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Contribution of Green Roofs to the Biodiversity of Lisbon

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2024

Aos meus sobrinhos e sobrinhas,

aos de sangue e aos de coração,

aos que já cá estão e aos que hão de chegar:

que o mundo que vos deixo seja melhor do que aquele que encontrei.

Acknowlegments

Há pessoas com sorte, e depois existo eu – a mais sortuda de todas. Por estar rodeada de pessoas que me apoiam, quer na minha vida pessoal, quer académica. Por ter conseguido fazer uma Dissertação a trabalhar com dois grupos que adoro e me fascinam (as aves e os artrópodes). Por nessa jornada ter sido acompanhada pelas melhores orientadoras que podia pedir. É bom ser-se orientada por boas cientistas, mas ter a oportunidade de ser acompanhada por quem é tão boa pessoa quanto boa cientista é ainda melhor. Ao longo deste ano foram fonte de motivação e de confiança, e tiveram a capacidade incrível de acalmar a minha ansiedade e me fazer acreditar que iria conseguir (e não é que consegui mesmo?). Obrigada, Ana e Patrícia, espero que esta seja apenas a primeira vez que tenho o privilégio de fazer ciência convosco.

Passando então aos agradecimentos à multidão de pessoas que me acompanhou, antes de mais, quero agradecer aos meus pais, pois foi o seu apoio inabalável que me permitiu chegar até aqui. Por entre fases de falhanço e sucesso, questões de saúde física e mental e, em geral, os stresses (grandes e pequenos) da vida académica e do Mestrado (e correspondente Dissertação), nunca me senti só. Tudo isto se leva melhor quando temos alguém que nos ouve reclamar durante 5 minutos sem parar, seguidos de mimos e um episódio de uma dada série de crimes que ainda agora começou e já sabemos quem é o culpado. Obrigada pelo vosso amor, paciência e dedicação. Este trabalho é tão meu quanto vosso, pois foram vocês que fizeram de mim quem sou.

À Maria, ao Lucas, à Gabriela e ao Yoda, os pequeninos da minha vida, obrigada por fazerem parvoíces e me fazerem rir até me esquecer de todas as minhas responsabilidades.

Ao João, obrigada por me distraíres quando precisei, me ajudares a focar quando tinha de ser e, acima de tudo, obrigada por me ouvires a falar de bicharada como se tudo o que eu digo fizesse o maior sentido do mundo para ti.

Mil obrigadas ao Tiago e à Beatriz, os melhores ajudantes que podia ter tido, em todos os aspetos. Vocês tornaram isto o mais fácil e agradável possível, especialmente quando o trabalho de campo era tão bem coordenado que dava para passar a beber um cafezinho e comer qualquer coisinha doce.

Obrigada a todos os que partilharam comigo a 2.5.41, trabalharam a meu lado e muitas vezes me acompanharam no "alguém quer café?" e "vou ao bar, alguém quer vir?" – Rita, Leonor, Ritinha, Sérgio, Cati, Manel, Inês, (Maria) Inês, e ao Rafael, que também me acompanhou muito na saga do "que bicho é este?" e confiou no meu *expertise* relativo à sua bicharada também.

Obrigada, Joana, Constança, Daniela, Madalena, Fattha e Duda, que mesmo não pescando nada do tema, só vos faltou abanarem pompons e gritar "tu consegues!".

Obrigada ao Afonso e ao Gonçalo pela ajuda no tratamento estatístico, quase me fizeram gostar a sério disso!

Obrigada a todas as pessoas do TMB, que foram dando sugestões e me orientaram e apoiaram da melhor maneira, e que elogiaram as bolachas que faço para os piqueniques. Ainda um obrigada especial ao Professor Jorge Palmeirim, que ainda ajudou este trabalho dando-nos acesso à bonita cobertura verde do seu condomínio.

À Viviana agradeço pela ajuda que deste sempre que pudeste, mesmo com tanta coisa que também tinhas por fazer, e dou-te ainda os parabéns. Voltar ao Mestrado depois de tanto tempo não é fácil, mas deu para ver que te deste de corpo e alma, e já podes dizer "consegui!".

Obrigada a toda a equipa do GRAVITY, com um obrigada especial à Joana Pernes e à Ana Paula Falcão, que fizeram a identificação das coberturas verdes utilizadas neste trabalho. Obrigada ainda à Cristina, coordenadora do projeto. São pessoas como ela, que acreditam na importância da interdisciplinaridade (e acham piada a isto da Biologia!), que tornam tudo isto possível.

Obrigada à Fundação Calouste Gulbenkian e à Fábrica de Água de Alcântara, em especial a Dra. Paula Côrte-Real e a Dra. Sara Duarte, que foram o nosso contacto com estas entidades e nos receberam sempre como se fôssemos da casa.

Finalmente, obrigada a todas as pessoas não mencionadas aqui pelo nome que tiraram algum do seu tempo para me ouvir, a toda a gente que me colocou questões ou fez sugestões, e a toda a gente que me permitiu esquecer as minhas responsabilidades, mesmo que durante pouco tempo (afinal isto não se escreve sozinho!).

