Living Vertically:

Exploring the Biodiversity and Ecological Relationships of Arthropods on Green Walls

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MSc Thesis Bio Inspired Innovation

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In collaboration with

Abstract

In urban environments, green spaces are replaced by human infrastructure. This has a negative impact on biodiversity and ecosystem services. Green walls (GWs) are suggested to aid in the biodiversity crisis by providing a habitat for arthropod species. However, the actual effects of green walls on arthropods have not been sufficiently quantified. This study investigates the arthropod metrics; abundance, richness, diversity and composition on 9 living walls (LWs) and 5 green facades (GFs) in the Randstad region of the Netherlands. We compare the wall types to each other, and investigate which local- and landscape-level variables influence these metrics. Lastly, we explore ecological relationships between arthropod species. Our findings reveal that both wall types provide unique habitats for various arthropod species. Both local- and landscape-level characteristics are important in shaping arthropod communities. Notably, the number of flowering plants positively influences arthropod diversity and abundance of flower visiting insects. Surrounding blue- and green infrastructure are positively correlated with abundance, richness and diversity. Local- and landscape-level factors had a variable impact on different arthropod orders and families. This highlights the importance of considering lower-taxonomic relationships when developing biodiversity-conservation strategies based on GWs. Additionally, multiple intricate ecological relationships between arthropods on green walls have been found. Lastly, this study also offers recommendations for green wall design and urban planning strategies. These insights aim to effectively address the arthropod diversity crisis.

Statement of collaboration

This research was performed in a duo. This means this research was done with another Master's student [Mateo Pearson]. We have worked intensively together, and have picked and visited the locations, and collected samples with the two of us. As a consequence, the methods are similar and the result section of the research has overlap. However, my research described in this report focusses more on Local Habitat Characteristics and Alpha-Diversity metrics, whereas the other report has Landscape Level Characteristics and Beta-Diversity as main focus. Furthermore, we have researched different ecological relationships. I have written my abstract, layman's summary, introduction, results and discussion independently.

Layman's Summary

Cities are growing fast, and as they expand, green spaces are replaced by human infrastructure. The disappearance of greenery creates many problems, one of which is the loss of habitat for arthropods. Arthropods are a group of animals which includes all insects, spiders, millipedes and mites. Insects alone account for 57% of all living species on our planet. Arthropods are of great importance to the functioning of ecosystems and provide important services to humans. They clean up nature, are a food source for many other animals and they pollinate our fruit and vegetables. To increase habitat for arthropods in densely populated cities, green walls offer a unique solution by growing plants vertically onto walls. In cities, green spaces are often small and spread out. Green walls could act as stepping stones to create natural bridges to connect these scattered green spots. There are two main types of green walls: Living walls are characterized by plants growing on panels attached to the wall; and green facades are characterized by climbing plants that grow up the wall.

Unfortunately, research on how green walls can offer a home for arthropod species is lacking. In order for green walls to help address the arthropod diversity crisis, we need to know which arthropods visit green walls and what factors about the walls are important to them. Multiple factors of green walls could be important for arthropods. These include factors related to plants such as the number of different plant species, how much of the wall is covered by plants and how many plants are flowering. Other important factors are related to the wall itself, such as the surface area and even the age of the green wall. These factors together add up to the local habitat. However, most arthropods don't just stay on the wall, they move around the city. This means that we need to consider the broader environment as well. These 'landscape-factors' include surrounding greenery and nearby waterbodies.

In this study the following questions will be answered: How do the livings walls and green facades compare in terms of the number of arthropods and their diversity? Which factors influence arthropod abundance and diversity on green walls? What are the ecological relationships of arthropods on green walls?

We have investigated 9 livings walls and 5 green facades located in the Randstad. In total we have identified 2000 arthropods on living walls and 501 arthropods on green facades. These arthropods belong to 125 unique families in 21 different orders. This shows the rich diversity of arthropods living on green walls. Living walls and green facades hosted different types of unique arthropods. This means that having both types of green walls in the city creates different homes for many kinds of arthropods.
We found a higher number and diversity of arthropods on walls with more flowering plants. The selection of plants for green walls should therefore be focussed on a variety of flowering species. Additionally, we have discovered that having more green spaces and waterways around a green wall increases the number and variety of arthropods on that wall. This means that considering the broader environment is important for urban planners and green wall design.
Different groups of arthropods react differently to certain factors. For example, a big wall area may be beneficial for beetles, while most flies are also fine with a smaller wall. While this insight might seem trivial, it highlights the importance of understanding the preference of specific arthropods. We discovered fascinating ecological relationships between arthropods on green walls such as mites that hitchhike on mosquitoes, and parasitoid wasps that act as biological control agents on aphids. These insights reveal complex ecological relationships which support the hypothesis that green walls can acts as valuable habitats for many arthropod species.

Still, we need to know much more about arthropods living on green walls. Based on the gaps in our current knowledge, it is clear that ecologists should more often collaborate with urban planners and green wall designers, to better address the arthropod diversity crisis.

Contents

Introduction

Urbanisation is a global trend in the twenty- and twenty-first century. The number of people living in urban areas is predicted to increase to 68% by 2050, amounting to a population of 6 billion (Kundu, Sietchiping and Kinyanjui, 2020). Urbanisation causes rapid increase in land-use and expansion of built-up areas. As urban areas expand, green spaces are replaced by human infrastructure, thereby creating environmental and health-related challenges (Zhang, 2016).

Green infrastructure (GI) is an umbrella concept, bringing together natural and semi-natural areas designed and managed to deliver a wide range of ecosystem services (ES) to solve challenges caused by urbanisation (Russo *et al.*, 2017). In densely populated urban areas, where space is invaluable, the abundance of 'green' can be increased by growing plants vertically, a concept known as Green Walls Systems (GWS). GWS involve all systems which enable the greening of a vertical surface. GWS can be subdivided into two main systems; Green Facades (GFs) and Living Walls Systems (LWS) (Manso and Castro-gomes, 2015) (Figure 1).

GFs are systems of climbing plants that grow up a wall, or a supporting system. The plants are rooted in the ground, or in containers at the base of the structure and climb upwards. Most climbing plants on GFs usually grow up to 6 meters high and take about 3-5 years to achieve full coverage (Chiquet, 2014; Jim, 2015). While GFs are considered a cheap solution of vertical greening, the number of plant species that can be used are limited.

Living wall systems (LWS) are self-contained and grow on panels or modules that are fixed to a vertical surface. In contrast, the plants are grown hydroponically, or in a soilless substrate and usually involves an irrigation- and nutrient-delivery system (Manso and Castro-gomes, 2015). This allows for more plant species, including shrubs, grasses and several perennials to grow in the limited space of the urban environment. The main restriction in plant choice is the final plant weight in relation to the support structure (Chiquet, 2014).

Benefits of GFs over LWS include low cost in terms of materials and maintenance, low environmental burden, while disadvantages include slow surface coverage, scattered growth, limited plant selection and surface deterioration. In contrast, LWS offer increased aesthetic potential due to uniform growth, higher plant diversity and the benefit of controlled irrigation and drainage allowing them to flourish year-round if managed well.

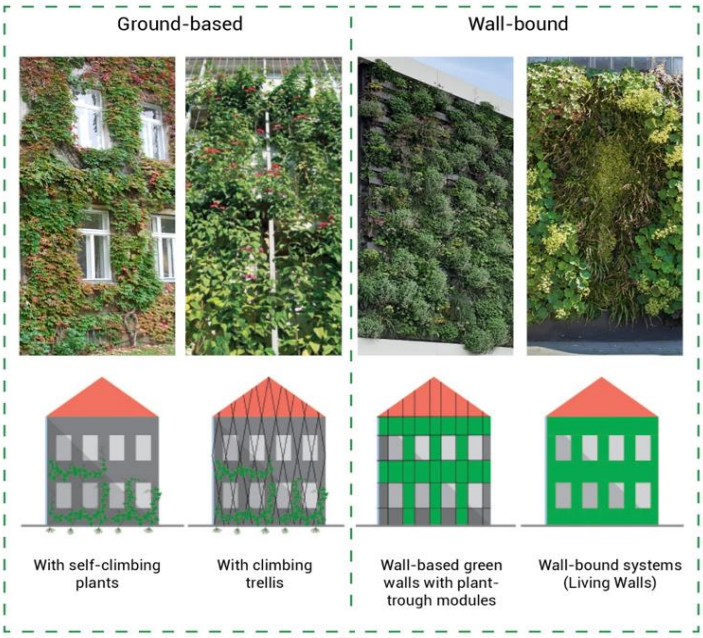

Figure 1. *Ground-Based Green Facades (GFs) and Wall Bound Living Wall Systems (LWS). Adapted from the European federation of Green Roofs & Walls.*

Without occupying space at street level, green walls can improve the urban environment by providing several ecosystem services (Manso and Castro-gomes, 2015). Regulating services provided by GWs include temperature reduction, reduction of the urban heat island effect and improving air quality, thereby having major positive benefits to human health (Pugh *et al.*, 2012; Coma *et al.*, 2017; Bakhshoodeh, Ocampo and Oldham, 2022). Green walls can provide important cultural services as well by providing psychological and social benefits to individuals and communities living in urban environments which are often disconnected from nature. The presence of vegetation has been shown to lower stress levels and has positive influence on anti-social behaviour (Marselle, Korn and Irvine, 2019). Collectively, these benefits translate into enormous economic-, social- and health-benefits.

While the provisioning, regulating and cultural services are well-known (Filazzola, Shrestha and Macivor, 2019), the supporting services provided by green walls are not well documented. In the ES-framework, supporting services enable all other services to function. The theory of biodiversity-ecosystem functioning (BEF) highlights the importance of biodiversity for maintaining ecosystem services (Cardinale *et al.*, 2012). It posits that the more diverse an ecosystem, the more productive and resilient it is likely to be. Different species and their traits contribute to different ecosystem functions such as air and water purification, nutrient cycling, pollination and habitat provisioning (Hooper *et al.*, 2012). Biodiversity is therefore essential to the supporting services, and by extension, indirectly influences the functionality of other ecosystem services as well. The lack of research on the supporting services of GI is concerning as it can cause misconceptions about the role that biodiversity plays in maintaining ES (Cardinale *et al.*, 2012). Without this understanding it is hard to design effective GI strategies that provide long-term benefits to urban areas.

Green walls can improve plant biodiversity by providing a unique vertical habitat for plants to grow, with each type of living wall providing their own microhabitat for specific plant species. The ecosystem services green walls provide are related to the floral diversity. For example, the mechanisms for providing cooling effects varied between species (Cameron, Taylor and Emmett, 2014) and variation in functional diversity of plants, such as size and shape can lead to a higher Leaf Area Index (LAI) and foliage thickness, which are important factors for the cooling capacity of green walls (Li, Wei and Li, 2019). These findings suggest, that plant diversity can increase the cooling capacity of green walls and their resilience to disturbances, as multiple cooling mechanism ensure cooling under different circumstances. Furthermore, a positive correlation was found between plant diversity and air pollution removal on green roofs and green walls (Vera, Viecco and Jorquera, 2021). These results complement other findings about agroecosystems that show that plant biodiversity has a positive influence on weed and pest suppression, pollinator diversity, ecosystem stability and soil-nutrient- and carbon accumulation (Isbell *et al.*, 2017). Together, these findings suggest that GWS, if designed in a well-balanced way have the potential to contribute to multiple ES categories concurrently.

Moreover, green walls can function as habitats for animals such as arthropods and birds (Mayrand, Clergeau and Vergnes, 2018). Arthropods constitute the most diverse and largest group of organisms and occupy a wide array of niches and microhabitats. Insects alone are estimated to account for 57% of all species living on our planet (Millenium Ecosystem Assessment, 2005). Arthropods provide ES such as pollination, biological pest control, nutrients cycling, decomposition and seed dispersal (Rossetti, 2020) and are therefore crucial to the productivity of many ecosystems (Chakravarthy & Sridhara, 2016). While the complex composition of the urban environment can have varied effects on the local species diversity Calviño et al., 2023, it has negatively impacted the diversity and abundance of terrestrial arthropods (Rossetti, 2020). It is suggested that this is primarily caused by urbanization-related processes such as the conversion of natural areas into impervious surfaces and habitat fragmentation. GI could be a possible measure to counteract the loss of arthropod abundance and biodiversity (Seibold *et al.*, 2019; Rossetti, 2020)

Multiple factors have been shown to influence arthropod abundance and diversity on GI. These can be roughly divided into three categories; GI-characteristics, plant-characteristics and landscape level characteristics.

GI-characteristics include surface area Fabián et al. (2021), height, orientation, age and maintenance of the GI-element (Forestry & Greening, 2018). Plant characteristics include plant diversity, vegetation coverage, number of flowering plants and local environmental factors such as temperature and humidity. On green roofs, arthropod abundance and richness are positively linked to vegetation cover (College and Griffith, 2011; Salman and Blaustein, 2018), plant species richness and flowering status (Braaker *et al.*, 2017; Brenneisen, 2017). The GI- and plant characteristics can be grouped into local-habitat characteristics.

Landscape level characteristics are considered an important factor in shaping arthropod communities in urban areas. Urban green spaces often consist of small, fragmented and isolated areas. Green roofs and green walls could act as stepping stones between larger urban and rural green spaces (Mayrand and Clergeau, 2018). Metacommunity ecology is an important framework for understanding how ecological processes such as dispersal and colonization operate across different spatial scales (Leibold, 2004). Metacommunities that are well-connected have greater resilience to random disturbance events (Beninde, Veith and Hochkirch, 2015). However, the extent to which green roofs and green walls contribute to functional connectivity and the conservation of biodiversity remains unclear (Ksiazek-Mikenas, Fant and Skogen, 2019; Louis-lucas *et al.*, 2022).

Although GWs are frequently suggested to have benefits for arthropod biodiversity, the actual effects have not been sufficiently quantified (Filazzola, Shrestha and Macivor, 2019). Most of these claims are made in review papers and papers that make use of conceptual frameworks rather than actual data-driven experiments. Furthermore, green walls are greatly underrepresented in GI-research related to biodiversity as most papers are focussed on other types of GI such as green roofs (Sutton, 2015). Most studies show contradictory results and lack a basic experimental framework, including appropriate controls and paired comparisons within the same regional characteristics (Filazzola, Shrestha and Macivor, 2019).

This research aims to investigate arthropod abundance, diversity and composition on green walls. The study will first compare Living Walls (LWs) and Green Facades (GFs) to their respective control counterparts and to each other. Subsequently, the investigation will focus on identifying factors such as wall-, plant-, and landscape-level characteristics that influence the abundance, diversity, and composition of arthropods. Finally, the study will aim to determine important ecological relationships between arthropods on living walls.

Materials & Methods

Study area and study design

For this study, green living wall (LW) systems were provided by Sempergreen®. The Sempergreen® living wall systems consist of a supporting carrier on which modular panels our mounted. These panels comprise of a felt system with pockets, containing rockwool fibres as substrate in which the plants are embedded (S. Figure 1). An irrigation and drainage system ensures that the plant can grow hydroponically by receiving a supply of water and nutrients (S. Figure 2).

Research sites are present within the Randstad, a conurbation in the Netherlands. It connects and consists of the four biggest cities; Amsterdam, Rotterdam, The Hague and Utrecht and many towns in between. Nine LWs were investigated; two in Utrecht, three in Woerden, two in Odijk and two in Hoofddorp. A complete description of each location can be found in the supplementary (S. Figure 3).

For each site we selected green facades (GF) within a radius of 200 meter of the corresponding LW. Criteria for choosing GFs were similar orientation and similar proximity to nearby green to eliminate as much environmental variability. For each LW- and GF-site, negative controls were selected. In the context of GI, a negative control is represented by the conventional counterparts and is used to evaluate the effect of GI- implementation. For this, bare walls or facades adjacent to the LW or GF were chosen to minimize the differences caused by environmental factors such as heat, light and humidity. Our study design was set up so that we could compare between 5 locations, and simultaneously make comparisons between LW, GF, and their control counterparts within one location (Figure X). In total, 9 Living Walls, 9 Control Walls, 5 Green Facades, and 5 Control Facades were examined between 5 and 15 June, 2023.

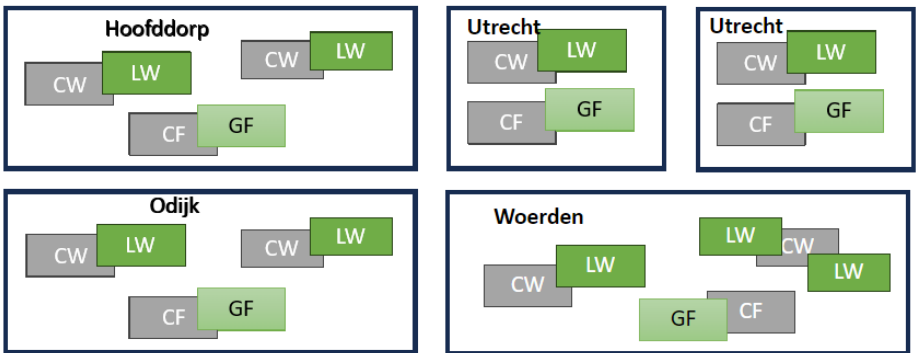

***Figure 2**. Experimental set up. LW = Living Walls, CW = Control Wall, GF = Green façade, C F= Control Façade.*

Data collection

For each wall we determined or measured characteristics such as the orientation, wall height (m), wall area (m2). Furthermore, categories were made for (wide vs tall; based on a high or low (ground-contact to area-ratio), ground level (yes or no) and the urban-rural gradient (urban/sub-urban/rural).

Next to the urban-rural gradient, the influence of the surrounding environment was further investigated by calculating the percentages of green-, blue- and grey infrastructure surrounding each site in ArcGIS Pro 3.1. We used the map LGN-2022 (https://lgn.nl/bestanden), a grid database presenting Dutch land use at a spatial resolution of 5m (Hazeu, 2021). It's 60 land use classes were grouped into these three categories. The coordinates of the wall sites were imported and polygons at the different radii (r=20m, 100m, 200m and 500m) were created. Zonal statistics was used to calculate the percentages for each of the categories. It's important to note that the map is from 2022 and the field work was done in 2023. Certain buildings were not yet depicted on the map for the locations 'Hoofddorp' and 'Marco Pololaan'. These polygons were therefore manually changed with current land-use data as these

differences would have caused a big discrepancy between our model and reality, especially at the smaller scale.

Sampling of arthropods was done in a period with very stable weather conditions without any rainfall. Average temperature and relative humidity (RH) for each location were acquired from the Royal Netherlands Meteorological Institute (KNMI) (http://www.knmi.nl/nederland-nu/klimatologie/daggegevens). The pan-trap method was used to collect arthropods (María Virginia Sánchez Domínguez et al. (2020). Pan traps capture a wide range of arthropods, including flying and crawling insects, are easy to set up and can be used to capture insects over a period of time, allowing for long-term monitoring and analysis. Furthermore, they are inexpensive and can be used in a variety of habitats, making them suitable for studies in different locations and ecosystems.
Pan-traps with yellow, blue and white plastic-bowls were filled up to 2/3rd with water and each receiving a droplet of soap. Traps were placed so that each three m2 of reachable area of the green wall was covered, without any overlap between any of the quadrants. The traps are removed after 48 hours. Arthropods were collected using tweezers and a cloth-filter method was used for extremely small arthropods. The arthropods were stored into falcon tubes with 96% ethanol solution for conservation (Sánchez Domínguez *et al.*, 2020). Specimens were identified to order and family level using a stereomicroscope (Zeiss XY). Dichotomous keys (S. Table. 1) and insect identification applications were used. Certain species will be used for DNA – metabarcoding for the Naturalis ARISE Project, but due to time constraints this will not be included in this research.

At each site a complete plant species list was made. Plant lists provided by Sempergreen were further complemented with species identified with the aid of available literature and plant identification applications. For the area (1,2m by 1,2m), surrounding each trap, total coverage, plant species richness, plant diversity, number of flowering species and native-to-non-native ratio were determined. Plant coverage was calculated using ImageJ with the thresholding method, whereby the original picture is turned into a greyscale- and binary image. For each quadrant lists were made with all plant species, containing information on their flowering and native/non-native status. To calculate the nativeness-ratio we divided the total number of native plants by the total number of plants present in each quadrant.
For calculating plant diversity, we used the Shannon-Wiener Index (see Table 1). For both of these calculations we did not use the actual number of plants, but instead we used a proxy by dividing each area into a 4x4 quadrants and measuring the number of quadrants in which that plant species occurs. This was done in order to take into account the size and coverage of the plant rather than just its occurrence.

Table 1. Formulas

Index	Formula	Interpretation
Shannon-Wiener-Index	$H = \sum[(pi) \times \ln(pi)]$ $with$ $pi = n/N$	The higher the index, the higher the diversity of the investigated community. The more species there are and the more evenly individuals are spread over species, the higher the index.
	(N) = Total number of individuals in a community (N) in the plant analysis context: The total number of quadrants (n) = number of individuals of a given species (n) in plant analysis context: number of quadrants each species occurs in	
Nativeness	$(R = \frac{Nnative}{(Nnative+Nnonnative)})$.	The higher ratio is to 1 the more native is the plant composition.
	$Nnative$ = number of quadrants in which native plants occur $Nnonnative$= number of quadrants in which non-native plants occur	

Statistical analysis

Statistical analysis was performed in R version 3.4.0 (R Development Core Team, 2023). Family by site matrices were created and the arthropod metrics; total abundance, family richness and arthropod diversity (Shannon-Index) were calculated for each trap.

