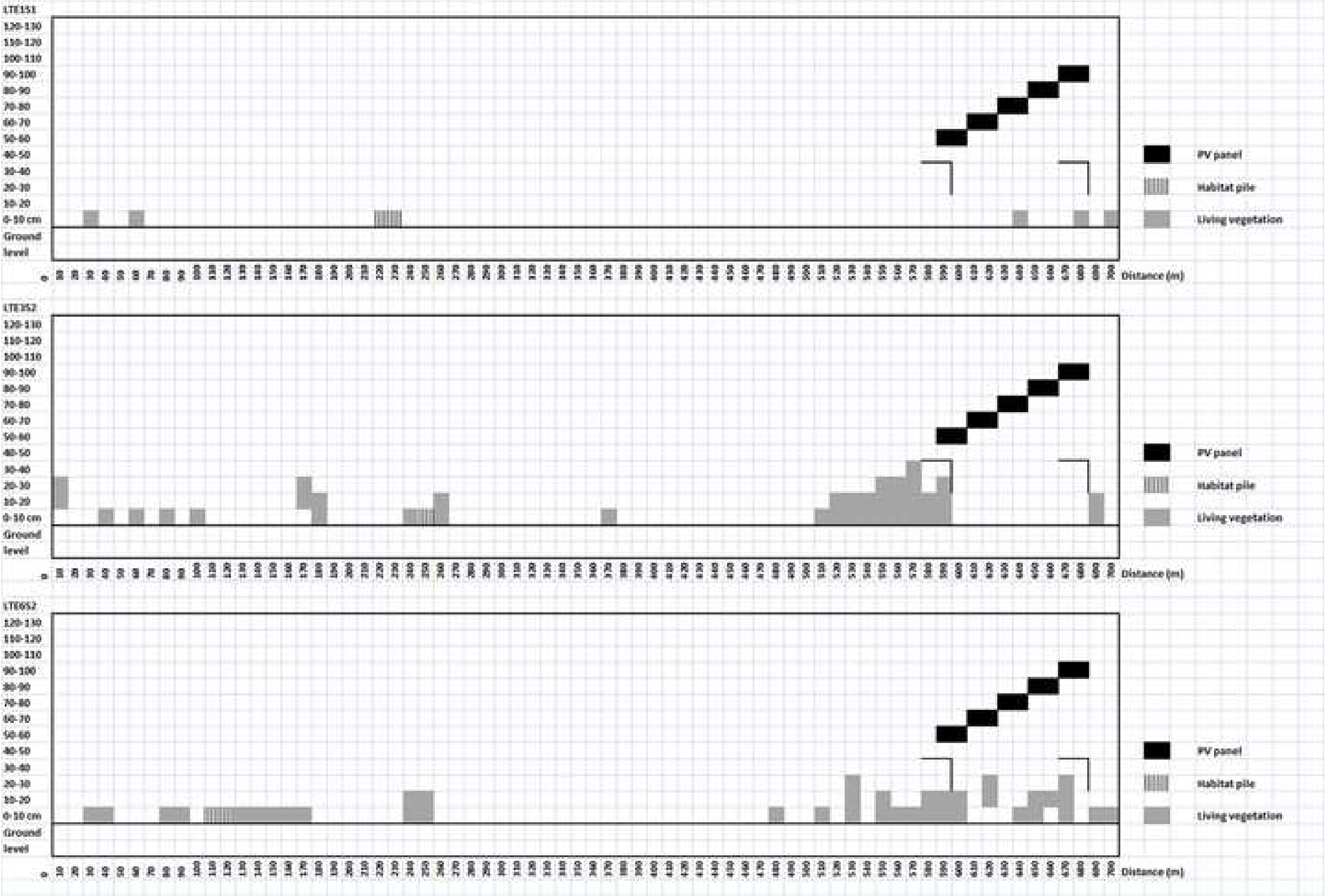


Figure 8