Esperem que gostem tanto de ler a minha Dissertação quanto eu gostei de a fazer, mas espero que não demorem tanto a lê-la quanto eu levei a fazê-la.

Resumo

Prevê-se que o crescimento da população humana e a sua progressiva concentração em áreas urbanas irá levar à contínua expansão das cidades nas próximas décadas. Este aumento exige mais espaço e mais recursos, resultando inevitavelmente na fragmentação e destruição de habitats naturais. Perante este cenário, torna-se cada vez mais urgente procurar soluções que possam mitigar, pelo menos em parte, os impactos negativos na biodiversidade. Nesse contexto destacam-se as Soluções Baseadas na Natureza (ou Nature-Based Solutions – NBS) que, especificamente no contexto urbano, têm como objetivo promover um crescimento urbano sustentável integrando questões ambientais, sociais e económicas.

As Coberturas Verdes são um exemplo de Solução Baseada na Natureza em que a infraestrutura construída, como os telhados de edifícios ou áreas por cima de parques de estacionamento subterrâneos, é parcial ou totalmente coberta por vegetação. Estas infraestruturas oferecem uma série de benefícios bem descritos e analisados, tanto para as áreas urbanas como para o bem-estar humano, como a retenção de águas pluviais, a redução da temperatura, a melhoria da qualidade do ar e até benefícios económicos. No entanto, existe uma desproporção entre o número de estudos que se focam nestas questões e aqueles que se dedicam a explorar a importância destas infraestruturas para a biodiversidade urbana e a sua integração na matriz das cidades. A cidade de Lisboa não é exceção a esta realidade. Estudos prévios feitos nesta cidade focaram-se principalmente na viabilidade económica da sua instalação, dando ênfase aos seus benefícios melhor descritos, como a regulação térmica, isolamento sonoro e valor estético, com menos atenção dada ao impacto das coberturas verdes na biodiversidade. Lisboa tem diversos espaços verdes, espalhados pela cidade, com tamanhos, comunidades vegetais e estrutura variáveis. O maior destes espaços verdes é o Parque Florestal de Monsanto (PFM), com cerca de 900 hectares, que está conectado a vários pontos da cidade através de corredores verdes. As coberturas verdes oferecem novas possibilidades para a implementação de mais áreas verdes na matriz urbana de Lisboa, contribuindo para estes corredores.

As aves são um grupo faunístico bem conhecido e amplamente utilizado em estudos ecológicos, sendo relativamente fáceis de detetar e observar, têm amplas distribuições e são bons indicadores de alterações ambientais. Especificamente em meio urbano, alguns autores têm vindo a descrever as aves como indicadores da complexidade ecológica da matriz urbana, já que respondem a diferentes aspetos dentro da mesma. Alguns exemplos incluem o favorecimento de espécies generalistas em zonas com maior desenvolvimento urbano e diminuição da riqueza específica com o aumento da perturbação, por oposição aos espaços verdes, que apresentam níveis mais elevados de riqueza e *evenness* (a proporção de abundância de cada espécie relativamente às outras espécies dentro da comunidade). Relativamente a coberturas verdes, há também estudos que indicam que as coberturas podem oferecer recursos adicionais às comunidades de aves e aumentar a conectividade de habitat, inclusive durante a época de reprodução.

Os artrópodes são outro grupo faunístico que é usado com frequência como indicador ambiental, já que são relativamente fáceis de amostrar, são um grupo altamente diverso (inclusive funcionalmente), e respondem de forma relativamente rápida a alterações ambientais. No passado já foi demonstrado que a riqueza de artrópodes tende a diminuir de forma geral com níveis mais altos de urbanização, e que um aumento de impermeabilização das superfícies contribui para diminuição da diversidade deste grupo. Em ambientes urbanos, as coberturas verdes parecem complementar espaços verdes pré-existentes, podendo ser colonizadas pelas comunidades de zonas circundantes, especialmente coberturas com maiores dimensões e instaladas em paisagens urbanas com mais vegetação. Foi também demonstrado

em estudos anteriores que, quando comparadas a telhados convencionais, os telhados verdes apresentam maior abundância de artrópodes.

Assim, este estudo tem três objetivos principais: (1) caracterizar as comunidades de aves e artrópodes que utilizam as coberturas verdes de Lisboa, (2) comparar estas comunidades em duas tipologias de coberturas verdes (Intensivas e Extensivas), e (3) comparar as comunidades das coberturas verdes com as de outras estruturas presentes na matriz da cidade, utilizados como controlos – jardins urbanos (jardins convencionais, que não configuram coberturas) e áreas cinzentas (áreas com pouca a nenhuma vegetação).