Comparison of wall types

Two methods were used for the comparison of LWs and GFs to their control counterparts. First, averages were calculated for each response variable for the controls for each wall-site. For all traps on the LWs and GFs, the difference with their controls was calculated. One-sample t-tests were performed on these differences. The second method tested the differences between the response variables per site, by performing an independent samples t-test between the GW-traps and their controls for that site. For each arthropod metric, boxplots were made to visually support our observations. As sites WCV and WCS had a similar control wall, these sites were clustered for these tests.

To compare Living Walls and Green Facades per location, averages were calculated for locations with multiple LW-sites, leading to a single mean per location. Paired T-test were performed for all three response variables.

To further explore differences between wall types, the percentage of each order was calculated and visualized using stacked bar charts. Lastly, Beta diversity was calculated using the Bray-Curtis dissimilarity index (vegan package). Beta-Diversity is a measure used to compare how much the composition differs between sites. To visualize the differences in arthropod community composition between sites or groups, Principal Coordinates Analysis (PCoA) was performed on the Bray-Curtis dissimilarity matrix. The significance of the observed differences in beta diversity was tested using permutational multivariate analysis of variance (PERMANOVA) (Adonis R package).

Influencing Factors

The second aim of this research was to investigate which factors explain patterns in the arthropod metrics and arthropod composition. The explanatory variables can be divided into three categories; wall characteristics (height, area, wide/tall, ground level and age), plant characteristics (plant species richness, plant diversity, number of flowering species, total coverage, and nativeness ratio) and landscape-level characteristics (green/grey/blue ratio's and rural/urban gradient). The wall and plant-characteristics are clustered together as local-habitat characteristics.

Linear Models

First, an Exploratory Data Analysis (EDA) was performed. For all variables and arthropod metrics, the assumptions of linearity, homoscedasticity and normality of residuals were tested using diagnostics plots. This exploration resulted in the log-transformation of arthropod abundance and the square root transformation of family-richness in order meet these assumptions. Univariate analysis was performed to examine the influence of variables in isolation. Next, multivariate analysis was performed to explore relationships and patterns among multiple variables within each category.

Variable selection was performed based on the recommendations of (Heinze and Dunkler, 2018). Within each cluster, the Variance Inflation Factors (VIFs) were calculated to exclude highly correlated variables (VIF > 5). Next, a stepwise model selection by Akaike Information Criterion (AIC) was used with both forward and backward selection to ensure robustness of the model.

For the plant- and wall-variables, linear mixed effects models (nlme- and lme4-package) were used to account for random effects caused by our locations and sites within those locations. For the habitat characteristics a regular Linear Model was used as these variables are inherently linked to the location and therefore taking out the random effects caused by the locations would not be appropriate in this case. The use of different model types meant that combining all variables into one model was not

possible. The plant- and wall-variables were therefore clustered into local-habitat characteristics, while analysing the landscape variables independently.

CCA

A Canonical Correspondence Analysis (CCA) was used to explore the influence of the environmental variables on arthropod order composition. CCA model selections (vegan package (ordistep)) were performed to identify and retain variables that significantly contributed to explaining order composition. Within each category, VIFs were calculated to exclude highly correlated variables. CCA plots were made to visualize relationships between the arthropods data and the environmental variables. The arrow-length of an environmental gradient indicates the strength of its correlation with the arthropod data. The distance of an arthropod point from the origin (0,0) indicates the strength of its association with the environmental gradients.

Ecological relationships

CCA was used to explore the relationships between arthropod families and plant species on Living Walls. Arthropod families and plant species below an occurrence threshold of 10 were excluded to improve the reliability of the analysis. Next, a correlation analysis was performed to assess the relationships between arthropod families. Families with a count lower than five were removed to improve robustness and to reduce the impact of rare families. Spearman's Rank Correlation was used as this is a non-parametric method suitable for non-normal and non-linear data. Lastly, observations during field work and microscopy analysis were used to inform about ecological relationships.

Results

Wall type comparison

Total individuals, species, families, and orders

In total, 3268 specimens of arthropods were collected and identified of which 2000 from LWs and 501 from GFs. These arthropods belong to 125 families and 21 orders (S. Tables 1 & 2). Not all arthropods could be identified to genus or species level due to challenges in the determination process. However, identification still led to the finding of 170 unique genera and 149 unique species.

Living Walls compared to Control Walls

Arthropod abundance, family richness and arthropod diversity were compared between LWs and CWs with two methods (see methodology). The one-sample t-test resulted in a significant increase in arthropod abundance (t (42) = 3.08, p = [0.0036]) on LWs (mean difference = 17.85, SD = 37,95). No difference was found for family richness. Interestingly, a significant higher arthropod diversity (t (42) = -3.85, p = 0.0004) was found on CWs compared to LWs (mean difference = -0,29, SD = 0.5).

The second methods compared these variables per site. Arthropod abundance was higher on 7 of the 8 LWs (Figure 3), while arthropod diversity was found to be higher on 7 out of the 8 CWs (Figure 5). No trends were observed for family richness (Figure 4). These findings reflect the results of the first method. Another interesting observation is the large variation in arthropod abundance among some of the LWs, even within the same location such as (HAG vs HAO) and (OSL vs OSR) (Figure 3).

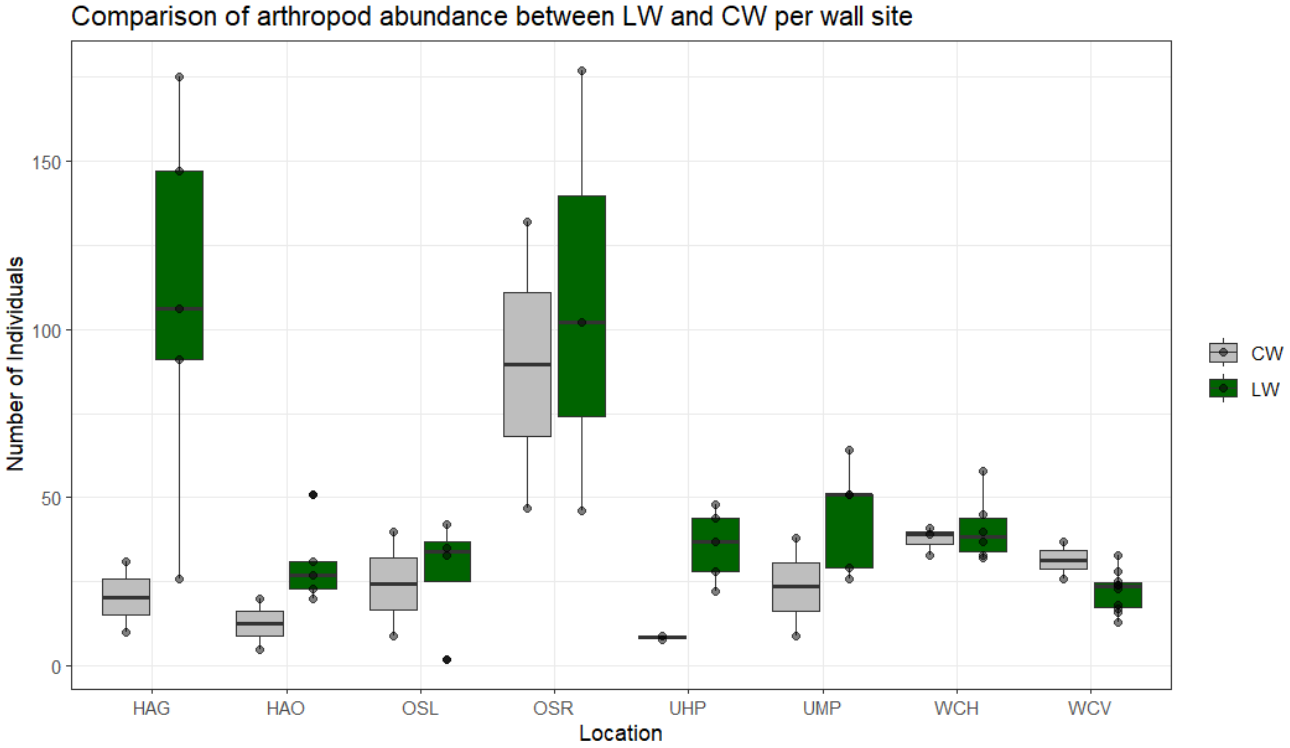

Figure 3. *Boxplots showing the arthropod abundance per site for both LWs and CWs. Arthropod abundance was higher for 7 out of 8 living walls. Significant differences were found for only two sites; HAG (p = 0.024) and UHP (p = 0.0046).*

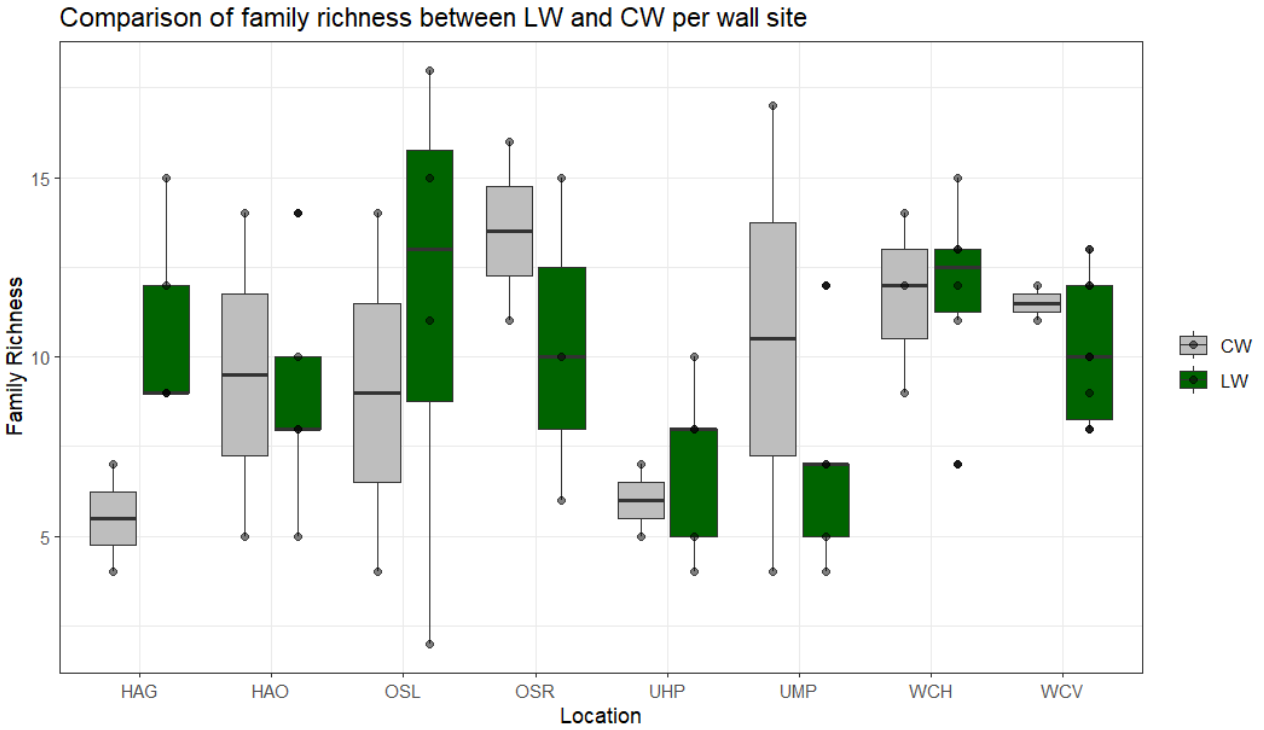

Figure 4. *Boxplots showing the family richness per site for both LWs and CWs. No significant differences were found.*

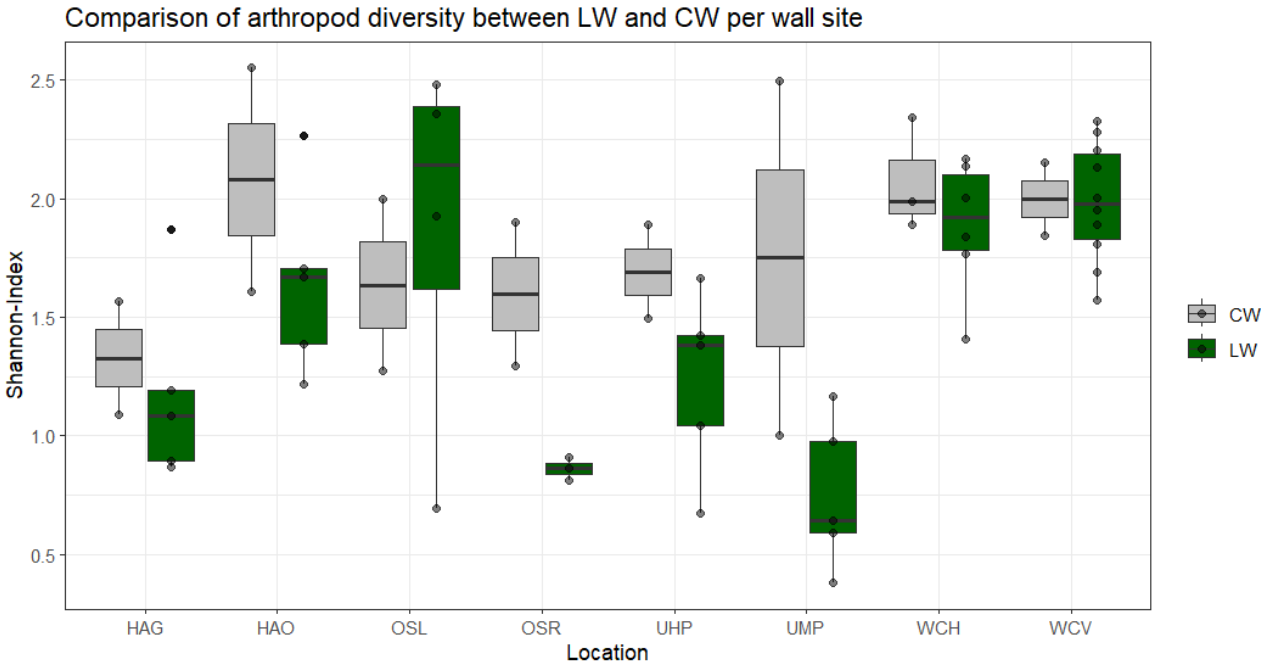

Figure 5. *Boxplots showing the arthropod diversity per site for both LWs and CWs. For 7 out of 8 sites the arthropod diversity was lower, however no significant differences were found.*

Green Facades vs Control Facades

Arthropod abundance, family richness and arthropod diversity were compared between GFs and CFs. One sample t-tests revealed no significant difference for arthropod abundance, family richness and diversity. The second analysis, which assesses these variables at individual sites, did not reveal discernible trend or consistent patterns across the sites (Figures 6-8).

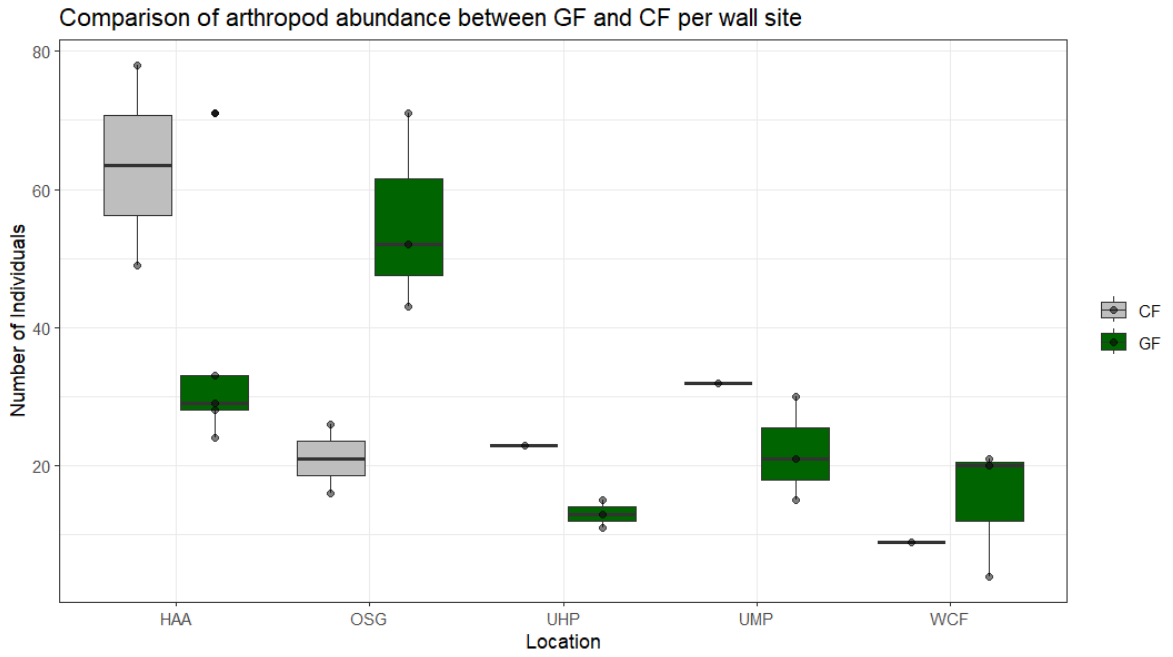

Figure 6. *Boxplots showing the arthropod abundance per site for both GFs and CFs. A significant difference was found for site OSG (p = 0.039). T-tests could not be performed for UHP, UMP and WCF since these had just one CF measurement.*

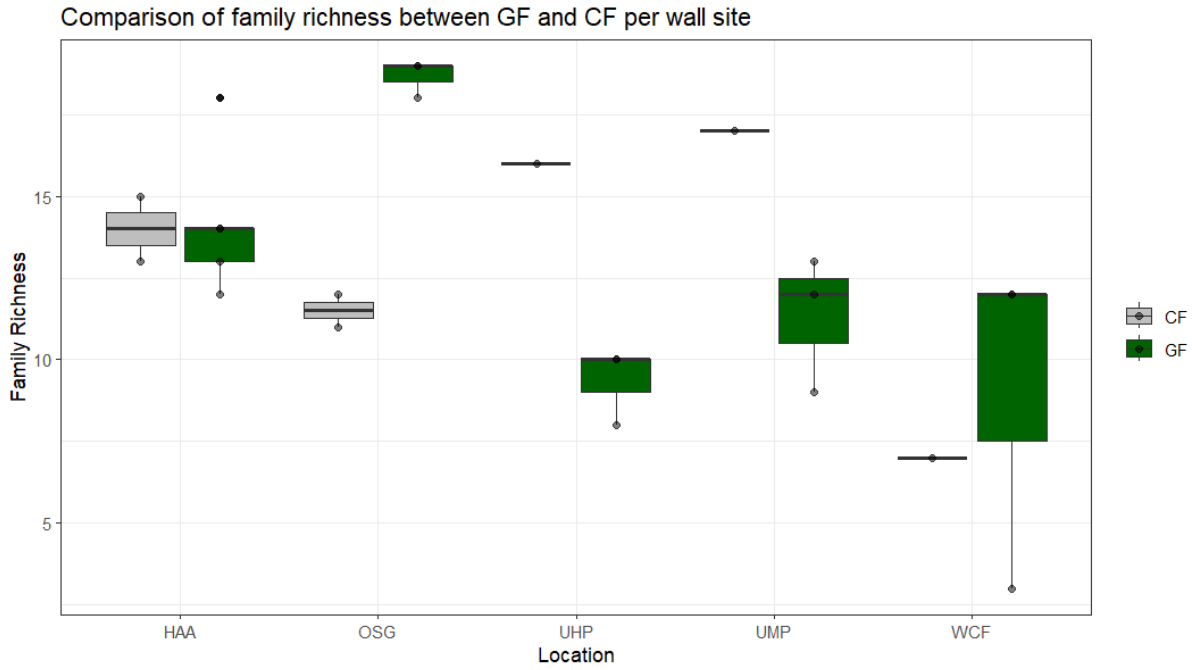

Figure 7. *Boxplots showing family richness per site for both GFs and CFs. A significant difference was found for site OSG (p = 0.008). T-tests could not be performed for UHP, UMP and WCF since these had just one CF measurement.*

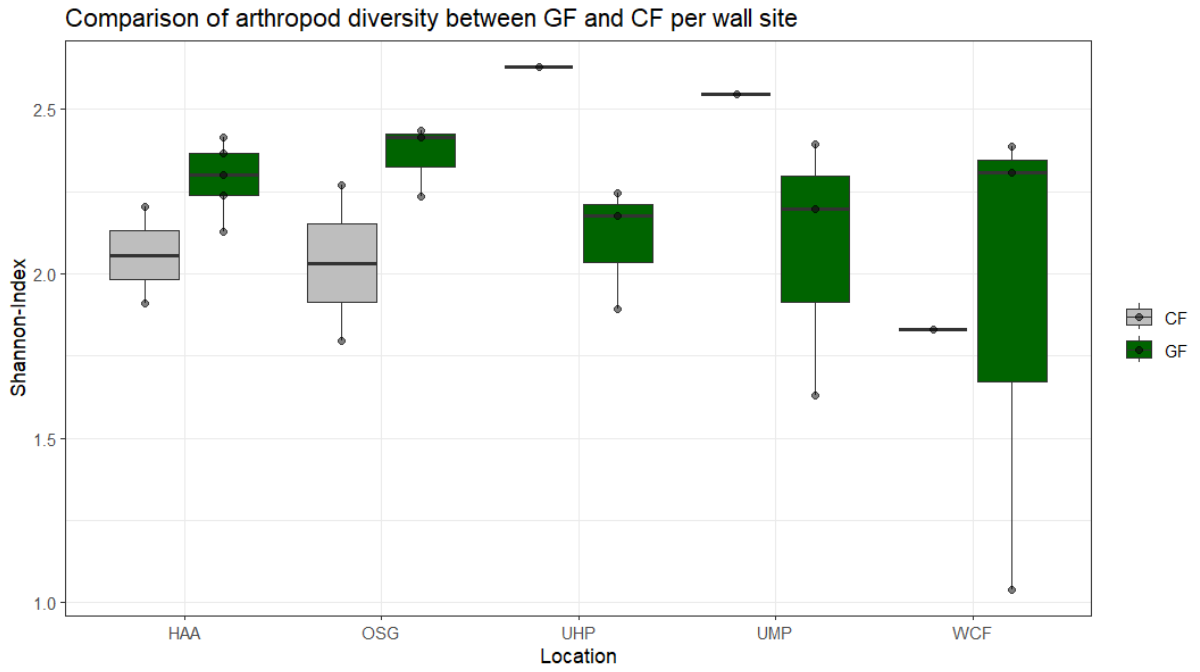

Figure 8. *Boxplots showing arthropod diversity per site for both GFs and CFs. No significant differences were found. T-tests could not be performed for UHP, UMP and WCF since these had just one CF measurement.*

Living Walls vs Green Facades

Next, we compared the Living Walls and Green Facades in terms of arthropod abundance (Figure 9), family richness (Figure 10) and diversity (Figure 11). A paired t-test revealed a significant difference in arthropod abundance for LWs (M=49,27, SD = 18,79) and GFs (M=28,47, SD = 17.73) with conditions (t(4) = 5.72, p=0.0046) with a mean difference of (20.80) (Figure 9).