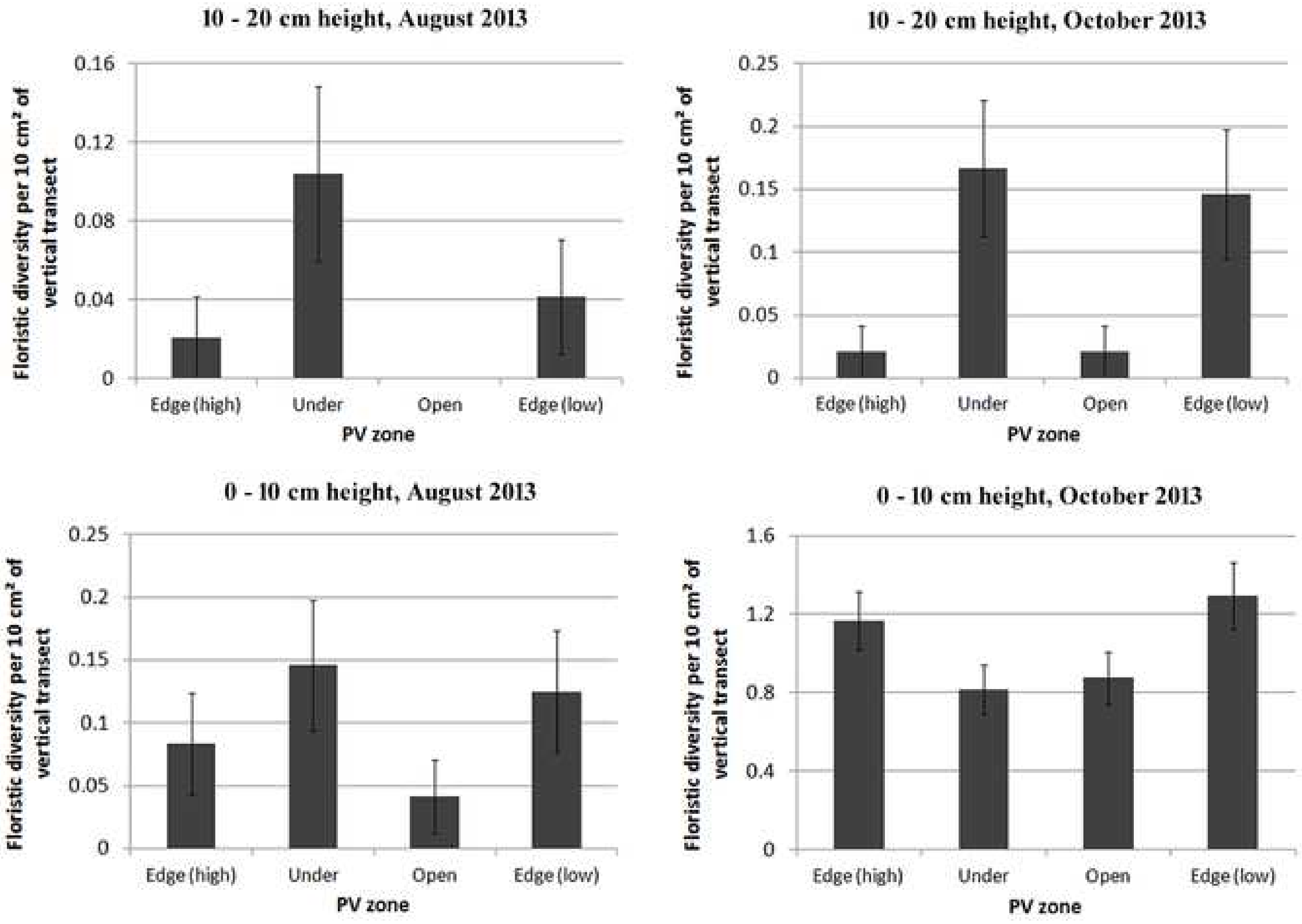
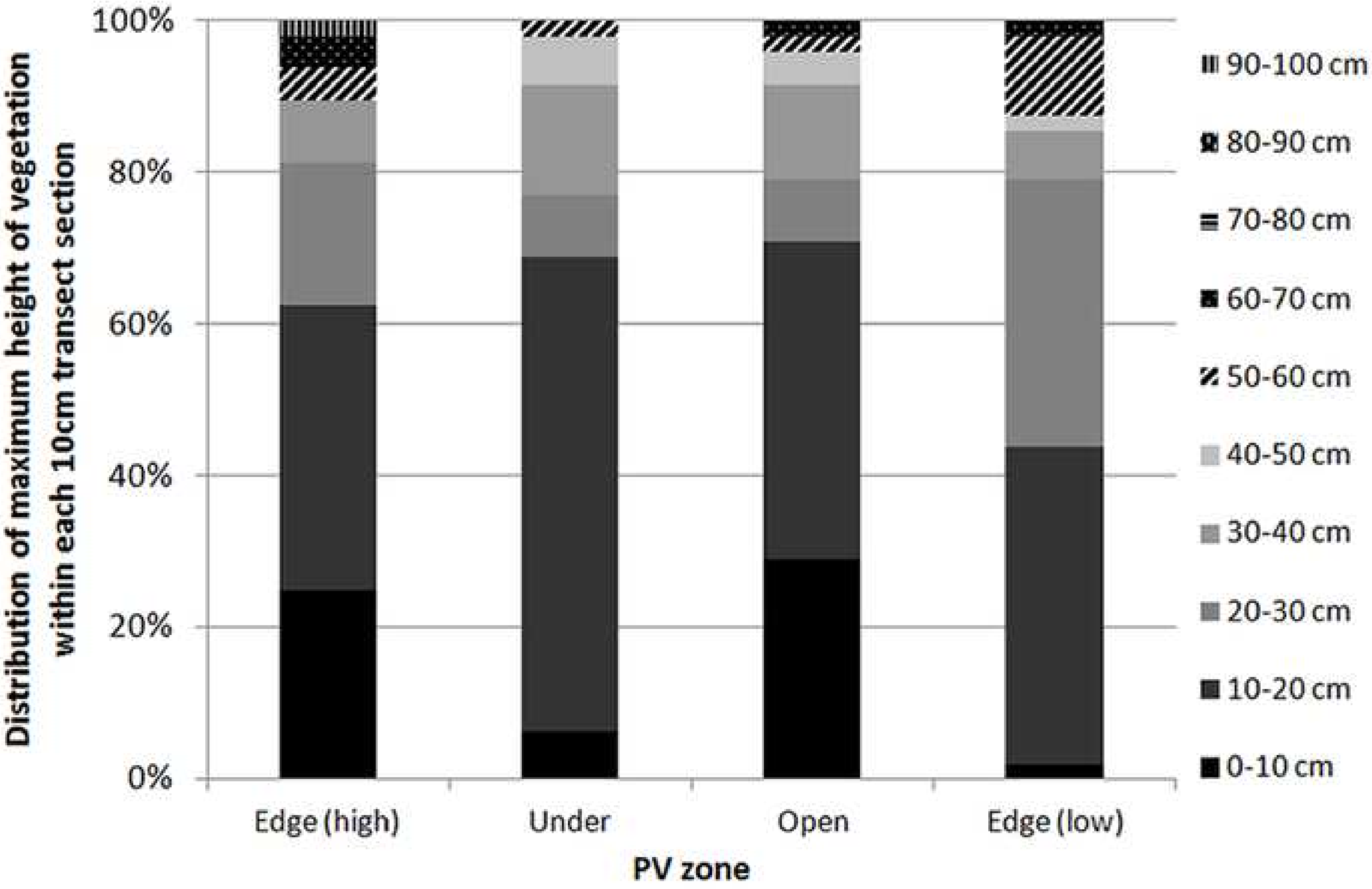