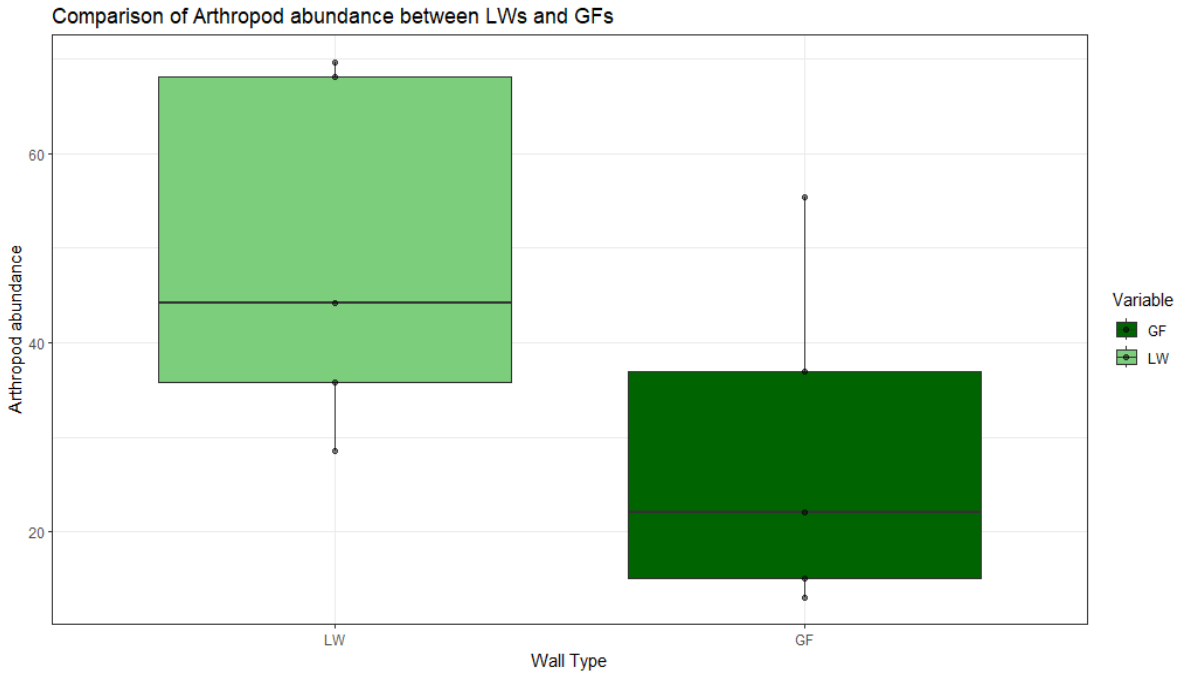

Figure 9*. Boxplot showing the difference in arthropod abundance between LWs and GFs.*

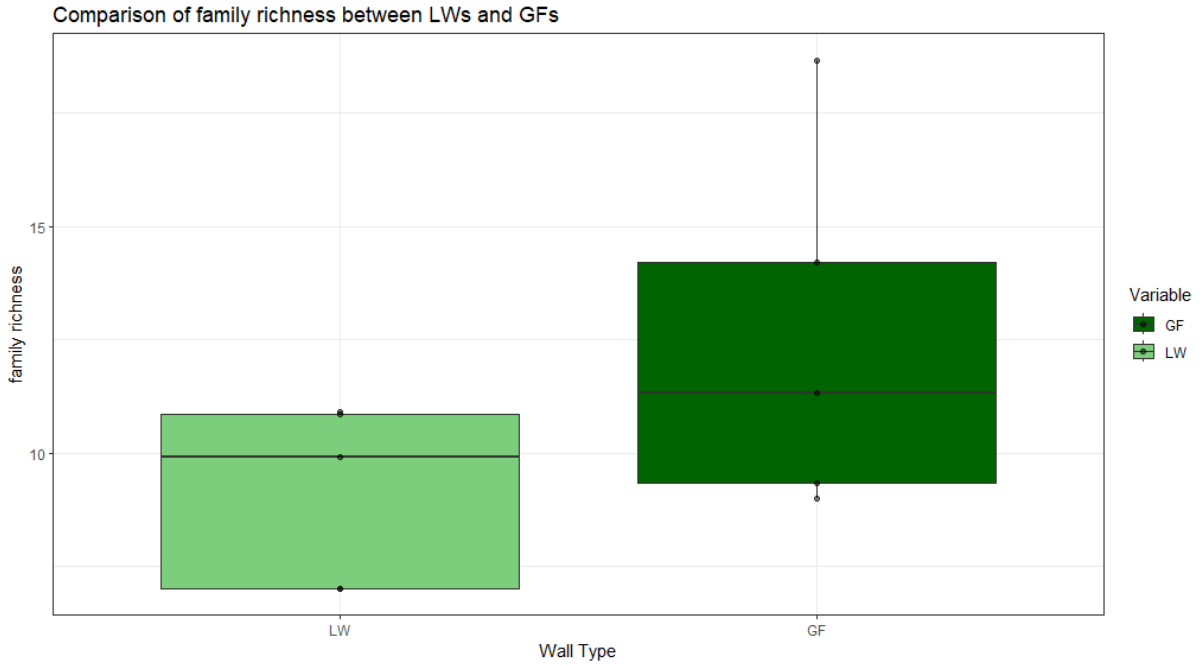

Figure 10. *Boxplot showing the difference in family richness between LWs and GFs.*

Paired t-test revealed no significant difference in species richness for LWs (M=9,14, SD = 1.99) and GFs (M=12.50, SD = 4.02) with conditions (t (4) =-2.14, p=0.096 and mean difference = -3.37). Arthropod diversity was found to be significantly higher on GFs (M=2.15, SD = 0.18) compared to LWs (M=1.34, SD = 0.43), with conditions (t (4) = -3.5, p=0.025 and mean difference = -0.80).

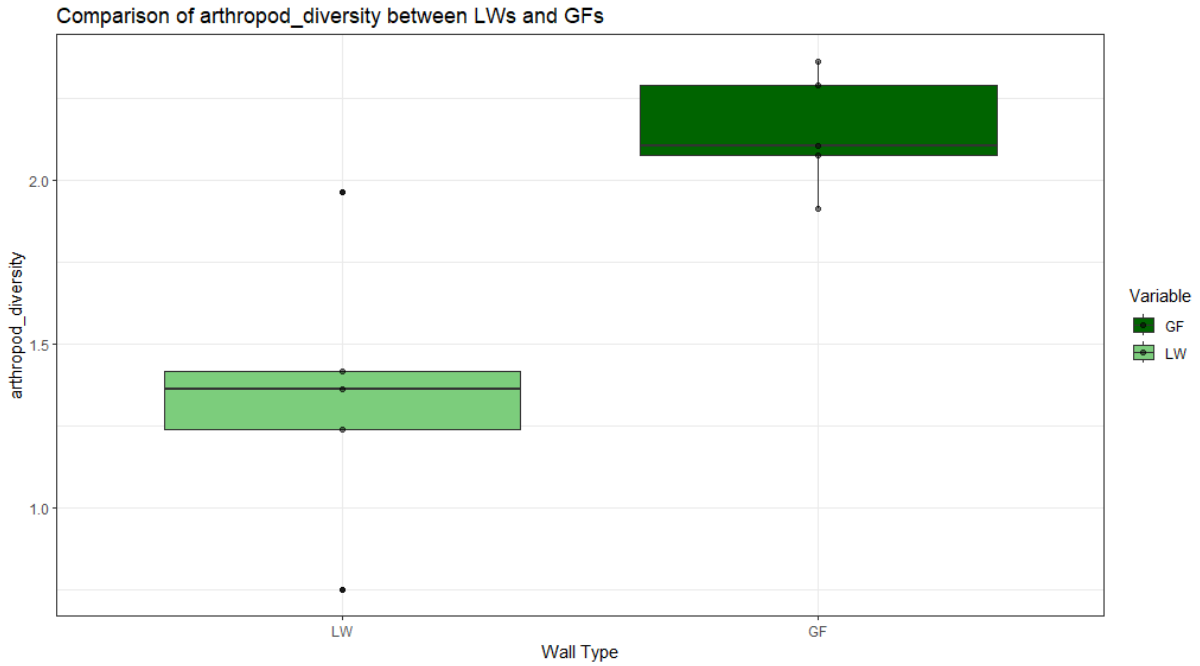

Figure 11. *Boxplot showing the difference in arthropod diversity between LWs and GFs.*

In general, when comparing the wall types, an inverse relationship was observed between the variables arthropod abundance and arthropod diversity. This relationship suggests that walls with higher arthropod abundance might have a dominance of a few species, leading to a less even distribution of species within the community, resulting in a lower diversity index.

Arthropod composition

The order composition of LWs and GFs, and their control counterparts, were compared and visualized using stacked bar charts (Figure 12). The overall distribution of arthropod orders shares considerable similarity across the wall types, with only slight variation observed in the relative abundances of Aranea (spiders), Coleoptera (beetles), Hemiptera (true bugs) and Hymenoptera (wasps, bees and ants).

However, for some orders there are noticeable differences in the relative abundances. For example, collembola (springtails) represent 43.7% on LWs, 20.4% on CWs, while only accounting for 1.9% for both GFs and CFs. In contrast, Diptera (flies and mosquitos) are more prevalent on GFs, CFs and CWs, representing 54.5%, 53.2% and 45.7% respectively, while only representing 11.8% on LWs.

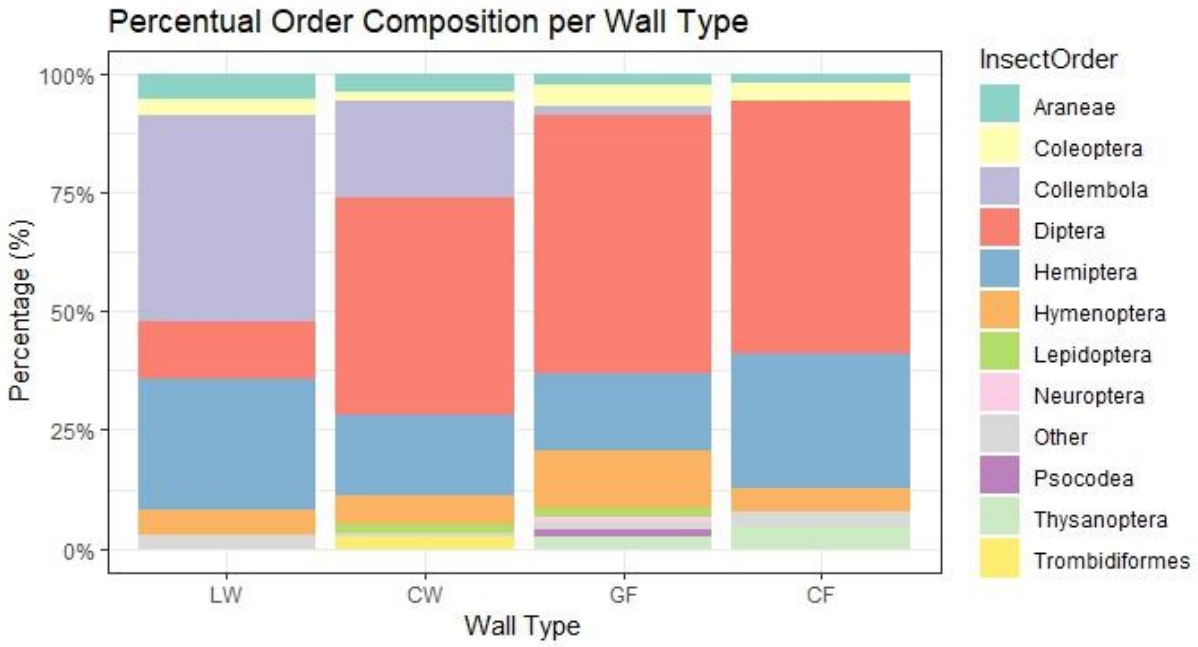

Figure 12. *Stacked Bar chart presenting the order composition of the four wall types. Orders representing <1% for that wall type were grouped into the category 'other'. The complete order list can be found in supplementary table X.*

To further analyse the differences in composition between the wall types, beta-diversity serves as a valuable tool to assess the extent to which community compositions differ among sites. Figure 13 illustrates the dissimilarity of arthropod order composition. The closer the samples are to each other in space, the more similar their compositions. The PC1- and PC2-axis explain 30.1% and 18.4% of the variation, respectively. The distinct clustering of LW samples highlights their unique community composition compared to the other wall-types. Conversely, the overlapping confidence intervals of GFs, CFs and CWs suggests similarities in their community composition. PERMANOVA results substantiate the significant influence of wall type on community structure ($F = 7.2387$, $R^2 = 0.20738$, $p = 0.001$). This indicates that 20.74% of the variation in community composition can be explained by the grouping factor; type of wall.

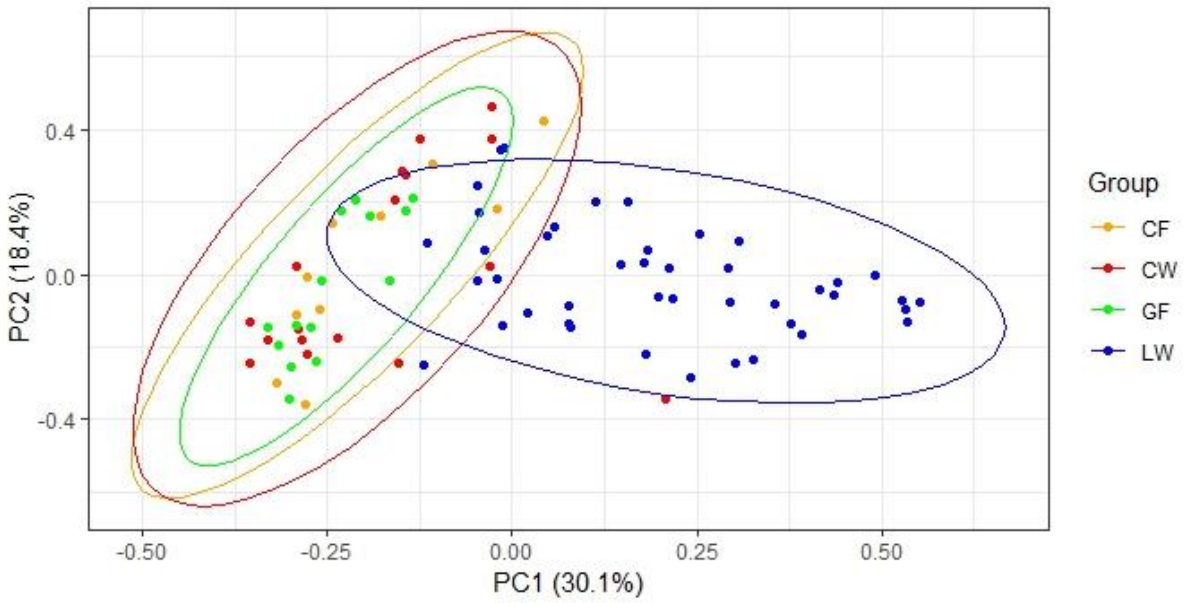

***Figure 13**: Principal coordinate analysis (PCoA) plot showing the composition differences (Bray-Curtis distances) of arthropod communities between LWs, GFs, CWs and CFs.* Ellipses represent the 95% confidence interval around the centroid of each group. *Each point on the plot represents a sample from the dataset. The proximity of points to each other indicates the level of similarity between those samples.*

Influencing Factors

Influencing factors on arthropod abundance and diversity

Living Walls

Univariate analysis showed that local habitat characteristics (wall & plant variables) did not have a significant influence on both arthropod abundance and family richness (S. Tables 3 & 4). Arthropod diversity was only significantly influenced by the variable 'number of flowering species' (S. Table 5).

Univariate analysis showed that landscape-level characteristics significantly predict family richness and arthropod diversity, while none of these factors significantly influenced arthropod abundance (S. tables 3-5). Family richness on LWs was found to be positively influenced by the variables blue_100, blue_200 and green_200, while grey_200 and grey_500 negatively impacted family richness on LWs (S. Table 4). Arthropod diversity was found to be positively influenced by the variables green_20, green_100 and blue_20, blue_100 and blue_200, while grey_20 and grey_100 negatively impacted arthropod diversity on LWs (S. Table 5).

Multivariate analysis and model selection resulted in the following models:

Response variable	Explanatory variable(s)	Estimate	Std. Error	t value	F (1, 41) statistic	p-value	R-squared	Model type
Arthropod Abundance	Blue 20	-0.038	0.02	-0.188	3.53	0.067	7.4%	lm
Family Richness	Blue 200	0.21	0.45	-2.81	7.90	0.008**	16.2%	lm
Arthropod Diversity	Number of flowering species	0.278	0.072	3.854	5.86	0.00005***	29.9%	lme
Arthropod Diversity	Blue_20	0.047	0.014	3.365	12.92	0.0017**	39.2%	lm

Table 2. *Multivariate models for influencing factors on Living Walls.*

Blue_200 emerges as a significant predictor for family richness, exerting a positive influence that accounts for 16,2% of the variation in family richness. Arthropod diversity is predominantly shaped by two key factors: the 'number of flowering species' and the 'blue_20' gradient, accounting for 29.9% and 39.2% of the variability, respectively. While it's important to note that the actual R-squared values should be adjusted, given that the models for local and landscape variables were developed independently, these variables emerge as significant predictors for arthropod diversity.

Green Facades:

For Green Facades, the explanatory variables from the category wall characteristics had very low variation and some were not measurable. Therefore, it was decided to exclude these variables from our univariate- and multivariate analysis of green facades.

Univariate analysis showed that all plant characteristics did not have a significant influence on arthropod abundance, family richness and arthropod diversity (S. Tables 6-8).
Univariate analysis showed that landscape-level characteristics significantly predict arthropod abundance and family richness, while none of these factors significantly influenced arthropod diversity (S. Tables 6-8). Both arthropod abundance and family richness were found to be positively influenced by the variables green_200 and green_500, while grey_200 and grey_500 negatively impacted these arthropod metrics (S. Tables 6 & 7).

Multivariate analysis resulted in the following models:

Response variable	Explanatory variable(s)	Estimate	Std. Error	t value	F (1, 15) statistic	p-value	R-squared	Model type
Arthropod Abundance	Green_500	0.02	0.006	3.347	11.2	0.004***	42.8%	lm
Family Richness	Green_500	0.017	0.005	3.05	9.32	0.008**	38.3%	lm

Table 3. Multivariate models of influencing factors on Green Facades

The 'Green_500' gradient emerges as the best predictor for both arthropod abundance and family richness on green facades, explaining 42.8% and 38.8% of the variation, respectively. Nearby greenery thus positively influences both of these factors significantly.

Overall, the findings from both univariate and multivariate analysis of LWs and GFs, suggest that landscape level characteristics outperform local habitat characteristics as predictors for abundance, richness and diversity of arthropods. With the exception of 'the number of flowering species' which significantly influenced arthropod diversity.

Influencing factors on arthropod composition

Next, the influence of local habitat- and landscape level characteristics on arthropod composition were investigated. This was done solely for LWs, as GFs had a lower amount of datapoints and variability of certain variables. For this purpose, a Canonical Correspondence Analysis (CCA) can be used to explore the relationships between arthropod order abundance and environmental variables.

Plant Characteristics

CCA model selection for the plant variables resulted in three variables; number of flowering species (p = 0.01**), total coverage (p = 0.035*) and nativeness ratio (p = 0.06.), that impacted arthropod order composition.

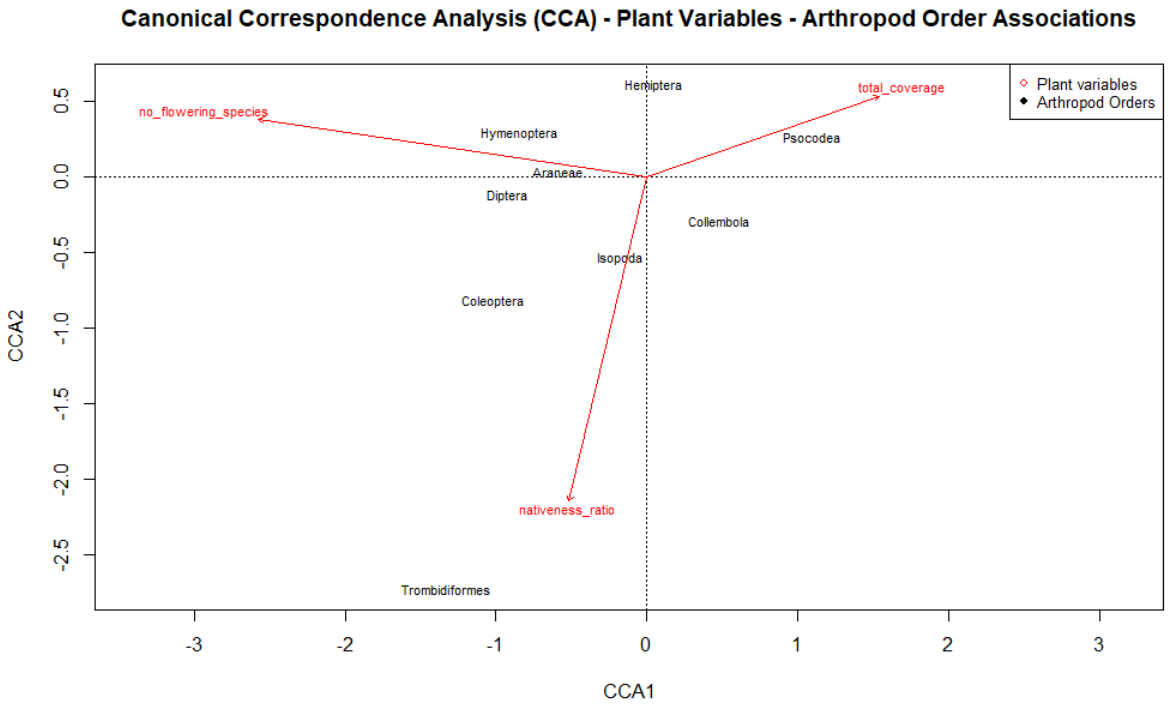

***Figure 14**. CCA of the plant variables. Included variables; plant species richness, plant diversity, number of flowering species, total coverage and the nativeness ratio.*

The environmental variables included in this model accounted for 19.08% (inertia = 0.1838) of the variance (F (3) = 3.07, p = 0.002**). The CCA1- and CCA2-axis explain 53.89% and 26.6% of the plant variable – arthropod order relationships, respectively (Figure 14).

Specifically, the number of flowering species exhibited a positive association with several arthropod orders, including Hymenoptera, Coleoptera, and Diptera. The nativeness ratio demonstrated a positive correlation with Trombidiformes, Coleoptera and Isopoda, but a negative association with Hemiptera. Lastly, Total Coverage was positively associated with the presence of Psocodea.

Wall characteristics

CCA Model selection for the wall characteristics resulted in two wall variables; ground level (p = 0.055.) and wall area (p = 0.005**), that shaped arthropod order composition.

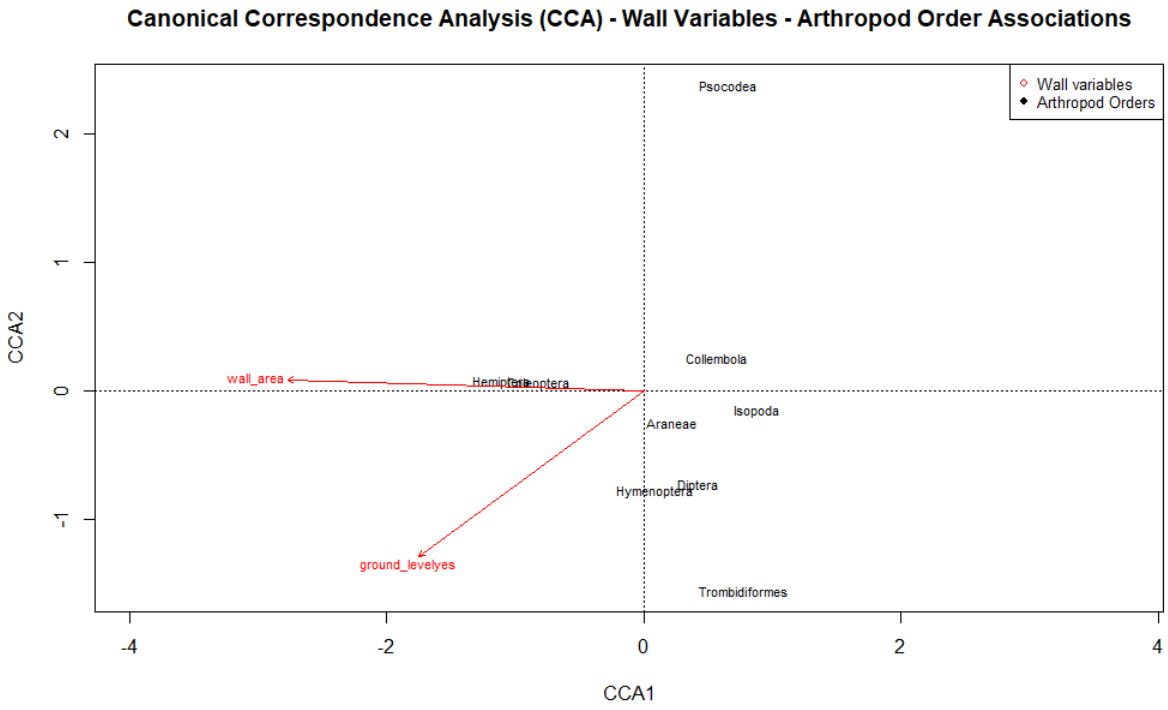

Figure 15. *CCA of the wall variables. Included variables; wall area, orientation, wide or tall, wall age and ground level.*

The environmental variables included in this CCA model accounted for 34.89% (inertia = 0.3361) of the variance in arthropod orders (F (2) = 10.72, p < 0.001***). The first two canonical axes (CCA1 and CCA2 explain 30.99% and 3.9% of the variance in within this model, respectively (Figure 15).

The arthropod orders, Hemiptera and Coleoptera are positively associated with a bigger wall area while most other arthropod order do not show a clear association with this variable. The variable 'ground level' does not have significant influence (p = 0.055) and the CCA2 axis explains very little of the observed variance. This makes it difficult to interpret the results for this variable.

Another factor of interest is the age of the green wall. For this, a case-study was done on the two LWs in Hoofddorp (HAG and HAO). This site was chosen as they share the exact same wall- and landscape-level characteristics and the wall-designs allowed for multiple independent replicates to be measured (S. Figure 3). This means that these walls differ only in terms of their age and plant composition, with HAG being 11-, and HAO being 3 months old.

A comparison of the arthropod communities between the two walls was made (Figure 16). On the LWs of HAG 545 individuals were found, compared to just 152 individuals on HAO. A big difference was found for the relative abundance of Hemiptera which have a higher relative occurrence on HAG with 54.9% compared to just 16.5% on HAO. Another order that shows large relative and absolute differences is Coleoptera which has a relative abundance of 1.2% on HAG and 21.7% on HAO.

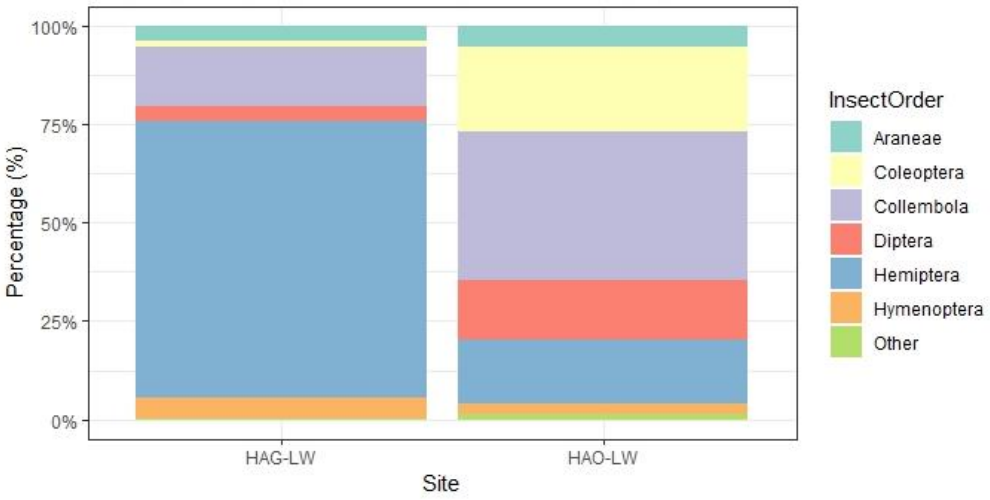

Figure 16. Stacked Bar chart presenting the arthropod order composition of the sites HAG and HAO.

Dissimilarity of the arthropod order composition was further substantiated by the PCoA which showed significant differences between the two groups of arthropod communities ($F = 8.21$, $p = 0.008$) (S. Table 6). The HAO-LW group was also more tightly clustered together compared to the HAG-LW group, indicating more heterogeneity within the HAG-LW community structure.

Landscape-level Characteristics

CCA's were performed for all four radii of the Green/Grey/Blue (GGB)-infrastructure separately as these environmental variables could not be combined in one model due to multicollinearity issues. For each of the GGB-models only the green- and blue-variables were used as green and grey percentages have a strong inverse relationship and high multicollinearity as a result. In the CCA plots (S. Figures 8-11), the grey-arrow could be imagined to point in the opposite direction of green in the biplot.

The following table was made using visual inspection of each plot (S. Figures 8-11) and by analysing the summary statistics. This was done in order to discover trends with regards to blue or green infrastructure across multiple radii.

Orders	Blue20	Blue100	Blue200	Blue500	Green20	Green100	Green200	Green500
Coleoptera	0	+	+	-	+	-	+	+
Hemiptera	0	+	+	-	+	-	-	+
Areneae	+	+	0	+	+	0	0	-
Hymenoptera	+	+	+	+	+	+	+	+
Diptera	+	+	+	+	0	+	+	+
Isopoda	+	-	-	+	0	+	-	-
Trombidiformes	+	+	+	+	0	+	-	-
Collembola	-	-	-	0	-	+	+	-
Psocodae	-	-	-	-	-	0	-	-

Table 4. Interpretation of the CCA plot (Figures S. 1-4). Positive or negative relationships of the arthropod order with the variable are signified by "+" or " –". No clear association as "0". The colour coding is based on the strength of this relationship and is influenced by the explanatory power of each axis and the alignment of the variables with those axes.

Across all radii, blue infrastructure has a positive association with the orders; Araneae, Hymenoptera, Diptera and Trombidiformes, while negative associations were found with the occurrence of Collembola and Psocodae (Table 4). Green infrastructure is correlated with higher numbers of Hymenoptera and lower numbers of Psocodae across all measured distances from the site (Table 4).

For some other arthropod orders, associations were found when solely looking at the smaller or larger scale landscape variables, as the direction of the association of certain arthropods varied between these scales. At the larger scale (200m & 500m), green infrastructure is positively correlated with the abundance of Coleoptera and Diptera, but it is negatively correlated with Isopoda, Trombidiformes, and Psocodae (Table 4).

Another method used to understand the influence of the broader landscape on arthropod communities was the use of CCA by grouping the walls into the category rural, sub-urban and urban. Figure 17 illustrates the dissimilarity of arthropod order composition of the groups rural, sub-urban and urban. The PC1- and PC2-axis explain 39.6% and 19.9% of the variation, respectively.

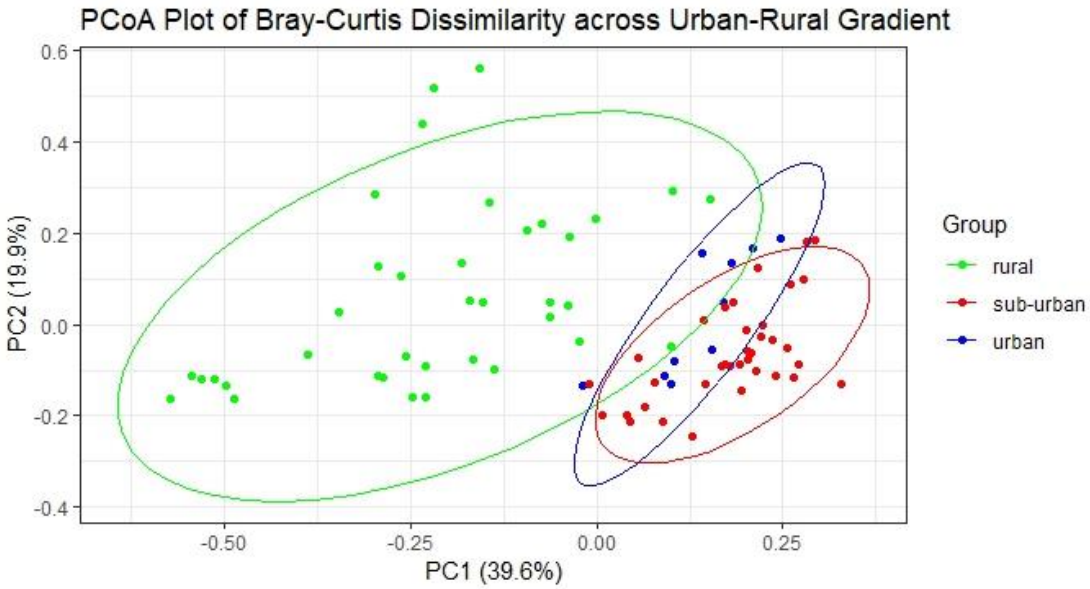

Figure 17. Principal coordinate analysis (PCoA) plots showing the composition differences (Bray-Curtis distances) of arthropod orders on all wall types along the urban, sub-urban and rural gradient. Ellipses represent the 95% confidence interval around the centroid of each group. *The proximity of points to each other indicates the level of similarity between those samples.*

The distinct clustering of rural samples highlights their unique community composition compared to the other to the urban and sub-urban areas. Conversely, the confidence intervals of the urban and sub-urban show slight overlap suggesting more similarities between community composition. PERMANOVA results substantiate the significant influence of the rural-urban gradient on community structure ($F = 20.503$, $R^2 = 0.3361$, $p = 0.001$). This indicates that 33.6% of the variation in community composition can be explained by the urban-rural gradient.

Ecological Relationships on Living Walls

In order to discover ecological relationships on living walls, two methods were used. First a CCA was performed to discover relationships between individual plant species and arthropod families (figure 18). The environmental variables included in this model accounted for 52.35% (inertia = 1.0036) of the variance (F (7) = 3.05, p = 0.001***). The CCA1- and CCA2-axis explain 43.22% and 17.82% of the arthropod-plant relationships, respectively.

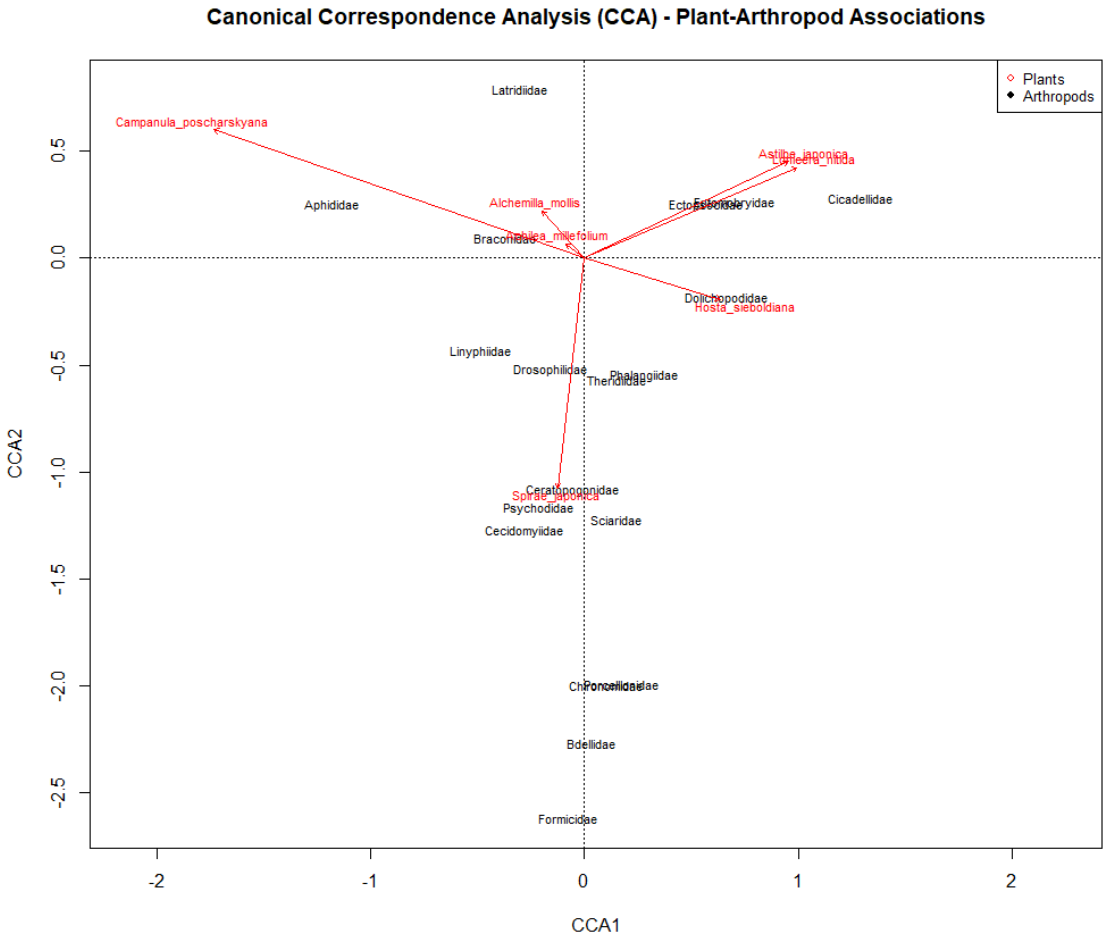

Figure 18. CCA of plant species and arthropod families.

Multiple association between plant species and arthropod families have been found. *Campanula Porscharskyana* shows a strong association with Aphididae (hemiptera, true bugs). *Lonicera nitida* and *Astilbe japonica* were both associated with Cicadelidae (hemiptera, true bugs) and Entomobryidae (collembola, springtails). Lastly, *Spirae japonica* was found to be associated Formicidae (ants), Porcellonidae (isopoda) and Bdellidae (trombidiformes, mites) and many Nematocera (mosquito) families; Chironomidae, Cecidomyiidae, Psychodiae, Sciaridae and Ceratopogonidae.

Co-occurrence of Arthropod Families

The next method was designed to make a targeted search for ecological relationships between arthropod families. The following figure was made by calculating the co-occurrence of arthropod families. Co-occurrence is defined here as the simultaneous presence of two species within a single sample. A higher correlation indicated a more frequent co-occurrence of these species. Figure 19 will be used as starting point of the ecological relationships which can be found in the discussion.