10 - 20 cm height, August 2013
0.16
0.12
0.08
0.04
0
Floristic diversity per 10 cm² of vertical transect
Edge (high)
Under
Open
Edge (low)
PV zone
10 - 20 cm height, October 2013
0.25
0.2
0.15
0.1
0.05
0
Floristic diversity per 10 cm² of vertical transect
Edge (high)
Under
Open
Edge (low)
PV zone
0 - 10 cm height, August 2013
0.25
0.2
0.15
0.1
0.05
0
Floristic diversity per 10 cm² of vertical transect
Edge (high)
Under
Open
Edge (low)
PV zone
0 - 10 cm height, October 2013
1.6
1.2
0.8
0.4
0
Floristic diversity per 10 cm² of vertical transect
Edge (high)
Under
Open
Edge (low)
PV zone

Figure 9i

Click here to download Figure: Figure_9i.tif



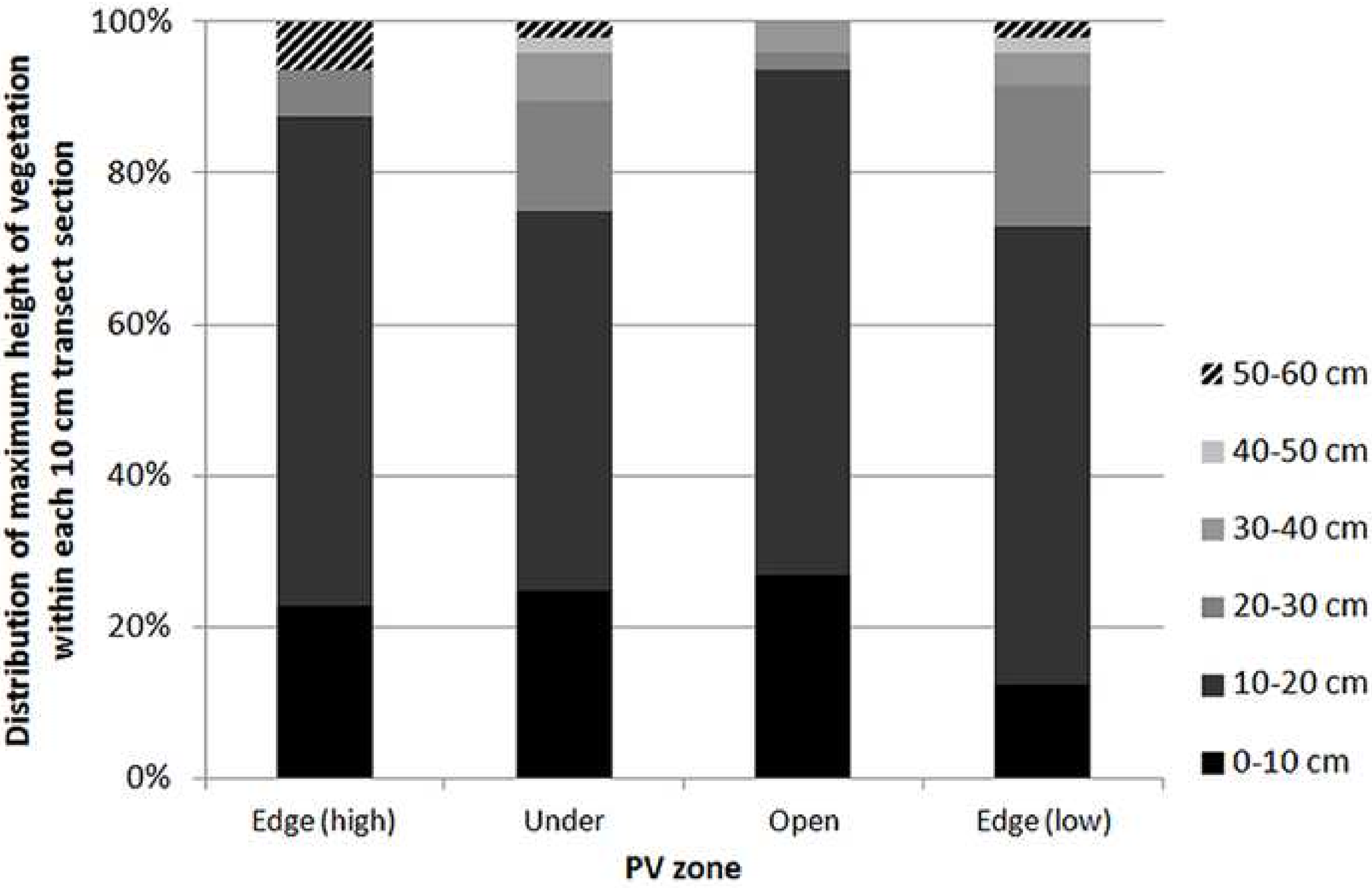
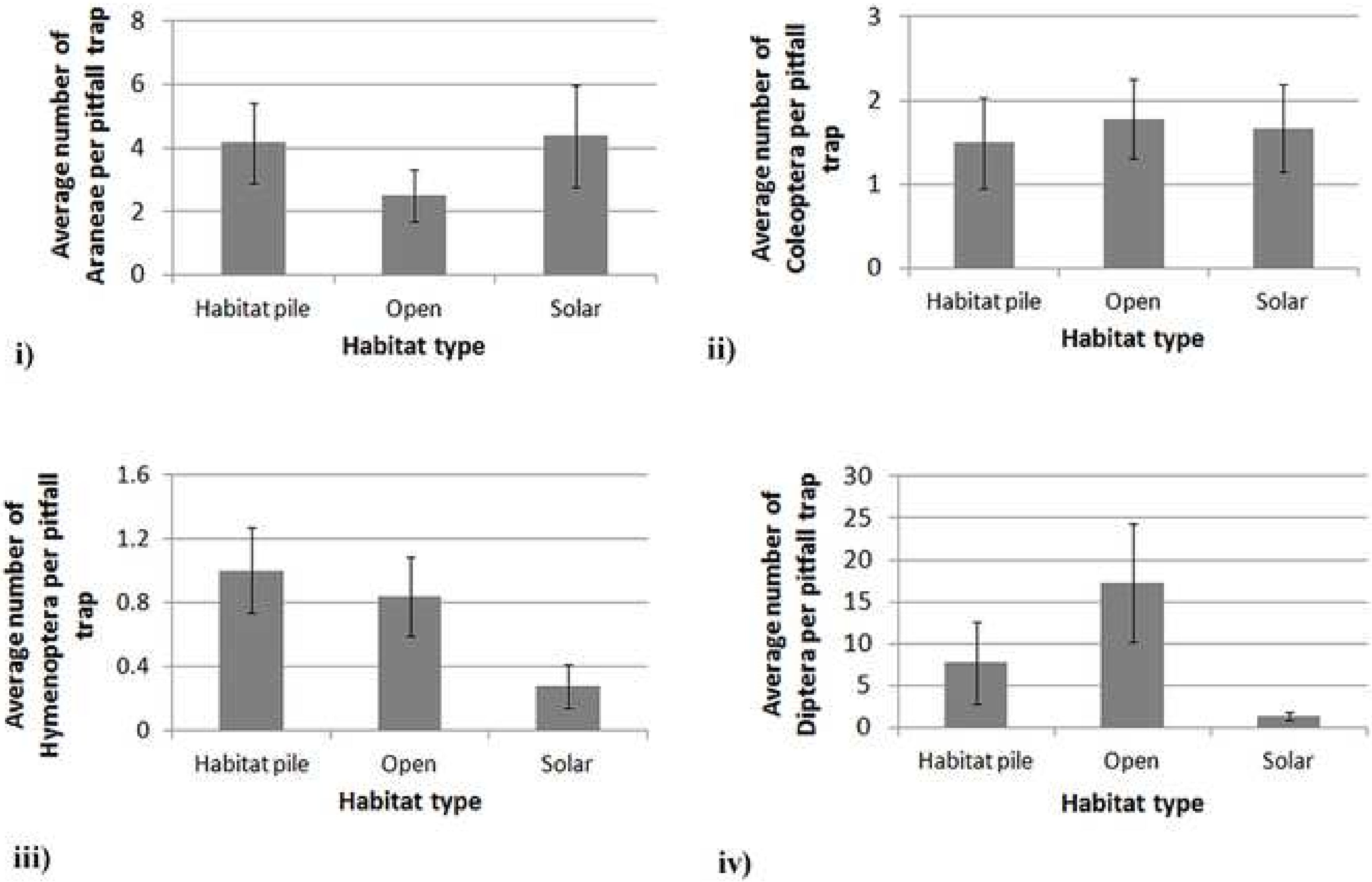