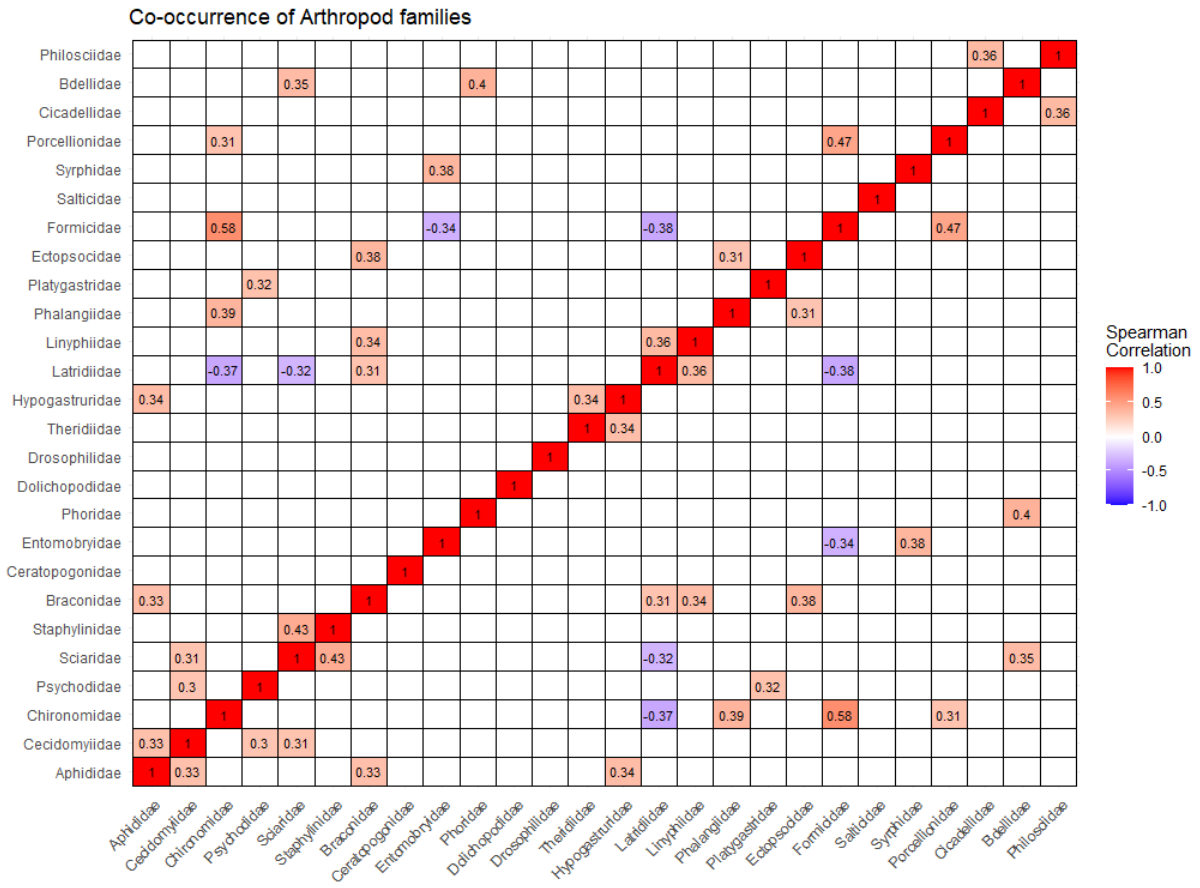

Figure 19. A heatmap showing correlations of co-occurrence of arthropod families. Each cell represents the strength and direction of the correlation between two families. Non-significant correlations ($p > 0.05$) were filtered out and marked as white.

Discussion

Wall Type Comparison

The first objective of this study was to validate if LWs and GFs improve arthropod abundance and diversity compared to their control counterparts.

LWs vs CWs

LWs were shown to significantly improve arthropod abundance, which was found to be higher at 7 of the 8 sites (Figure 3). Interestingly, no significant difference was found for family richness (Figure 4), and arthropod diversity was even found to be significantly lower on LWs compared to CWs (Figure 5). The difference in abundance can be mostly explained by the dominance of a single arthropod family; Entomobryidae (slender springtails), which comprised 43.6% of all individuals collected from LWs (S. Table 2). The dominance of Entomobryidae also explains the lower arthropod diversity on LW as the Shannon Diversity Index lowers with an uneven spread of individuals over families. When Entomobryidae were excluded from the analysis, the significant differences in both abundance and diversity between LWs and CWs vanished (S. Figure 4 & 5), suggesting a substantial influence of this single family on the overall results.

GFs vs CFs

The comparison of GFs and CFs resulted in no significant differences for arthropod abundance, family richness and diversity. Comparison of each site individually also resulted in no clear trends. The limited sample size for GFs and CFs may have affected the reliability of these results. This highlights the need for a robust experimental design in ecological research, especially when dealing with a limited number of sites.

LWs vs GFs

Comparison of LWs to GFs showed that LWs have a significant higher arthropod abundance while GFs have a significantly higher arthropod diversity. But again, the significant difference for both variables disappeared when not taking into count the Entomobryidae.

Altogether, these results do not support the hypothesis that LWs and GFs improve arthropod abundance, species richness and diversity compared to their control counterparts. This outcome contradicts field observations, which suggested more arthropods on LWs and GFs than on bare walls. Our results diverge from those of (Madre *et al.*, 2015) and (Chiquet, 2014) which both concluded that vertical greening had a strong positive effect on arthropod abundance. The discrepancy between our findings and these previous studies, as well as our field observations, is most likely explained by our sampling method. The pan-trap method collects arthropods based on the visual attraction properties. Such active sampling methods are inclined to attract arthropods that are mobile and active in the wider environment, rather than those specifically inhabiting the immediate vicinity of the trap. Moreover, these traps are more conspicuous against the bare control walls than on vegetated surfaces, possible skewing the results. This hypothesis is supported by our finding that LWs, which had the highest foliage cover of all wall types, were found to consistently have the lowest relative abundance of the mobile orders; Diptera, Hymenoptera, Lepidoptera and Neuroptera (Figure 12), for which the main mode of locomotion is flying.

Passive sampling methods such as leaf collection and suction traps, or simply observational sampling, may be preferred for future studies, although each having their own limitations (Yi *et al.*, 2012). Our findings suggests that pan-traps may not be the most effective method for assessing the impact of vertical greening on arthropod abundance and diversity. Future research should consider using a combination of sampling techniques to mitigate biases associated with individual methods.

Comparison of arthropod composition among wall types

Next, the wall types were compared in terms of arthropod composition. The overall distribution of arthropod orders shares considerable similarity across the wall types (Figure 12), with only slight variation observed in the relative abundances of Aranea (spiders), Coleoptera (beetles), Hemiptera (true bugs) and Hymenoptera (wasps, bees and ants). However, for some orders there are noticeable differences in the relative abundances. For example, collembola (springtails) represent 43.7% on LWs, 20.4% on CWs, while only accounting for 1.9% for both GFs and CFs. In contrast, Diptera (flies and mosquitos) are more prevalent on GFs, CFs and CWs, representing 54.5%, 53.2% and 45.7% respectively, while only representing 11.8% on LWs. These findings were further supported by the PCoA (Figure 13), from which it can be concluded that wall type significantly influenced arthropod composition, with LWs showing a distinct cluster compared to GF, CF and CW. This variation in order distribution may reflect differences in habitat preferences and environmental conditions provided by different wall types.

From a total of 125 arthropod families observed in our study, 45 were unique to LWs and 27 were unique to GFs. The presence of unique families on each wall type suggests that both LWs and GFs provide distinct habitats for various arthropod species. This suggest that urban planners should consider the concurrent use of these wall types in order to improve arthropod biodiversity.

Influencing factors

Linear models were used to test which influencing factors explain patterns concerning arthropod abundance, family richness and arthropod diversity on LWs and GFs. Moreover, CCA was used to investigate the influence of environmental variables on each arthropod order independently. Initially, our approach involved studying the influencing factors by taking the relative values of the response variables. This would be obtained by subtracting the control values from the absolute values. However, considering that the sampling method impacted our controls (Figure 3-8), we decided to work with the absolute values instead.

Local habitat characteristics

Plant Variables

Our results indicate that most plant variables do not significantly predict arthropod abundance, family richness, or diversity on LWs. An exception here is the *number of flowering species*, which positively influences arthropod diversity on LWs (Table 2 and S. Table 5). CCA reveals a positive association between the *number of flowering species* and several arthropod orders, including Hymenoptera, Coleoptera, and Diptera (Figure 14). Interestingly, these orders are part of 'the big four' of flower-visiting orders (Wardhaugh, 2015). Research on green roofs showed that flower abundance increased species richness of bees, although not for Coleoptera (Braaker *et al.*, 2017). These findings highlight a potential role of flowering species on LWs in supporting flower-visiting arthropod communities.

CCA results showed that *nativeness ratio* demonstrated a positive association with Trombidiformes, Coleoptera and Isopoda, but a negative association with Hemiptera (Figure 14). This negative association can be explained by the importance of the native host plants for aphids (Hemiptera), due to their specialized herbivorous feeding habits.
Despite lacking statistical significance, the *nativeness-ratio* shows a strong negative effect on arthropod abundance ($p = 0.38$), richness ($p = 0.07$) and diversity ($p = 0.31$) on LWs, as indicated by its large effect size (S. Tables 3-5). This challenges the assumption that native plants provide the best resources for arthropod biodiversity as native plants and local arthropods often co-evolve, leading to specialized relationships (Salisbury *et al.*, 2015). However, this relationship may be more complex due to three reasons. First, generalist arthropods, in contrast to specialist species, can thrive on a variety of plant types, including non-native species. Second, as non-native species have a different flowering

time, they are able to extend the flowering season (Salisbury *et al.*, 2015). Lastly, non-native plants can contribute to plant diversity creating more habitat complexity and offering more microhabitats for arthropods.
During the sampling period, *Spirae japonica* (non-native), *Bergenia cordifolia* (non-native), *Alchemilla mollis* (non-native) and *Achillea millefolium* (native) were the most prominent flowering species on LWs. Considering that most flowering plants were non-native, the negative relationship between plant nativeness with all arthropod metrics might be influenced by the flowering status of non-native plants rather than their nativeness status per se. A Pearson correlation test between these two plant variables showed a positive, but non-significant relationship ($r(41) = 0.199$, $p= 0.20$). We hypothesize that the use of non-native plants is not a limiting factor for arthropod communities perse, as long as they extend the flowering time. It might even be beneficial for generalist species as they may profit from longer flowering. This could be true especially for urban environments, as the abundance and richness of generalist arthropods increases with increasing landscape diversity (Jonsen and Fahrig, 1997). However, longer sampling periods and appropriate controls are necessary to accurately assess this relationship.

Both plant diversity and plant species richness did not significantly influence arthropod abundance and diversity on LWs and GFs using both the linear model (Table S3-8) and CCA approach (Figure 14). This finding corresponds with other research on LWs, which found that there was no significant relationship between plant richness and most insect orders, except Diptera (Chiquet, 2014). Multiple studies on green roofs show similar results. Species richness was found to have only a minor effect on green roof arthropod communities (Madre *et al.*, 2013), and plant species richness was not correlated with both insect abundance and family richness (College and Griffith, 2011). These findings challenge the resource heterogeneity theory which posits that an increase in habitat heterogeneity leads to an increase in species diversity. According to this theory, it would be expected that greater diversity of plants leads to a higher diversity of microhabitats and resources for arthropods, consequently increasing arthropod family richness and diversity. A possible explanation for the discrepancy could be that most studies assess arthropod abundance and diversity with a single sampling period. It could be the case that multiple sampling periods are necessary to observe the influence of plant diversity on arthropod diversity, as arthropod species exhibit temporal variations in their occurrence and abundance (Nuland and Whitlow, 2014).

Lastly, a CCA was performed to discover relationships between individual plant species and arthropod families (figure X). We conclude that some plant species affect the occurrence of certain arthropod orders. *C. Porscharskyana* showed a strong association with Aphididae (Hemiptera). *Lonicera nitida* and *Astilbe japonica* were both associated with Cicadelidae (Hemiptera) and Entomobryidae (Collembola). Lastly, *Spirae japonica* was found to be associated Formicidae (ants), Porcellonidae (Isopoda) and Bdellidae (Trombidiformes) and many Nematocera (mosquito) families; Chironomidae, Cecidomyiidae, Psychodiae, Sciaridae and Ceratopogonidae. To the best of our knowledge, this study is the first to report these relationships. Future studies should also consider exploring these relationships, enabling informed plant selections for green walls to help effectively address the arthropod diversity crisis.

Altogether, these findings show that plant related factors affect both arthropod diversity and play an important role in structuring arthropod communities.

Wall Variables

Our results indicate that wall characteristics do not significantly predict arthropod abundance, family richness, or diversity on LWs. However, CCA showed that *wall area* and *ground level* were in fact predictors at arthropod order level. The arthropod orders, Hemiptera and Coleoptera are positively associated with a bigger wall area while most other arthropod orders show a weak negative association with this variable (Figure X). These findings are very similar to (Chiquet, 2014), which concluded that surface area was positively related to Coleopteran species richness and Hemipteran abundance and

richness, while no relationship was found for Diptera, Hymenoptera and Araneae.
For green roofs, the effects of surface area on arthropod communities remains unclear. Most studies, show only a very weak connection between roof size and species abundance and diversity (Madre *et al.*, 2013; Braaker, Hazoul and Brist, 2014; Kyrö *et al.*, 2018) while only Fabián et al. (2021) found a significant positive correlation. Similar to this study, surface area was important in shaping the abundances of individual species (Kyrö *et al.*, 2018), further highlighting the importance of lower taxonomic considerations for GI-design.

The variable 'ground level' appears to predominantly affect the order Psocodea, which exhibits a significant negative relationship with this factor. It is important to note, however, that the two non-ground level walls included in this study are located at the same site. This suggests that other location-specific factors may be the driving force behind the observed association. Therefore, it is challenging to draw conclusions for this variable.

To study the influence of the age of the wall, a case study was conducted on two LWs in Hoofddorp (HAG and HAO). It is important to note that these findings are based on a single comparison and the 8-month age gap may not be substantial. The following conclusions should therefore be approached with caution.
PCoA showed significant differences of the arthropod communities on these walls (S. Figure 6). The older wall hosted a considerably larger number of individuals (545) compared to the younger wall, HAO (152). Comparison of the relative abundances showed that Coleoptera were more prevalent on the younger wall, while Hemiptera had a significantly higher relative abundance on the older wall (Figure 16). Interestingly, earlier research also showed that the age of green walls and green roofs was found to have a negative relationship with beetle species abundance (Chiquet, 2014; Kyrö *et al.*, 2018).
Since these walls only differ in terms of their age and plant composition, a comparison of the plant composition of both walls was done. PCoA of the beta-diversity dissimilarity showed that plant composition between the two walls differed significantly ($F= 14.635$, $R^2= 64.5\%$, $p = 0.008$) (S. figure Y). Given that both age and plant composition could have impacted arthropod communities, drawing definitive conclusions solely about the effect of age is challenging. The effect of age is hypothesized to lie in the successional stages of vegetation and increase in habitat heterogeneity. Continual maintenance, which includes the removal of colonizing plant species, thus acts as another limiting factor to research the effect of age on arthropods.

Altogether, drawing conclusion about the influence of wall variables on arthropods is challenging. To address this, future studies should consider employing controlled experiments, in which multiple variables are held constant, to isolate and understand specific influences of certain factors.

Landscape-level Characteristics:

Landscape characteristics play a significant role in influencing family richness and arthropod diversity on LWs (Table 2). For both LWs and GFs, blue- and green infrastructure were found to be almost always positively correlated with abundance, richness and diversity, while grey infrastructure negatively influenced these metrics (S. Tables 3-8). On LWs, family richness was mostly influenced by larger scale land-cover (200-500 meter), whereas arthropod diversity was primarily influenced by small scale land-cover (20-100 meter) (S. Tables 4 & 5). Arthropod abundance and family richness on GFs were both primarily influenced by larger scale land cover variables (200 -500m) (S. Table 6 & 7).

Landscape-level characteristics influenced arthropod orders in different ways (Table 4). Across all radii, blue infrastructure has a positive association with the orders; Araneae, Hymenoptera, Diptera and Trombidiformes, while negative associations were found with the occurrence of Collembola and Psocodae. The positive associations could be explained as many nematocerans (mosquitoes) as well as some hymenopterans, are considered semiaquatic as they are adapted to semi-aquatic habitats during their larval stage. The increased presence of these groups can further explain the presence of Araneae

and Trombidiformes. Araneae feed on many dipteran and hymenopteran species, and trombidiformes are well known to use dipterans as means of transportation (see section: ecological relationships).

Across all measured radii, green infrastructure is associated with higher numbers of Hymenoptera and lower numbers of Psocodae (Table 4). Some arthropod orders are exclusively influenced by surrounding greenery at the larger scale (200m & 500m). At this scale, green infrastructure is positively correlated with the abundance of Coleoptera and Diptera, but it is negatively correlated with Isopoda, Trombidiformes, and Psocodae. These findings align with the CCA-plots that illustrate the urban-rural gradients (S. Figure 12). For instance, the order Psocodae and Isopoda are more commonly found in urban settings and less so in areas with more green infrastructure. Conversely, Coleoptera and Hemiptera show positive correlations with both rural environments (S. Figure 12) and with the presence of green infrastructure (Table 4).

The varied response of some arthropod orders on the landcover types and gradients, as well as varied responses at different radii, suggests that these interactions are very complex. This is supported by findings on green roofs which indicate that landscape- and connectivity-related factors shape arthropods in different ways (Braaker *et al.*, 2017). Mobility related traits of arthropods were suggested as the main explanatory factor (Braaker, Hazoul and Brist, 2014).

The importance of landscape-level characteristics on arthropod communities is further highlighted by the distinct clustering of the rural area compared to urban and sub-urban areas (Figure 17). Together, these results suggest that wall designs should be informed by broader environmental context in order to effectively enhance biodiversity.

However, this study is not sufficient to fully understand the effect of these landscape characteristics due of two main reasons. First, the separation of the gradients in three categories: blue, green, and grey, generalizes the landscape. Other factors related to connectivity such as distance to nearby vegetation and type of vegetation are not considered here. Second, this study assessed these questions on arthropod order- and family-level, not taking into account the huge variations that exists in traits and habitat preferences within these taxonomic levels. Future studies should therefore take these factors into account in order to better understand the relationship between arthropod traits and landscape level characteristics.

Our approach of separating the influencing factors into three categories; wall-, plant- and landscape-characteristics, has its benefits and limitations. While it allows the identification of impactful variables within each group and simultaneously reduces the risk of overfitting, it makes it harder to observe interactions between variables across categories. Furthermore, it increases the difficulty of synthesizing our findings.

Ecological relationships between arthropods on green walls

Research on GI is almost exclusively focussed on general biodiversity metrics such as abundance and diversity, rather than specific ecological interactions. Understanding ecological dynamics among arthropods is crucial as it provides insights into the functional roles of these species in their ecosystems. Secondly, it aids in assessment of the resilience of these ecosystems against environmental disturbances. This part of the study focusses on the ecology of the most abundant families identified in our data (S. Table 1) and insights from arthropod co-occurrence in samples (Figure 19).

Mummified aphids and biological control agents

A total of 531 individuals of the green peach aphids, *Myzus persicae* (order: Hemiptera, family: Aphididae) were found across all sites. *M. persicae* is considered a pest as it has a wide host range, can transmit over 100-virus diseases between multiple plant families and it's resistant to many insecticides (Way, 1968). During the determination process, we encountered multiple individuals that were in a so-called mummified state (Figure 21). This is the result of the parasitoid relationship with one of its natural enemies, *Aphidius colemani* (order: Hymenoptera, family: Braconidae) (Figure 20).

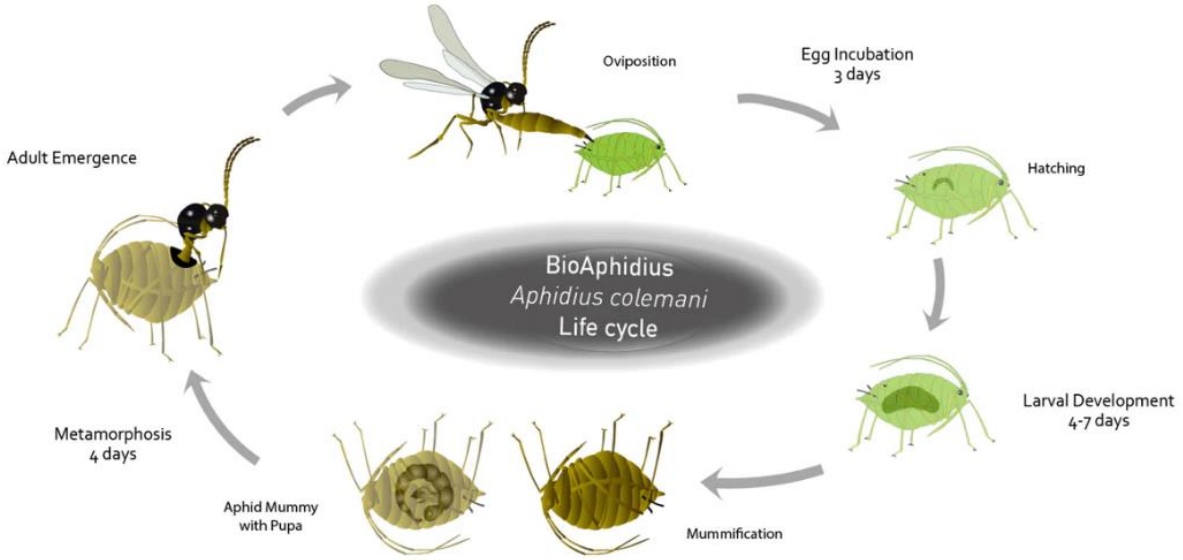

Figure 20. Life Cycle of Aphidius Colemani.

Because of this relationship, *A. colemani* is often used as a biological control agent to supress *M. Persicae* populations (Khatri, He and Wang, 2017). In 4 out of 5 locations, we found that *M. persicae* and *A. colemani* co-occurred in the same trap-samples. Other natural enemies of the green peach aphids (and Aphididae in general) are lady beetle larvae (Coccinellidae), flower flies (Syrphidae) and lacewings (Neuroptera (Chrysopidae) (Way, 1968). Interestingly, we also found that Coccinellidae, Syrphidae and Chrysopidae, co-occurred in trap-samples with Aphididae in 2, 2 and 4 out of the 5 locations, respectively. Together, these findings suggest that naturally occurring biological control is taking at place these living wall sites.

Springtails and ecosystem functioning

Springtails (Collembola) were by far the most abundant arthropod order accounting for 30% of all arthropods, with a total of 980 individuals. While most springtails inhabit floor habitats, some of them, mainly in the genera Entomobrya and Orchesella, are able to climb vertical vegetation (Rodgers and Kitchinjj, 1998). Indeed, almost all of the springtails found in this study are slender springtails from the genus Entomobrya (Figure 21).

Entomobrya are commonly found climbing leaves and bark, where they feed on algae, pollen and detritus. Springtails are crucial for ecosystem functioning as they contribute to nutrient cycling in ecosystems. They have been recognized as an important prey group for many generalist predators including beetles (Staphylinidae), spiders (Phalangiidae & Linyphiidae) and mites (Mesostigmata) (Bilde, Axelsen and Toft, 2000; Symondson, 2003). This makes them a crucial link within the food web, connecting the decomposition of organic matter to higher trophic levels. The above-mentioned families that predate springtails were all found at LWs in in this study (S. Table 1).

Hitchhiking mites

We observed three interactions of Acari (mites) with other arthropods. Two mites from the family Hydryphantidae (order: Trombidiformes) were found attached to mosquitos from the families Chironomidae (Figure 21) and Mycetophilidae. A mite from the family Discozerconidae (order: mesostigmata) was attached to a beetle from the Staphylinidae family (rove beetles). Mites developed diverse relationships with other arthropods, mainly Diptera, Coleoptera and Hymenoptera (Seeman and Walter, 2023). These relationships are often phoretic, which is a temporary symbiosis where a smaller animal uses a bigger animal of another species as a way to move to more suitable habitats. These mites are associated with insects that live in nutritionally rich but confined areas (Hunter and Rosario, 1988). This supports the hypothesis that green walls could acts as stepping stone habitats for high-mobility species (Braaker, Hazoul and Brist, 2014).

Figure 21. Arthropods found on Green Walls. ***Left****: M. persicae in a mummified state. Larval development of A. colemani is taking place within the aphid.* ***Middle****: An individual of the species Entomobrya multifasciata.* ***Right****. A mite from the family hydryphantidae attached to a Chironomidae species.*

Altogether, these insights reveal intricate ecological relationships occurring on living walls. This supports the hypothesis that green walls can acts as valuable habitats for many arthropod species. Arthropods are key elements of food webs and their availability in urban environments affects species at high trophic levels (Chatelain, Rüdisser and Traugott, 2023). Future research should therefore explore lower taxonomic relationships as they provide invaluable information essential to understand the ecology and consequently, the aid in conserving arthropod species through GI-interventions.

Conclusion

This study is the first to explore the ecological relationships between arthropod species on living walls. The results reveal intricate ecological relationships which supports the hypothesis that green walls can act as valuable habitats for many arthropod species. Our results do not clearly support the hypothesis that LWs and GFs improve arthropod abundance and diversity compared to their control counterparts. However, this is most probably an artefact of our sampling method. The presence of many unique families on LWs and GFs suggests that both wall types provide distinct habitats for various arthropod species.

Furthermore, this study found that both local- and landscape-level variables influence arthropod abundance, diversity and composition. The number of flowering plant species positively influenced arthropod diversity and abundance of flower visiting insects on LWs. For both LWs and GFs, surrounding blue- and green infrastructure were found to be almost always positively correlated with abundance, richness and diversity, while grey infrastructure negatively influenced these metrics.

The variable impact of the tested factors on different arthropod orders and families highlights the importance of considering lower-taxonomic relationships when developing biodiversity-conservation strategies based on GI. Recommendations based on our findings are presented in the table below.

Table of Recommendations

Future Research	**Recommendations and supporting references**
Sampling techniques	Use a combination of sampling techniques to mitigate biases associated with individual methods. (Yi *et al.*, 2012; Shi and Hodgson, 2022).
Sampling periods	Include multiple sampling periods to account for both the influence of temporal variation in plant flowering and arthropod occurrence. (Nuland and Whitlow, 2014; Salisbury *et al.*, 2015)
Experimental Design	Conduct controlled experiments, in which multiple variables are held constant, to isolate and understand causal relationships between variables. (Filazzola, Shrestha and Macivor, 2019)
Experimental Design	Conduct large-scale studies with a sufficient number of replicates for robust statistical analysis. (Filazzola, Shrestha and Macivor, 2019)
Ecological relations	explore lower taxonomic relationships as they provide invaluable information essential to understand the ecology of GI and consequently, the aid in conserving arthropod species through GI-interventions.
Landscape-characteristics	To better understand the impact of landscape characteristics on arthropods, factors related to connectivity such as distance to nearby vegetation and vegetation type need to be included. (Braaker, Hazoul and Brist, 2014; Braaker *et al.*, 2017; Adams *et al.*, 2020)
Green Wall Design & Urban Planning	**Findings, recommendations and supporting references**
Use flowering plants	The number of flowering plant species positively influenced arthropod diversity (Table 2) and abundance of flower visiting insects on LWs (Figure 14). This underscores the importance of informed plant selection which should be focussed on including multiple flowering species with different flowering times. (Salisbury *et al.*, 2015; Braaker *et al.*, 2017)
LWs and GFs complement each other	The presence of many unique families on LWs and GFs suggests that both wall types provide distinct habitats for various arthropod species (Figure 12 & 13). This suggest that urban planners should consider the concurrent use of these wall types in order to improve arthropod biodiversity. (Chiquet, 2014)
Integrate GI within a broader blue-green framework	The positive influence of surrounding blue- and green infrastructure (Table 2) underscore the importance of integrating GI implementation within a broader blue-green framework. (Saura, 2014; Braaker *et al.*, 2017; Mayrand, Clergeau and Vergnes, 2018)
Researchers need to conduct large-scale studies which requires many green-wall sites. Urban planners and green wall producers need more scientific insights regarding GI-ecology. As is evident from these needs, stronger collaboration between these parties is necessary to enhance the development of GI that can effectively address the arthropod diversity crisis.	

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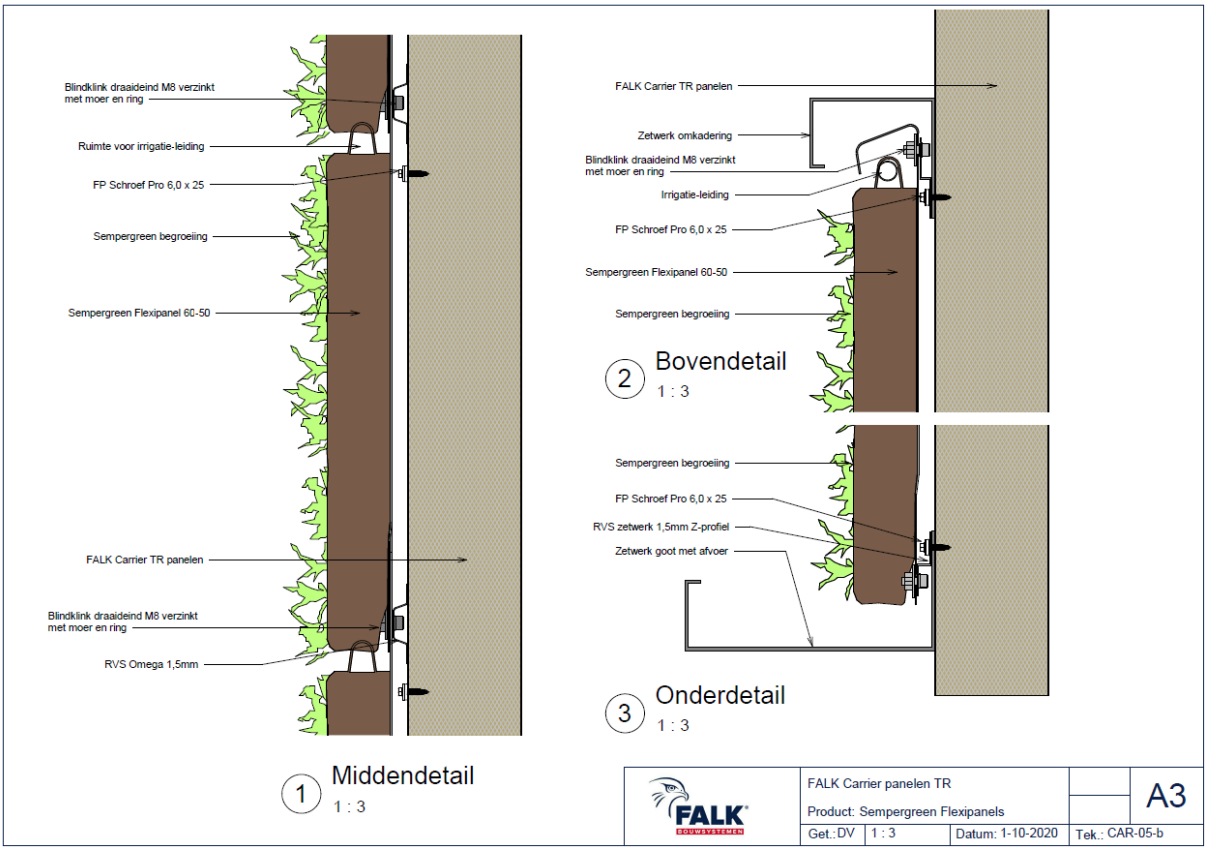
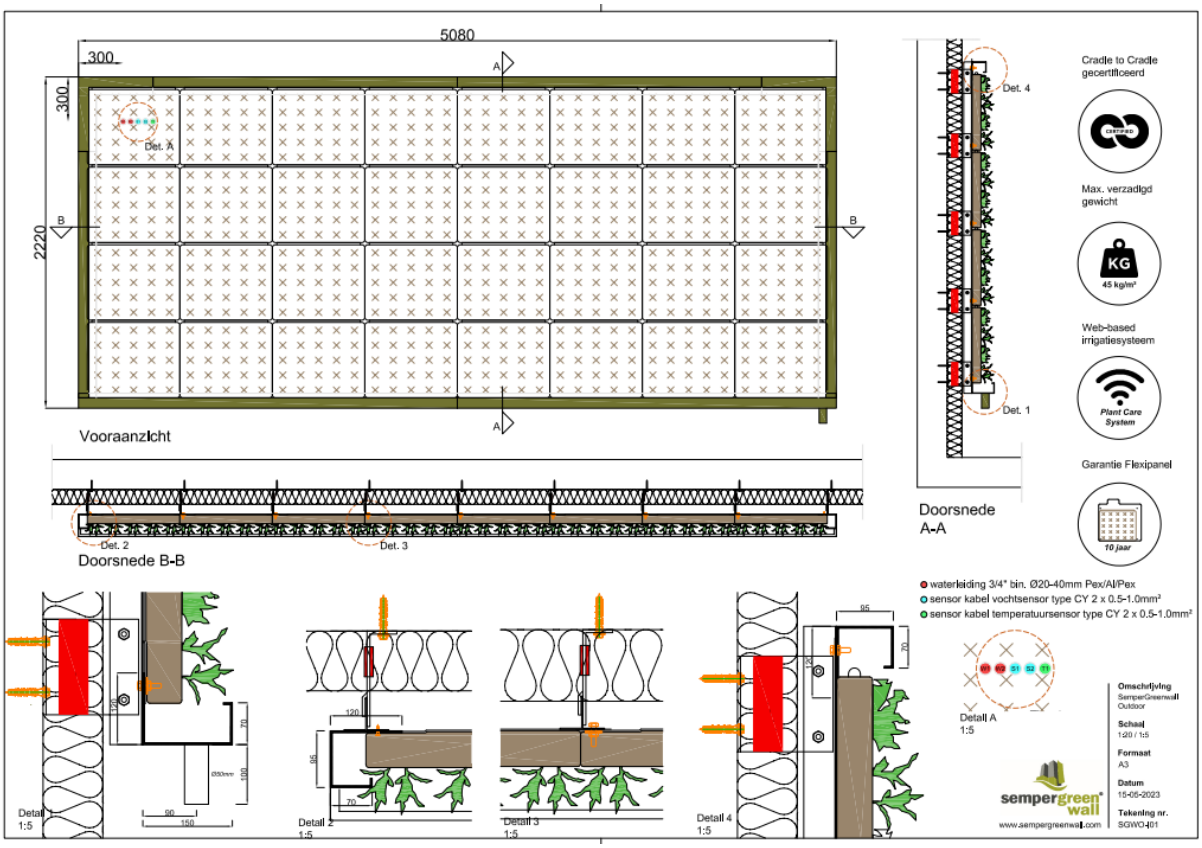
Supplementary





Supplementary Figure 1. Living Wall systems as provided by Sempergreen®.

EG-Fertiliser

24-2-2023

03060801, N-xt NPK 3-6-8 Cu Mg Mn

Total Nitrogen (N)	**2,80%**	
Amid Nitrogen (N)	**2,80%**	**ISO 6654**
Total Phosphate (P_2O_5)	**4,58%**	**EN 6966 ICP**
Total Potassium Oxide (K_2O)	**8,40%**	**EN 15477**
Total Sulphur Oxide (SO_3)	**1,00%**	**EN 15961**
Total Copper (Cu)	**0,20%**	**Annex IV Sub 9.2**
Total Magnesium Oxide (MgO)	**0,35%**	**EN 15961**
Total Manganese Oxide (MnO)	**0,21%**	**Annex IV Sub 9.2**

pH Level	**<2**
EC Level	**<1 mS/cm**
Density	**1,18 kg/liter**
Specific volume	**0,85 liter/kg**
Lowest storagetemperature	**-5,0 C**
C/N ratio	**0,4**
CO_2 emission ISCC	**341 gr CO_2/kg**
CO_2 emissie local	**162 gr CO_2/kg**

STORAGE

Fertilizer store in tanks of fiber polyester, plastic, steel, stainless steel, or other non-corrosive material. Tank must be placed from safe distance of open water or other water sources.
Clean spilled fertilizer with cloth or neutralize with lime.

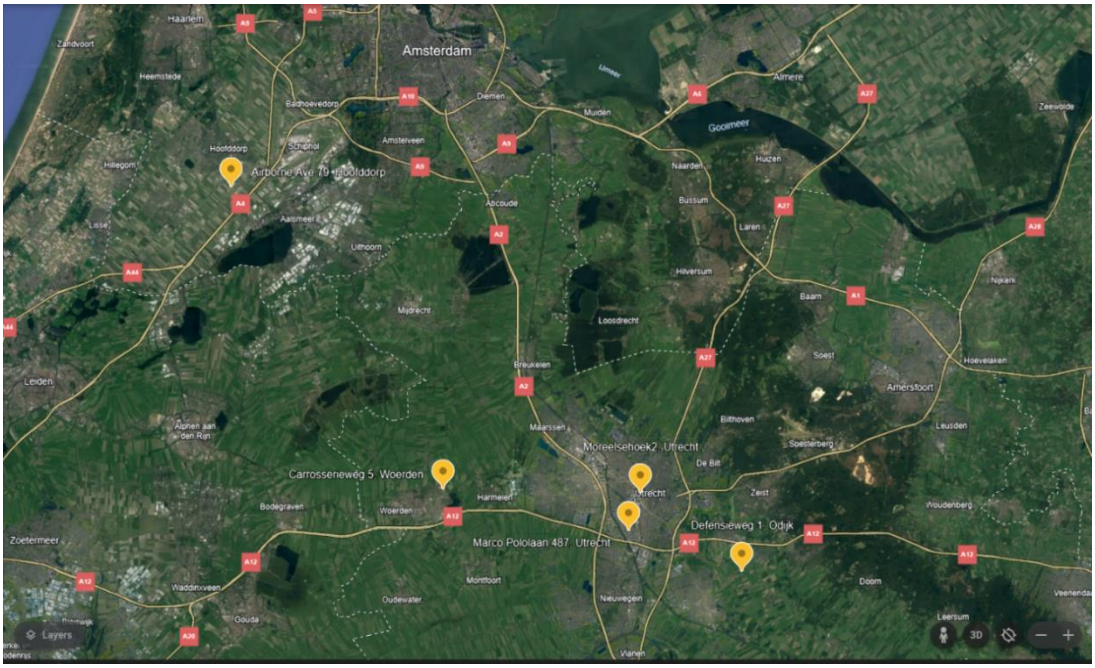
PERSONAL PROTECTION

This fertilizer is not agressive to the skin. Contact with the eyes will result in a burning feeling because of the high doses of salt. When this happens, rinse eyes with plenty of clean water and contact your physician. Strongly adviced is to wear safety goggles and gloves on handling this fertilizer.

Manufactured by : Healthy Soil BV, 1e Bokslootweg 17 7821 AT Emmen Nederland, E:productie@n-xt.com

Supplementary Figure 2. Nutrient list of irrigation system of the LWS as provided by Sempergreen®.

Detailed list of all locations:



Supplementary Figure 3. Map showing all locations. From left to right: Hoofddorp, Woerden, Utrecht (Kanaleneiland), Utrecht (center) and Odijk.

An overview of all the locations with green facades and control walls can be found in the file "overview locations.docx" which could not be include here due to issues with document size.

Living Walls Hoofddorp left: HAO-LW, right: HAG-LW (under construction)

Living Wall: Woerden WCV-LW (vertical wall)

Living Walls: Woerden WCH-LW and WCS-LW (horizontal walls)

Living Wall Utrecht (Kanaleneiland): UMP-LW

Living Wall Utrecht (Centre) UHP-LW

Living Wall Odijk: OSR-LW

Living Wall Odijk: OSL-LW

List of dichotomous keys:

Hymenoptera	https://www.cdc.gov/nceh/ehs/docs/pictorial_keys/hymenoptera.pdf
Hymenoptera	https://www.researchgate.net/publication/259227143_Hymenoptera_of_the_World_An_Identification_Guide_to_Families
Hymenoptera	https://www.antwiki.org/wiki/Lasius
Hymenoptera	http://www.sbs.utexas.edu/bio373l/docs/ants/antkey.pdf
Diptera	https://sites.google.com/view/mikes-insect-keys/mikes-insect-keys/keys-for-the-identification-of-british-true-flies-diptera/keys-for-the-identification-of-british-muscidae
Diptera	file:///C:/Users/thijs/Downloads/Bucketal2009-KeytoDipteraFamilies-MCAD.pdf
Diptera	https://shire.science.uq.edu.au/bb/parasitology/diptera/diptera-key1.html#section2b
Diptera	http://www.faculty.ucr.edu/~legneref/medical/dipterafamilykey.htm#nine
Diptera	https://www.britannica.com/animal/dipteran/Classification
Diptera	https://sites.google.com/view/mikes-insect-keys/mikes-insect-keys/keys-for-the-identification-of-british-true-flies-diptera/keys-for-the-identification-of-british-dolichopodidae
Diptera	https://sites.google.com/view/mikes-insect-keys/mikes-insect-keys/keys-for-the-identification-of-british-true-flies-diptera/keys-for-the-identification-of-the-british-species-of-mycetophilidae
Diptera	https://www.diptera-in-beeld.nl/Ref-Key%20to%20the%20British%20families%20of%20Nematocera.pdf
Diptera	https://canvas.umn.edu/courses/71992/files/3195519/download?download_frd=1
Diptera	https://v3.boldsystems.org/index.php/Taxbrowser_Taxonpage?taxid=106664
Diptera	https://nasmus.co.za/wp-content/uploads/2019/01/Suricata-4-12-KEY-TO-DIPTERA-FAMILIES-ADULTS-low-resolution_Part1.pdf
Araneae	https://araneae.nmbe.ch/key
Araneae	https://araneae.nmbe.ch/matrixlinkey
Collembola	https://www.collembola.org/key/entomobr.htm
Collembola	https://www.janvanduinen.nl/sleutel/key120.php
Coleoptera	https://sites.google.com/view/mikes-insect-keys/mikes-insect-keys/keys-for-the-identification-of-british-beetles-coleoptera/key-for-the-identification-of-british-latridiidae
Hemiptera	https://influentialpoints.com/Gallery/Identify_common_aphids.htm
Hemiptera	https://idtools.org/id/AphID/polycosmo10.html
Forums	https://www.reddit.com/r/insects/
Forums	https://forum.insectnet.com/viewforum.php?f=6

Supplementary Table 1 Arthropod order and their abundances.