100%
80%
60%
40%
20%
0%
Distribution of maximum height of vegetation within each 10 cm transect section
Edge (high)
Under
Open
Edge (low)
PV zone
50-60 cm
40-50 cm
30-40 cm
20-30 cm
10-20 cm
0-10 cm

Figure 10


Average number of Araneae per pitfall trap
8
6
4
2
0
Habitat pile
Open
Solar
Habitat type
i)
Average number of Coleoptera per pitfall trap
3
2
1
0
Habitat pile
Open
Solar
Habitat type
ii)
Average number of Hymenoptera per pitfall trap
1.6
1.2
0.8
0.4
0
Habitat pile
Open
Solar
Habitat type
iii)
Average number of Diptera per pitfall trap
30
25
20
15
10
5
0
Habitat pile
Open
Solar
Habitat type
iv)

Appendix 1: Seed mixes used on the MPC green roof

Wildflowers for green roofs seed mix

% of mix	Scientific name	Common name
5	*Agrimonia eupatoria*	Agrimony
5	*Anthyllis vulneraria*	Kidney Vetch
2.5	*Centaurea nigra*	Common Knapweed
2	*Clinopodium vulgare*	Wild Basil
5	*Galium verum*	Lady's Bedstraw
2.5	*Hypericum perforatum*	Perforate St John's Wort
5	*Iberis amara*	Wild Candytuft
7.5	*Knautia arvensis*	Field Scabious
2.5	*Leontodon hispidus*	Rough Hawkbit
5	*Leucanthemum vulgare*	Oxeye Daisy
3	*Linaria vulgaris*	Common Toadflax
10	*Lotus corniculatus*	Birdsfoot Trefoil
3	*Malva moschata*	Musk Mallow
2.5	*Origanum vulgare*	Wild Marjoram
2.5	*Plantago media*	Hoary Plantain
8	*Sanguisorba minor*	Salad Burnet
8	*Primula veris*	Cowslip
2.5	*Prunella vulgaris*	Selfheal
5	*Salvia verbenaca*	Wild Clary
7.5	*Scabiosa columbaria*	Small Scabious
5	*Silene vulgaris*	Bladder Campion
1	*Verbascum nigrum*	Dark Mullein

Special cornfield mixture

% of mix	Scientific name	Common name
30	*Agrostemma githago*	Corn Cockle
5	*Anthemis austriaca*	Corn Chamomile (Austrian)
5	*Bupleurum rotundifolium*	Thorow-wax
25	*Centaurea cyanus*	Cornflower
15	*Glebionis segetum*	Corn Marigold
10	*Papaver rhoeas*	Common Poppy
10	*Silene noctiflora*	Night-flowering Catchfly

Appendix 2: Plug plants used on the MPC green roof

Number	Scientific name	Common name
125	*Centaurea nigra*	Common knapweed
125	*Echium vulgare*	Viper's bugloss
125	*Galium verum*	Lady's bedstraw
125	*Hypericum perforatum*	Perforate St John's Wort
125	*Lotus corniculatus*	Birdsfoot trefoil
125	*Origanum vulgare*	Wild marjoram
125	*Primula veris*	Cowslip
125	*Silene latifolia*	White campion

Appendix 3: List of plant species recorded on the MPC green roof during summer 2013. Seeded/plug planted species are marked with *.

Scientific name	**Common name**	**Family**	**Life cycle**
Achillea millefolium	Yarrow	Asteraceae	Perennial
*Agrostemma githago**	Corn cockle	Caryophyllaceae	Annual
Agrostis stolonifera	Creeping bent	Poaceae	Perennial
Anagallis arvensis	Scarlet pimpernel	Primulaceae	Annual
*Anthyllis vulneraria**	Kidney vetch	Fabaceae	Perennial
Arenaria serpyllifolia	Thyme-leaved sandwort	Caryophyllaceae	Annual
Artemisia vulgaris	Mugwort	Asteraceae	Perennial
Buddleja davidii	Butterfly bush	Scrophulariaceae	Perennial
*Bupleurum rotundifolium**	Thorow-wax	Apiaceae	Annual
Capsella bursa-pastoris	Shepherd's purse	Cruciferae	Annual/biennial
Catapodium rigidum	Fern grass	Poaceae	Annual
*Centaurea cyanus**	Cornflower	Asteraceae	Annual
*Centaurea nigra**	Black knapweed	Asteraceae	Perennial
Cerastium fontanum	Mouse-ear chickweed	Caryophyllaceae	Perennial
Chenopodium album	Fat hen	Chenopodiaceae	Annual
Cirsium vulgare	Spear thistle	Asteraceae	Biennial/perennial
*Clinopodium vulgare**	Wild basil	Lamiaceae	Perennial
Conyza canadensis	Canadian fleabane	Asteraceae	Annual
Crepis capillaris	Smooth hawksbeard	Asteraceae	Annual
Cymbalaria muralis	Ivy-leaved toadflax	Scrophulariaceae	Perennial
Diplotaxis tenuifolia	Perennial wall rocket	Brassicaeae	Perennial
*Echium vulgare**	Viper's bugloss	Boraginaceae	Biennial
Euphorbia peplus	Petty spurge	Euphorbiaceae	Annual
Festuca rubra	Red fescue	Poaceae	Perennial
Foeniculum vulgare	Fennel	Apiaceae	Perennial
Fragaria vesca	Wild strawberry	Rosaceae	Perennial
Galinsoga parviflora	Gallant soldier	Asteraceae	Annual
Galium aparine	Cleavers	Rubiaceae	Annual
*Galium verum**	Lady's bedstraw	Rubiaceae	Perennial
Geranium dissectum	Cut-leaved cranesbill	Geraniaceae	Annual
Geranium molle	Dovesfoot cranesbill	Geraniaceae	Annual
*Glebionis segetum**	Corn marigold	Asteraceae	Annual
Hirschfeldia incana	Hoary mustard	Brassicaeae	Annual/perennial
Holcus lanatus	Yorkshire fog	Poaceae	Perennial
*Hypericum perforatum**	Perforate St John's wort	Clusiaceae	Perennial
*Knautia arvensis**	Field scabious	Dipsacaceae	Perennial
Lactuca serriola	Prickly lettuce	Asteraceae	Annual
Lapsana communis	Nipplewort	Asteraceae	Annual
Leontodon autumnalis	Autumn hawkbit	Asteraceae	Perennial
*Leontodon hispidus**	Rough hawkbit	Asteraceae	Perennial
*Leucanthemum vulgare**	Oxeye daisy	Asteraceae	Perennial
Linaria purpurea	Purple toadlfax	Scrophulariaceae	Perennial
*Linaria vulgaris**	Common toadflax	Scrophulariaceae	Perennial
Lolium perenne	Perennial rye grass	Poaceae	Perennial
*Lotus corniculatus**	Birdsfoot trefoil	Fabaceae	Perennial
Malva sylvestris	Common mallow	Malvaceae	Perennial
Medicago lupulina	Black medick	Fabaceae	Annual/perennial
Melilotus albus	White melilot	Fabaceae	Biennial/annual
Mercurialis annua	Annual mercury	Euphorbiaceae	Annual
Myosotis arvensis	Field forget-me-not	Boraginaceae	Annual
Oenothera biennis	Common evening primrose	Onagraceae	Biennial
*Origanum vulgare**	Wild marjoram	Lamiaceae	Perennial
*Papaver rhoeas**	Common poppy	Papaveraceae	Annual
Phleum pratense	Timothy grass	Poaceae	Perennial