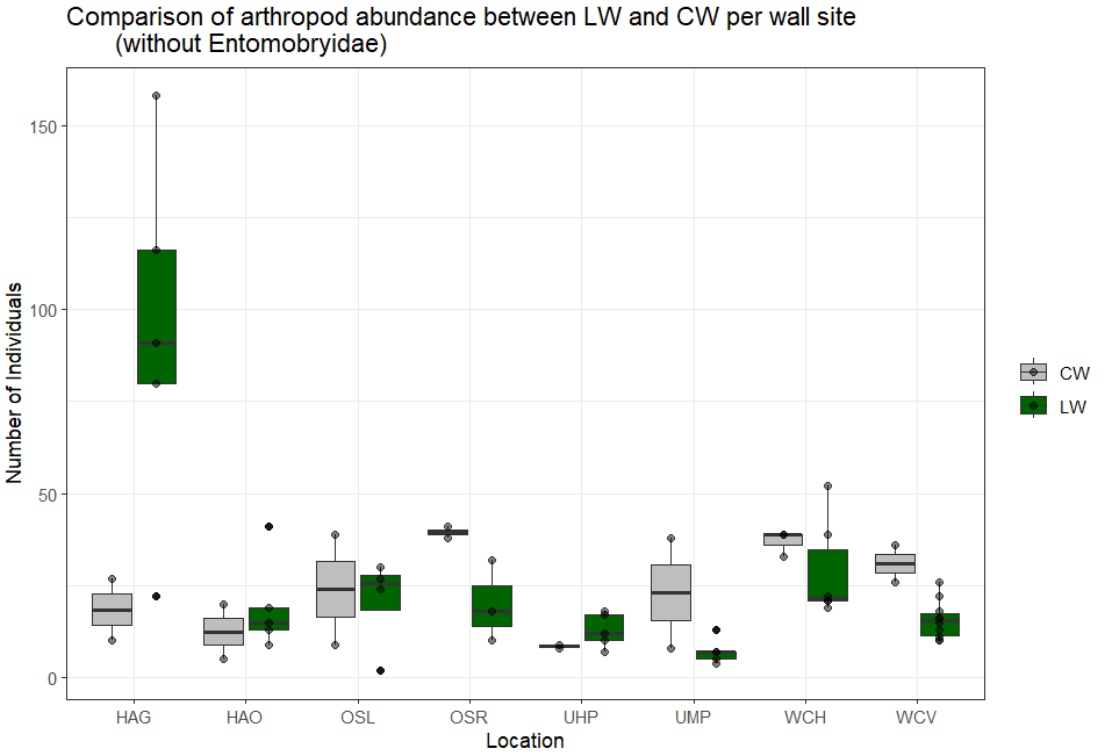
Arthropod Orders	Common English Names	Total Individuals
Collembola	Springtails	991
Diptera	Flies	877
Hemiptera	True Bugs	794
Hymenoptera	Bees, Wasps, and Ants	213
Araneae	Spiders	145
Coleoptera	Beetles	104
Psocodea	Barklice, Booklice	30
Trombidiformes	(Includes many mites)	27
Thysanoptera	Thrips	26
Lepidoptera	Butterflies and Moths	20
Isopoda	Woodlice, Pill Bugs	19
Neuroptera	Lacewings, Antlions	8
Ephemeroptera	Mayflies	4
Odonata	Dragonflies, Damselflies	2
Mesostigmata	(A group of mites)	2
Blattodea	Cockroaches	1
Trichoptera	Caddisflies	1
Orthoptera	Grasshoppers, Crickets	1
Julida	(A group of millipedes)	1
Lithobiomorphia	Centipedes	1
Scolopendromorpha	Centipedes	1

Supplementary Table 2 Arthropod families and their abundances found on all sites.

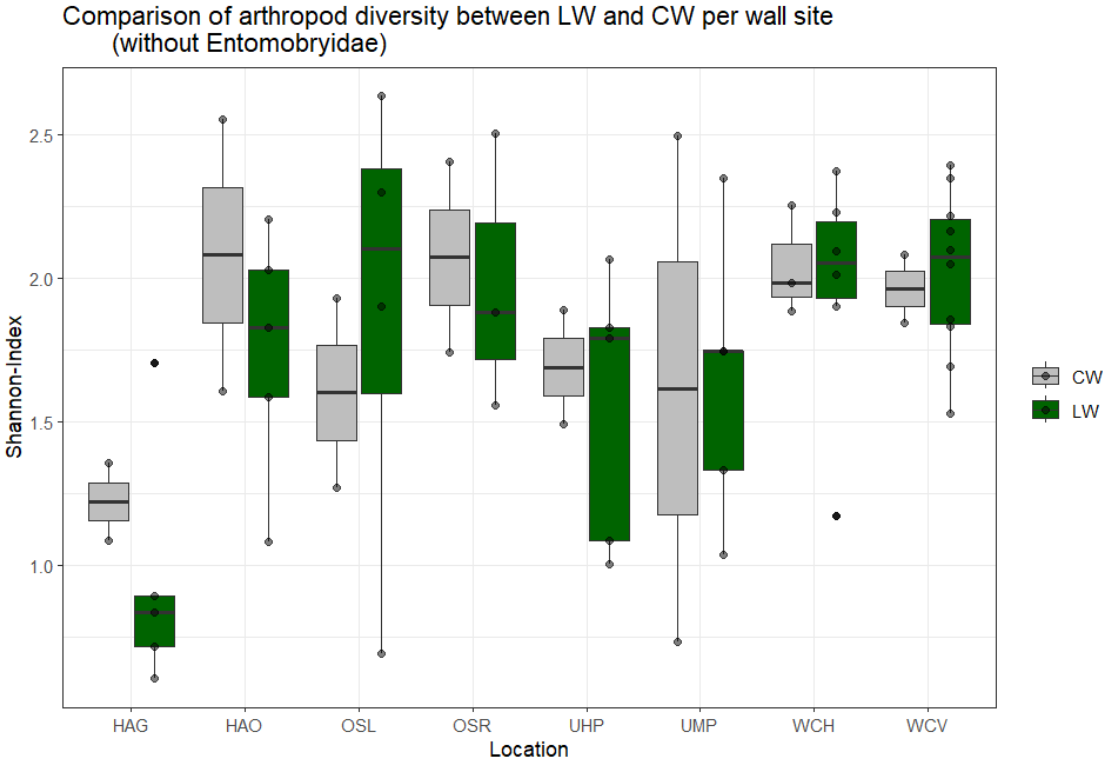
Arthropod Families	Common English name	Total Individuals
Entomobryidae	Slender springtails	980
Aphididae	Aphids	741
Chironomidae	Non-biting Midges	164
Cecidomyiidae	Gall Midges	123
Dolichopodidae	Long-legged flies	118
Sciaridae	Dark-winged fungus gnats	106
Braconidae	Braconid Wasps	74
Psychodidae	Moth flies	71
Formicidae	Ants	69
Ceratopogonidae	Biting midges	68
Phalangiidae	Harvestmen	48
Latridiidae	Minute brown scavenger beetles	44
Muscidae	House flies	41
Ectopsocidae	Barklice	38
Phoridae	Hump-backed flies	34
Drosophilidae	Fruit flies	34
Linyphiidae	Sheet weavers or money spiders	33
Theridiidae	Cobweb spiders	28
Thripidae	Thrips	26
Tipulidae	Crane fly	22
Cicadellidae	Leafhoppers	21
Staphylinidae	Rove beetles	18
Hydryphantidae	Family of water mites	15
Salticidae	Jumping spiders	15
Apidae	Bees	13
Nitidulidae	Sap beetles	12
Bdellidae	Snout mites	12
Empididae	Dance flies	11
Porcellionidae	Family of terrestrial isopods	11
Syrphidae	Hoverflies	10

Platygastridae	Family of parasitoid wasps	9
Anthocoridae	Flower bugs	9
Stratiomyidae	Soldier flies	8
Calliphoridae	Blowflies	8
Micropezidae	Stilt-legged flies	7
Rhagionidae	Snipe flies	7
Chrysopidae	Green lacewings	7
Tortricidae	Tortrix moths	7
Philosciidae	Family of terrestrial isopods	7
Triozidae	Jumping plant lice	6
Hypogastruridae	Springtails	6
Pyralidae	Snout moths	6
Hydrophilidae	Water scavenger beetles	6
Lygaeidae	Seed bugs	6
Araneidae	Orb-weaver spiders	6
Anthomyiidae	Root-maggot flies	5
Chalcididae	Chalcid wasps	5
Scelionidae	Family of parasitoid wasps	5
Megaspilidae	Family of parasitoid wasps	5
Lonchopteridae	Spear-winged flies	5
Coccinellidae	Ladybugs	5
Halictidae	Sweat bees	4
Hybotidae	Family of dance flies	4
Baetidae	Mayflies	4
Clubionidae	Sac spiders	4
Pteromalidae	Family of parasitoid wasps	4
Lauxaniidae	Family of flies	4
Mycetophilidae	Fungus gnats	3
Chrysomelidae	Leaf beetles	3
Mimetidae	Pirate spiders	3
Opomyzidae	Family of flies	3
Corylophidae	Minute hooded beetles	3
Katiannidae	Family of springtails	3
Tineidae	Clothes moths	3
Culicidae	Mosquitos	3
Cynipidae	Gall wasps	3
Diapriidae	Family of parasitoid wasps	3
Chaoboridae	Phantom midges	2
Rhinotermitidae	Subterranean termites	2
Leptoceridae	Long-horned caddisflies	2
Coenagrionidae	Pond damsels	2
Platystomatidae	Signal flies	2
Aphelinidae	Family of parasitoid wasps	2
Simuliidae	Black flies	2
Curculionidae	Weevils	2
Miturgidae	Prowling spiders	2
Trichoceridae	Winter crane flies	2
Ichneumonidae	Ichneumon wasps	2
Scraptiidae	False flower beetles	2
Geometridae	Inchworms (Geometer moths)	2
Discozerconidae	Family of mites	2
Sepsidae	Black scavenger flies	2
Sarcophagidae	Flesh flies	2
Pompilidae	Spider wasps	2
Tenthredinidae	Sawflies	2
Rhinophoridae	Woodlouse flies	2
Pentatomidae	Stink bugs	2
Tephritidae	Peacock flies	2

Crabronidae	Crabronid wasps	1
Therevidae	Stiletto flies	1
Cheiracanthiidae	Prowling spiders	1
Aleyrodidae	Whiteflies	1
Mymaridae	Fairyflies	1
Muscoidea	Superfamily of flies	1
Brachycera	Suborder of flies	1
Issidae	Issid planthoppers	1
Aphalaridae	Family of psyllids	1
Miridae	Plant bugs	1
Proctotrupidae	Family of parasitoid wasps	1
Vespidae	Wasps	1
Scarabaeidae	Scarab beetles	1
Scathophagidae	Dung flies	1
Pholcidae	Cellar spiders	1
Oniscidae	Family of woodlice	1
Tetragnathidae	Long-jawed orb weavers	1
Psychidae	Bagworm moths	1
Anobiidae	Deathwatch beetles	1
Dicyrtomidae	Family of springtails	1
Cicadidae	Cicadas	1
Melyridae	Soft-winged flower beetles	1
Byrrhidae	Pill beetles	1
Cerambycidae	Longhorn beetles	1
Arrhopalitidae	A family of springtails	1
Sphecidae	Thread-waisted wasps	1
Coniopterygidae	Dustywings	1
Colletidae	Plasterer bees	1
Elateridae	Click beetles	1
Philodromidae	Running crab spiders	1
Gryllidae	True crickets	1
Agelenidae	Funnel weavers	1
Brentidae	Straight-snouted weevils	1
Helophoridae	Water scavenger beetles	1
Julidae	Julid millipedes	1
Lithobiidae	Stone centipedes	1
Scolopendridae	Centipedes	1



Supplementary Figure 4. Boxplots showing the arthropod abundance per site for both LWs and CWs without the family Entomobryidae. No clear trend is visible. Significant differences were found for the sites; HAG (p = 0.026)).



Supplementary Figure 5. Boxplots showing the arthropod diversity per site for both LWs and CWs without the family Entomobryidae. No clear trend is visible and no significant differences were found for any of the sites.

Results Univariate Analysis

Living Walls:

Supplementary Table 3 Univariate analysis of **arthropod abundance** on living walls. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

Wall vars	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
wall_height	0.027	0.053	-0.143	0.197	0.016	0.646		105.493
wall_area	0.003	0.003	-0.008	0.014	0.042	0.466		110.534
Widetall(wide)	-0.081	0.42	-1.419	1.256	0.002	0.859		101.617
age_in_months	-0.008	0.008	-0.032	0.016	0.061	0.38		108.548
ground_level(yes)	-0.056	0.449	-1.484	1.372	0.001	0.909		101.513
orientation (SE)	-0.278	0.44	-1.678	1.123	0.028	0.573		94.329
Plant vars	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
no_flowering_species	-0.142	0.124	-0.395	0.11	0.039	0.259		102.925
plant_species_richness	0.042	0.096	-0.154	0.238	0.005	0.666		104.366
total_coverage	0.006	0.01	-0.015	0.026	0.013	0.563		108.732
plant_diversity	0.285	0.598	-0.932	1.501	0.007	0.637		100.672
nativeness_ratio	-1.065	1.22	-3.548	1.417	0.017	0.389		98.707
Landscape variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
green_20	-0.008	0.016	-0.06	0.043	0.015	0.641		107.887
grey_20	0.009	0.012	-0.029	0.047	0.033	0.507		108.171
blue_20	-0.041	0.035	-0.152	0.071	0.08	0.329		105.209
green_100	-0.01	0.012	-0.049	0.028	0.046	0.449		107.952
grey_100	0.011	0.012	-0.028	0.049	0.047	0.445		107.935
blue_100	-0.004	0.082	-0.266	0.259	0	0.967		104.919
green_200	-0.002	0.019	-0.063	0.059	0.001	0.919		107.833
grey_200	0.002	0.017	-0.053	0.058	0.001	0.896		108.007
blue_200	-0.03	0.113	-0.388	0.329	0.005	0.809		104.219
green_500	0.004	0.011	-0.031	0.04	0.009	0.73		108.746
grey_500	-0.003	0.012	-0.041	0.035	0.003	0.828		108.722
blue_500	-0.055	0.061	-0.249	0.138	0.05	0.43		104.634

Supplementary Table 4. Univariate analysis of arthropod **family richness** on living walls. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

expl_var	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
wall_height	0	0.033	-0.104	0.104	0	0.991		93.154
wall_area	0.001	0.003	-0.008	0.01	0.005	0.797		98.07
widetall	0.065	0.232	-0.674	0.803	0.003	0.799		89.131
age_in_months	-0.005	0.005	-0.021	0.011	0.043	0.386		95.845
ground_level	0.118	0.328	-0.924	1.161	0.007	0.742		88.464
orientation	0.409	0.224	-0.302	1.121	0.107	0.165		81.968
Plant variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
no_flowering_species	0.074	0.094	-0.116	0.264	0.017	0.434		90.453
plant_species_richness	0.028	0.074	-0.123	0.179	0.004	0.705		91.331
total_coverage	-0.005	0.007	-0.02	0.01	0.015	0.521		95.697
plant_diversity	0.09	0.457	-0.84	1.02	0.001	0.845		87.799
nativeness_ratio	-1.638	0.887	-3.443	0.167	0.062	0.074		83.45
Landscape variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**Sign**	**AIC**
green_20	0.006	0.008	-0.01	0.021	0.014	0.45		82.035
grey_20	-0.007	0.006	-0.018	0.005	0.032	0.247		81.22
blue_20	0.029	0.016	-0.003	0.061	0.075	0.076		79.296
green_100	0.007	0.005	-0.004	0.018	0.041	0.194		80.848
grey_100	-0.009	0.005	-0.02	0.002	0.066	0.095		79.689
blue_100	0.083	0.033	0.016	0.15	0.131	0.017	*	76.582
green_200	0.016	0.008	-0.001	0.033	0.082	0.063		78.973
grey_200	-0.016	0.007	-0.031	-0.001	0.104	0.035	*	77.925
blue_200	0.125	0.045	0.035	0.215	0.162	0.008	*	75.061
green_500	0.011	0.005	0.001	0.021	0.114	0.027	*	77.43
grey_500	-0.013	0.005	-0.023	-0.003	0.135	0.015	*	76.404
blue_500	0.012	0.028	-0.044	0.069	0.005	0.662		82.437

Supplementary Table 5. Univariate analysis of **arthropod diversity** on living walls. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

Wall variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
wall_height	0.012	0.047	-0.138	0.161	0.005	0.821		73.537
wall_area	0	0.004	-0.012	0.013	0.001	0.949		78.627
Widetall	-0.137	0.339	-1.215	0.94	0.012	0.712		69.473
age_in_months	0	0.008	-0.025	0.024	0	0.96		77.234
ground_level	0.131	0.456	-1.32	1.582	0.008	0.793		69.002
orientation	0.46	0.319	-0.555	1.475	0.147	0.245		63.685
Plant Variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**sign**	**AIC**
no_flowering_species	0.281	0.072	0.134	0.428	0.225	<0.001	*	63.497
plant_species_richness	0.067	0.066	-0.067	0.201	0.023	0.316		71.939
total_coverage	0	0.007	-0.015	0.015	0	0.982		77.225
plant_diversity	0.308	0.416	-0.538	1.154	0.013	0.464		68.668
nativeness_ratio	-0.831	0.802	-2.463	0.802	0.016	0.308		66.86
Landscape variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**significance**	**AIC**
green_20	0.018	0.007	0.004	0.032	0.139	0.014	*	73.508
grey_20	-0.017	0.005	-0.026	-0.007	0.222	0.001	*	69.146
blue_20	0.059	0.013	0.033	0.086	0.334	<0.001	*	62.435
green_100	0.01	0.005	0	0.021	0.091	0.049	*	75.819
grey_100	-0.013	0.005	-0.023	-0.003	0.14	0.013	*	73.457
blue_100	0.104	0.031	0.042	0.166	0.22	0.001	*	69.234
green_200	0.012	0.008	-0.005	0.029	0.049	0.152		77.763
grey_200	-0.014	0.007	-0.028	0.001	0.079	0.068		76.415
blue_200	0.151	0.041	0.068	0.233	0.249	0.001	*	67.651
green_500	0.007	0.005	-0.003	0.017	0.045	0.172		77.964
grey_500	-0.009	0.005	-0.019	0.001	0.072	0.082		76.741
blue_500	0.041	0.027	-0.012	0.095	0.056	0.127		77.471

Green facades:

Supplementary Table 6. Univariate analysis of **arthropod abundance** on green facades. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

Plant Variables	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**significance**	**AIC**
no_flowering_species	-0.173	0.565	-1.416	1.071	0.003	0.766		41.778
plant_species_richness	0.069	0.201	-0.373	0.512	0.008	0.736		43.854
total_coverage	-0.007	0.01	-0.028	0.014	0.045	0.455		49.434
plant_diversity	0.286	0.49	-0.793	1.365	0.034	0.572		41.851
nativeness_ratio	-0.511	0.756	-2.175	1.153	0.078	0.513		40.838
expl_var	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**significance**	**AIC**
green_20	0.013	0.009	-0.006	0.032	0.119	0.175		39.71
grey_20	-0.014	0.009	-0.033	0.006	0.133	0.15		39.43
blue_20	0.229	0.167	-0.127	0.585	0.111	0.191		39.857
green_100	0.025	0.014	-0.004	0.054	0.179	0.091		38.515
grey_100	-0.02	0.013	-0.047	0.007	0.147	0.129		39.167
blue_100	0.006	0.081	-0.167	0.179	0	0.945		41.856
green_200	0.03	0.009	0.01	0.05	0.409	0.006	*	32.922
grey_200	-0.026	0.009	-0.045	-0.007	0.369	0.01	*	34.029
blue_200	0.077	0.104	-0.144	0.298	0.036	0.467		41.242
green_500	0.02	0.006	0.007	0.033	0.427	0.004	*	32.38
grey_500	-0.02	0.006	-0.034	-0.007	0.402	0.006	*	33.117
blue_500	-0.095	0.055	-0.211	0.022	0.166	0.104		38.774

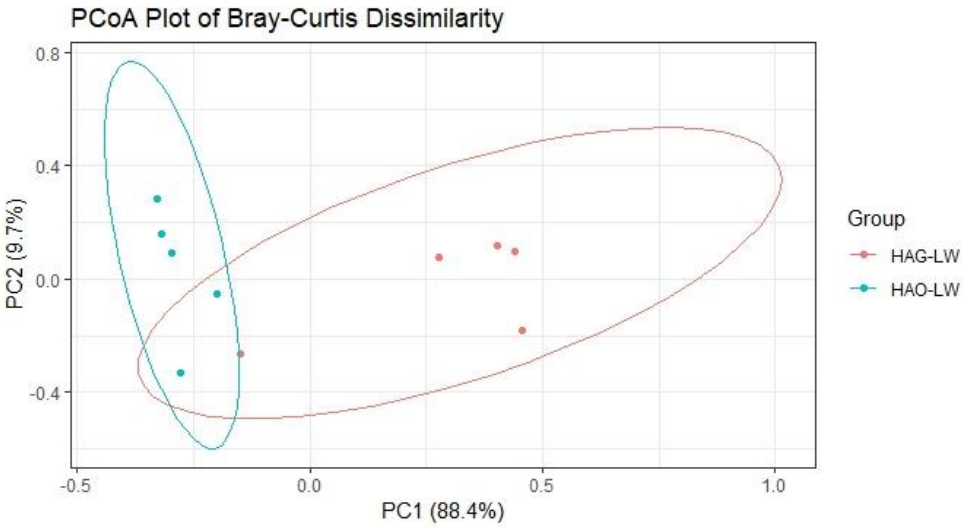
Supplementary Table 7. Univariate analysis of arthropod **family richness** on green facades. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

expl_var	estimate	std_error	lower_ci	upper_ci	rsquared	p_value	significance	AIC
no_flowering_species	0.033	0.539	-1.154	1.219	0	0.953		39.797
plant_species_richness	0.181	0.18	-0.216	0.578	0.072	0.338		41.162
total_coverage	-0.003	0.009	-0.023	0.017	0.01	0.739		47.876
plant_diversity	0.188	0.459	-0.822	1.198	0.017	0.69		39.942
nativeness_ratio	-0.46	0.698	-1.996	1.076	0.074	0.523		38.887
expl_var	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**significance**	**AIC**
green_20	0.012	0.008	-0.005	0.03	0.131	0.154		36.226
grey_20	-0.013	0.008	-0.03	0.004	0.143	0.135		35.99
blue_20	0.16	0.156	-0.172	0.492	0.066	0.32		37.45
green_100	0.019	0.013	-0.009	0.046	0.123	0.167		36.373
grey_100	-0.015	0.012	-0.041	0.01	0.103	0.209		36.76
blue_100	0.009	0.074	-0.148	0.167	0.001	0.9		38.589
green_200	0.025	0.009	0.006	0.044	0.352	0.012	*	31.232
grey_200	-0.022	0.008	-0.04	-0.004	0.311	0.02	*	32.263
blue_200	0.045	0.095	-0.158	0.248	0.015	0.641		38.352
green_500	0.017	0.006	0.005	0.029	0.383	0.008	*	30.39
grey_500	-0.017	0.006	-0.03	-0.004	0.353	0.012	*	31.202
blue_500	-0.091	0.049	-0.196	0.014	0.185	0.084		35.12

Supplementary Table 8. Univariate analysis of **arthropod diversity** on green facades. Std_error = Standard error, lower_ci = lower confidence interval, upper_ci = upper confidence interval, sign = significance, AIC = Akaike Information Criterion.

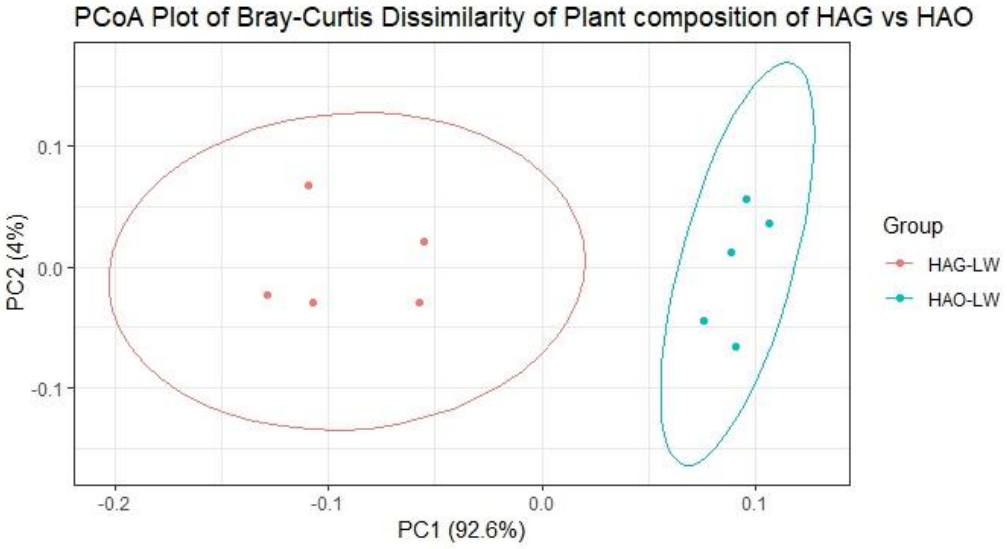
expl_var	estimate	std_error	lower_ci	upper_ci	rsquared	p_value	significance	AIC
no_flowering_species	0.145	0.377	-0.685	0.975	0.009	0.708		25.167
plant_species_richness	0.11	0.088	-0.084	0.304	0.089	0.238		26.649
total_coverage	-0.003	0.004	-0.011	0.006	0.027	0.517		34.006
plant_diversity	0.154	0.184	-0.251	0.559	0.042	0.421		26.031
nativeness_ratio	-0.19	0.196	-0.621	0.241	0.056	0.352		25.66
expl_var	**estimate**	**std_error**	**lower_ci**	**upper_ci**	**rsquared**	**p_value**	**significance**	**AIC**
green_20	0.002	0.005	-0.008	0.012	0.009	0.714		17.929
grey_20	-0.002	0.005	-0.012	0.008	0.012	0.676		17.882
blue_20	0.08	0.086	-0.103	0.262	0.055	0.367		17.132
green_100	0.003	0.008	-0.013	0.019	0.012	0.669		17.873
grey_100	-0.002	0.007	-0.017	0.012	0.007	0.744		17.962
blue_100	-0.014	0.04	-0.1	0.072	0.008	0.735		17.952
green_200	0.006	0.006	-0.006	0.018	0.068	0.313		16.895
grey_200	-0.005	0.005	-0.016	0.006	0.057	0.355		17.085
blue_200	0	0.052	-0.112	0.112	0	1		18.086
green_500	0.005	0.004	-0.003	0.013	0.1	0.216		16.297
grey_500	-0.005	0.004	-0.013	0.004	0.081	0.267		16.646
blue_500	-0.041	0.028	-0.1	0.019	0.124	0.166		15.836

Case study age: Hoofddorp



Supplementary Figure 3: Principal coordinate analysis (PCoA) plot showing the composition differences (Bray-Curtis distances) of arthropod communities between HAO-LW and HAG-LW. Ellipses represent the 95% confidence interval around the centroid of each group.

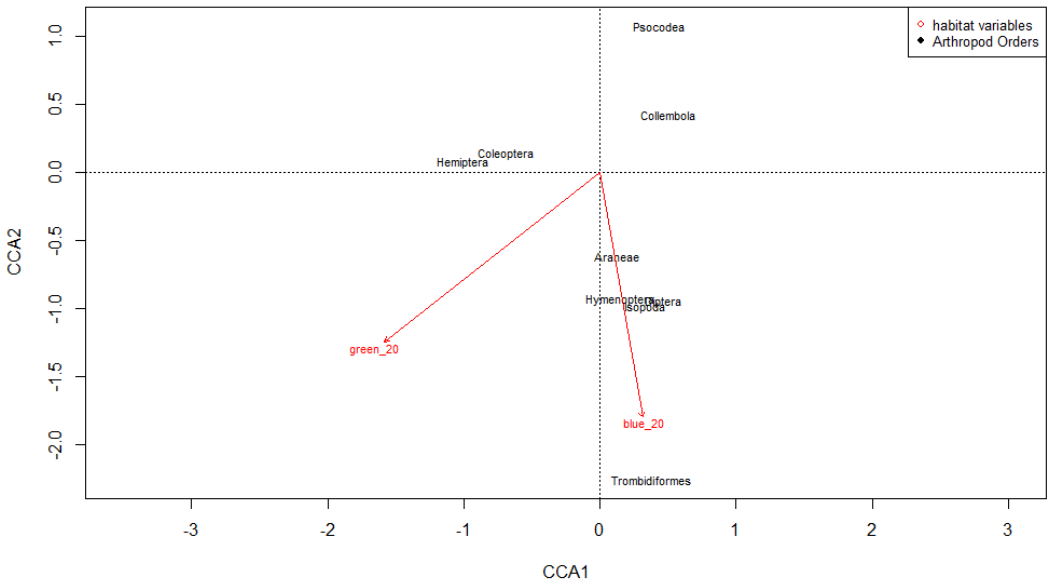
S. Figure 6 illustrates the dissimilarity of arthropod order composition. The PC1- and PC2-axis explain 88.4% and 9.7% of the variation, respectively. The distinct clustering two LWs highlights their unique community composition. PERMANOVA results substantiate the significant influence of wall type on community structure ($F = 8.21$, $R^2 = 0.50$, $p = 0.008$).



Supplementary Figure 4: Principal coordinate analysis (PCoA) plot showing the composition differences (Bray-Curtis distances) of plant communities between HAO-LW and HAG-LW. Ellipses represent the 95% confidence interval around the centroid of each

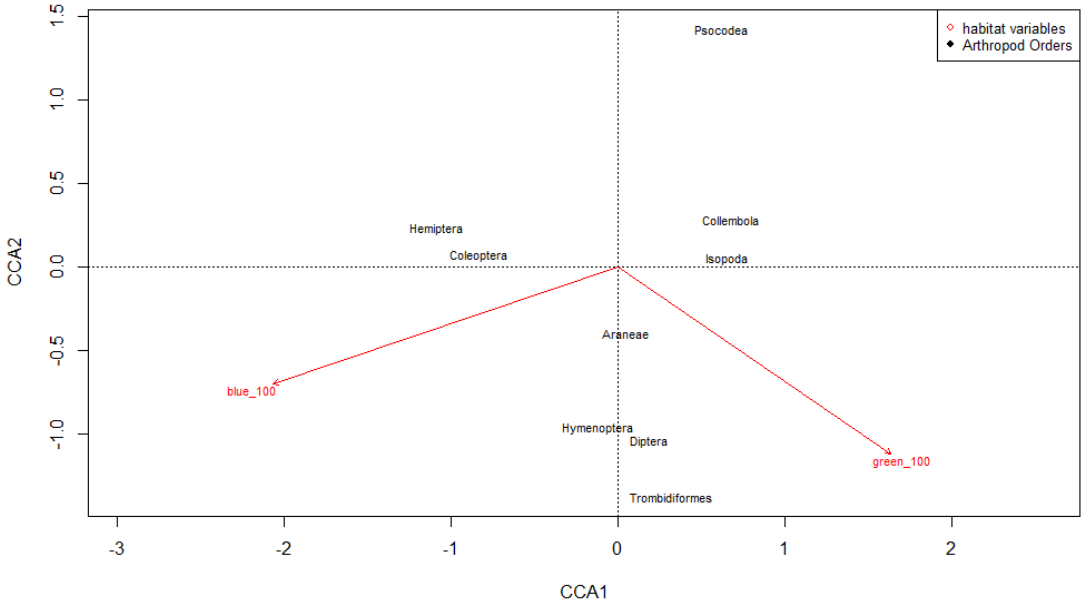
S. Figure 7 illustrates the dissimilarity of plant composition. The PC1- and PC2-axis explain 92.6% and 4% of the variation, respectively. The distinct clustering two LWs highlights their unique community composition. PERMANOVA results substantiate the significant influence of wall type on community structure ($F = 14.64$, $R^2 = 0.65$, $p = 0.008$).

Canonical Correspondence analysis of landscape-level characteristics



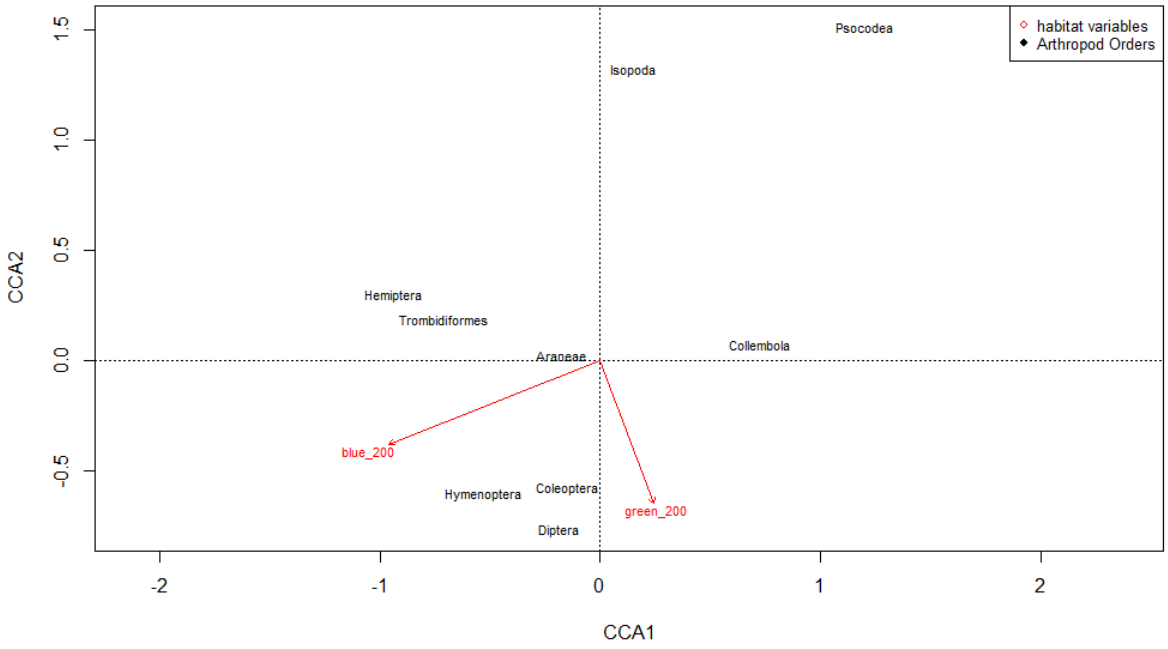
Supplementary Figure 8. CCA of landscape level characteristics at r = 20.

The environmental variables included in this model accounted for 30.22% (inertia = 0.2911) of the variance (F (2) = 8.66, p < 0.001***). In this model, the CCA1- and CCA2-axis explain 67.61% and 32.39% of the habitat variables on arthropod order relationships, respectively.



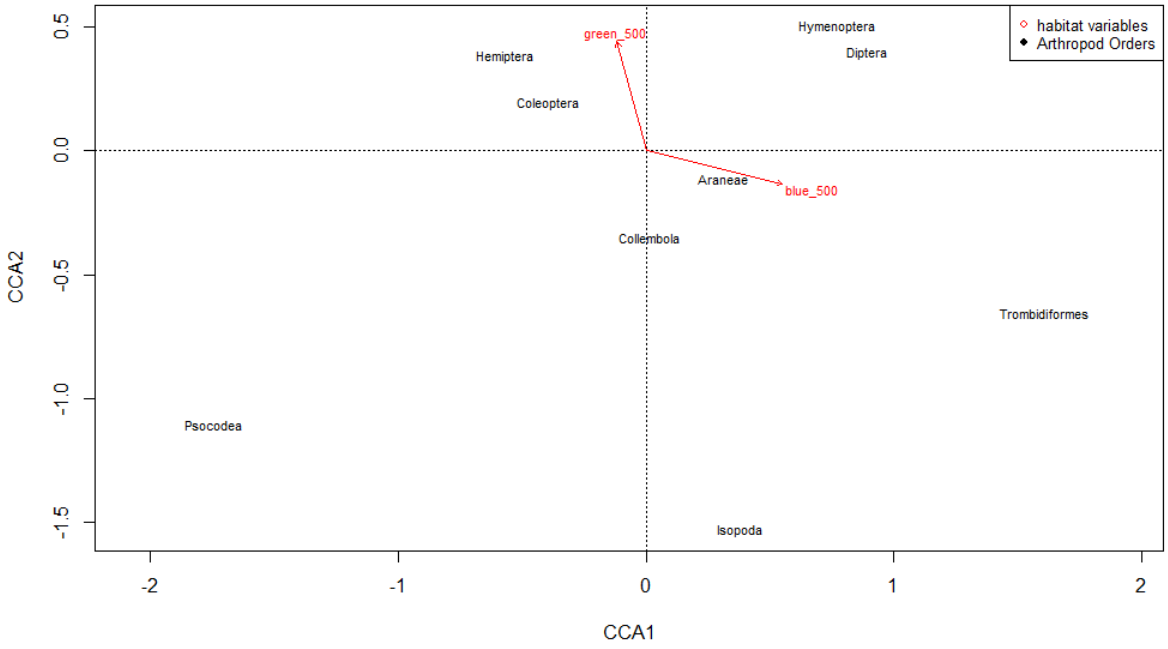
Supplementary Figure 9. CCA of landscape level characteristics at r = 100.

The environmental variables included in this model accounted for 40.94% (inertia = 0.3943) of the variance (F (2) = 13.86, p = 0.001***). The CCA1- and CCA2-axis explain 81.59% and 18.41% of the habitat_100 variable – arthropod order relationships, respectively.



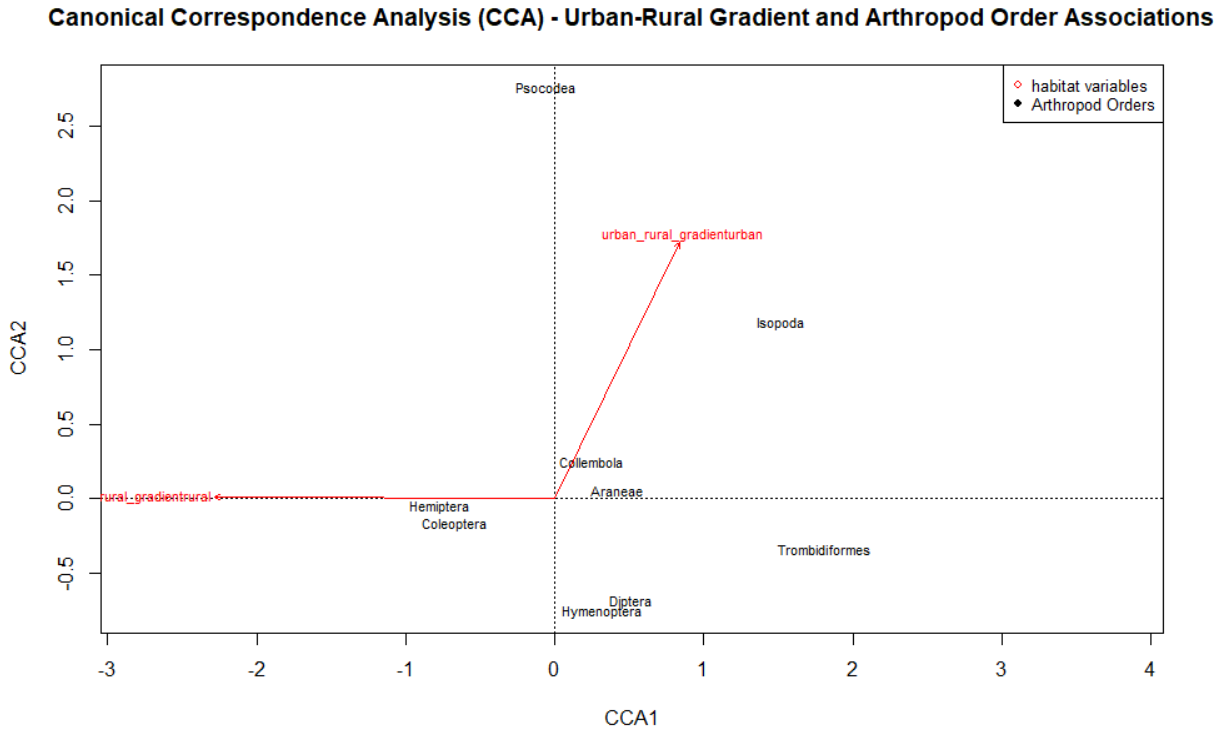
Supplementary Figure 10. CCA of landscape level characteristics at r = 200.

The environmental variables included in this model accounted for 30.38% (inertia = 0.2926) of the variance (F (2) = 8.72, p < 0.001***). The CCA1- and CCA2-axis explain 90.70% and 9.29% of the habitat_200 variable – arthropod order relationships, respectively.

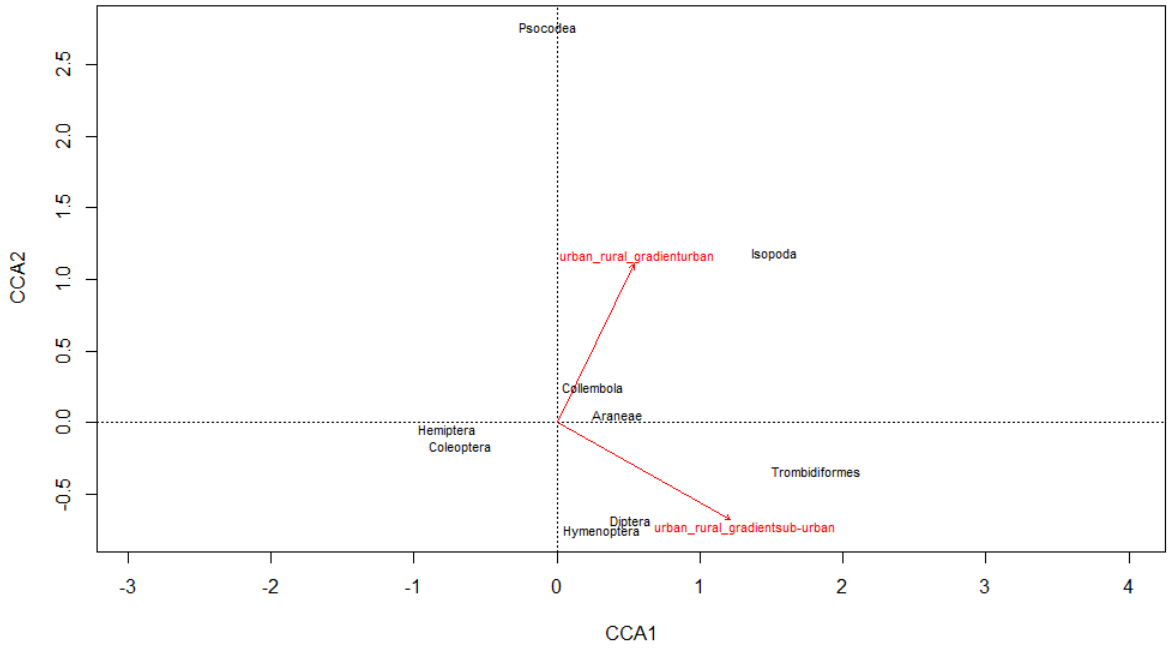


Supplementary Figure 11. CCA of landscape level characteristics at r = 500

The environmental variables included in this model accounted for 10.36% (inertia = 0.0998) of the variance (F (2) = 2.31, p = 0.028*). In this model, the CCA1- and CCA2-axis explain 73.33% and 26.66% of the habitat variables on arthropod order relationships, respectively.



Supplementary Figure 12. CCA of landscape level characteristics with the categorical variable (urban, sub_urban and rural). These two figures represent the same plot.



The environmental variables represented by the urban_rural_gradient in this model accounted for 13.19% (inertia = 0.1270) of the variance in the arthropod order composition (F (2) = 3.04, p = 0.008**). The CCA1 and CCA2 axes explain 70.02% and 29.98% of the urban-rural gradient – arthropod order relationships, respectively.