Picris echioides	Bristly oxtongue	Asteraceae	Annual/biennial
Picris hieracioides	Hawkweed oxtongue	Asteraceae	Perennial
Plantago lanceolata	Ribwort plantain	Plantaginaceae	Perennial
Plantago major	Greater plantain	Plantaginaceae	Perennial
*Plantago media**	Hoary plantain	Plantaginaceae	Perennial
Poa annua	Annual meadow-grass	Poaceae	Annual
Poa trivialis	Rough meadow-grass	Poaceae	Perennial
*Prunella vulgaris**	Selfheal	Lamiaceae	Perennial
Ranunculus acris	Meadow buttercup	Ranunculaceae	Perennial
Ranunculus repens	Creeping buttercup	Ranunculaceae	Perennial
Reseda lutea	Wild mignonette	Resedaceae	Perennial
Rumex crispus	Curled dock	Polygonaceae	Perennial
Rumex obtusifolius	Broad-leaved dock	Polygonaceae	Perennial
Sagina procumbens	Procumbent pearlwort	Caryophyllaceae	Perennial
*Sanguisorba minor**	Sald burnet	Rosaceae	Perennial
Scrophularia auriculata	Water figwort	Scrophulariaceae	Perennial
Senecio inaequidens	Narrow-leaved ragwort	Asteraceae	Perennial
Senecio jacobaea	Common ragwort	Asteraceae	Perennial
Senecio vulgaris	Groundsel	Asteraceae	Annual
*Silene latifolia**	White campion	Caryophyllaceae	Perennial/annual
*Silene vulgaris**	Bladder campion	Caryophyllaceae	Perennial
Silene x hampeana	Hybrid campion	Caryophyllaceae	Perennial
Solanum nigrum	Black nightshade	Solanaceae	Annual
Sonchus arvensis	Perennial sow-thistle	Asteraceae	Perennial
Sonchus asper	Prickly sow-thistle	Asteraceae	Annual
Sonchus oleraceus	Smooth sow-thistle	Asteraceae	Annual
Stellaria media	Common chickweed	Caryophyllaceae	Annual
Taraxacum officinale	Dandelion	Asteraceae	Perennial
Thymus polytrichus	Wild thyme	Lamiaceae	Perennial
Trifolium pratense	Red clover	Fabaceae	Perennial
Trifolium repens	White clover	Fabaceae	Perennial
Tripleurospermum inodorum	Scentless mayweed	Asteraceae	Annual
Urtica dioica	Common nettle	Urticaceae	Perennial
Veronica chamaedrys	Germander speedwell	Scrophulariaceae	Perennial
Veronica hederifolia	Ivy-leaved speedwell	Scrophulariaceae	Annual
Vicia hirsuta	Hairy tare	Fabaceae	Annual
Vicia tetrasperma	Smooth tare	Fabaceae	Annual
Vulpia bromoides	Squirrel-tail fescue	Poaceae	Annual

Appendix 4: Key species identified from pitfall trap samples on the MPC green roof, summer 2013. List includes key groups identified to species level Araneae, Coleoptera and Hymenoptera, plus other notable species.

Order	Family	Taxon	Records	Individuals	Status	UKBAP
Arachnida: Araneae	Hahniidae	*Hahnia nava*	1	1	Local	
Arachnida: Araneae	Linyphiidae	*Bathyphantes gracilis*	1	1		
Arachnida: Araneae	Linyphiidae	*Erigone arctica*	32	67	Local	
Arachnida: Araneae	Linyphiidae	*Erigone atra*	13	16		
Arachnida: Araneae	Linyphiidae	*Erigone dentipalpis*	48	86		
Arachnida: Araneae	Linyphiidae	*Gnathonarium dentatum*	1	1		
Arachnida: Araneae	Linyphiidae	*Lepthyphantes tenuis*	31	39		
Arachnida: Araneae	Linyphiidae	*Meioneta rurestris*	21	26		
Arachnida: Araneae	Linyphiidae	*Meioneta simplicitarsis*	1	1	Notable/Na	
Arachnida: Araneae	Linyphiidae	*Milleriana inerrans*	2	2	Local	
Arachnida: Araneae	Linyphiidae	*Oedothorax apicatus*	14	18	Local	
Arachnida: Araneae	Linyphiidae	*Oedothorax fuscus*	54	110		
Arachnida: Araneae	Linyphiidae	*Oedothorax retusus*	2	2		
Arachnida: Araneae	Linyphiidae	*Pelecopsis parallela*	3	5	Local	
Arachnida: Araneae	Linyphiidae	*Prinerigone vagans*	3	3	Local	
Arachnida: Araneae	Salticidae	*Euophrys frontalis*	1	1		
Arachnida: Araneae	Theridiidae	*Enoplognatha ovata/latimana sens. lat.*	3	4		
Arachnida: Araneae	Theridiidae	*Steatoda grossa*	1	1	Local	
Arachnida: Araneae	Theridiidae	*Steatoda nobilis*	1	1	Unknown	
Arachnida: Araneae	Thomisidae	*Ozyptila sanctuaria*	2	3	Local	
Coleoptera	Carabidae	*Amara eurynota*	12	18	Local	
Coleoptera	Carabidae	*Harpalus affinis*	4	4		
Coleoptera	Carabidae	*Notiophilus rufipes*	1	1	Local	
Coleoptera	Oedemeridae	*Oedemera lurida*	3	4	Local	
Diptera	Syrphidae	*Eupeodes corollae*	1	1		
Hymenoptera: Aculeata	Apidae	*Bombus humilis*	3	3	Local	UKBAP
Hymenoptera: Aculeata	Apidae	*Bombus lapidarius*	1	1		
Hymenoptera: Aculeata	Apidae	*Bombus lucorum*	8	8		
Hymenoptera: Aculeata	Apidae	*Bombus pascuorum*	1	1		
Hymenoptera: Aculeata	Apidae	*Bombus terrestris*	6	10		
Hymenoptera: Aculeata	Formicidae	*Lasius flavus*	7	8		
Hymenoptera: Aculeata	Formicidae	*Lasius mixtus*	2	2	Local	
Hymenoptera: Aculeata	Formicidae	*Lasius niger sens. str.*	19	24		
Hymenoptera: Aculeata	Formicidae	*Myrmecina graminicola*	1	1	Local	
Hymenoptera: Aculeata	Formicidae	*Ponera coarctata*	1	1	Notable/Nb	

Lepidoptera	Noctuidae	*Calophasia lunula*	1	2	RDB3