Para tal, foi realizada uma avaliação das comunidades que utilizam as coberturas verdes de Lisboa através de métodos tradicionais de amostragem: pontos de escuta de 10 minutos para as aves, e transetos de busca ativa de 30 metros para os artrópodes, em duas épocas (inverno 2023-2024 e primavera 2024), em coberturas verdes que abrangiam a maior diversidade possível de locais na cidade. O número de pontos de escuta e transetos realizados em cada cobertura variou, tendo em conta fatores como a área da cobertura e a estrutura da vegetação. As aves foram, na sua maioria, tratadas ao nível da espécie, enquanto os artrópodes foram identificados até ao nível taxonómico mais baixo possível, sendo tratados ao nível da família.

Para a seleção das coberturas verdes a amostrar foram tidas em conta as boas condições de manutenção) e acesso (com preferência para locais públicos), bem como área suficiente para proceder à amostragem quer de aves, quer de artrópodes. Procurou-se ainda, para o maior número possível de coberturas verdes, ter zonas controlo (jardins urbanos e zonas cinzentas) afastadas num raio máximo de 250 metros da cobertura correspondente. Para comparação entre tipos de coberturas, foram amostradas 19 coberturas verdes, divididas entre Extensivas (aquelas que apenas tinham substratos herbáceos e/ou arbustivos) e Intensivas (coberturas que incluem também um estrato arbóreo). Para comparação entre habitats, foram amostrados 11 locais de cada tipo: coberturas verdes, jardins urbanos e zonas cinzentas. Posteriormente, as comunidades foram então comparadas através de métricas como o índice de Shannon, a abundância e a riqueza de espécies (aves) ou famílias (artrópodes), além de (nalguns casos) curvas de rarefação e Non-Metric Multi-Dimensional Scaling (NMDS).

Os resultados mostram que, no caso das aves, existem diferenças estatisticamente significativas entre coberturas verdes Extensivas e Intensivas quando comparados o índice de Shannon e a riqueza específica, bem como os resultados das curvas de rarefação. As coberturas Intensivas apresentam comunidades de aves mais diversas. A análise NMDS mostra uma maior variabilidade nas coberturas Extensivas, enquanto as Intensivas parecem mais semelhantes entre si. Relativamente aos artrópodes, esta comparação não revelou resultados significativos, o que pode ser atribuído possivelmente ao tipo de amostragem utilizada e à diferença no número de locais entre amostras. Quando comparados os tipos de habitat, a maioria das análises – índice de Shannon, abundância, riqueza e curvas de rarefação – indicou que, para as aves, não há diferenças estatisticamente significativas entre os espaços verdes amostrados, coberturas verdes e jardins urbanos, mas que estes são distintos das zonas cinzentas. A exceção a estes resultados verifica-se na comparação da riqueza e abundância, especificamente no inverno, em que a diferença entre coberturas verdes e zonas cinzentas é apenas quase significativa – ainda assim, não se observa diferença entre as coberturas verdes e os jardins urbanos. A análise NMDS apresentou resultados que corroboram as análises realizadas na época da primavera. Em relação aos artrópodes, as análises mostraram resultados estatisticamente significativos na primavera, época na qual foram semelhantes aos obtidos para as aves, sem diferenças entre coberturas verdes e jardins urbanos.

Em geral, estes resultados evidenciam, por um lado, a importância da complexidade/diversificação dos habitats, que oferecem uma maior quantidade de recursos alimentares e de refúgio, e, por outro lado, salientam o potencial benéfico da instalação de coberturas verdes sempre que possível, em alternativa a infraestruturas sem vegetação. Assim, esta investigação não só contribui para uma compreensão mais completa das coberturas verdes e do impacto da sua estrutura vegetal nas comunidades faunísticas urbanas, como também as identifica como uma possível estratégia para aumentar a área ocupada por espaços verdes nas paisagens urbanas, enfatizando a sua importância crítica para a biodiversidade de ambientes urbanos.

Palavras-chave: ecologia urbana, coberturas verdes, aves, artrópodes, conservação da biodiversidade

Abstract

Green roofs are a type of Nature-Based Solution (NBS) where built infrastructure (as building rooftops or spaces above underground parking structures) is partially or fully covered by vegetation. These infrastructures offer well documented and analysed benefits for urban areas and human well-being, including rainwater retention, temperature reduction, air quality improvement, and economic benefits. However, there is a notable disproportion between the number of studies that focus on these aspects and those that explore the role of green roofs in supporting urban biodiversity and their integration into the urban matrix.

As such, this study aims to contribute to fill that knowledge gap, having three main objectives: (1) characterizing bird and arthropod communities using green roofs, (2) comparing these communities in different types of green roofs (Intensive and Extensive), and (3) comparing the communities of green roofs with those of other structures present in the city's matrix – urban gardens and grey areas (with little to no vegetation).

For this, biodiversity assessments were carried out in 19 green roofs in Lisbon, through the use of traditional sampling methods: point counts for birds, and active search transects for arthropods. Results show that, for birds, there was statistically significant differences between Extensive and Intensive green roofs, with the latter having more diverse bird communities. Furthermore, for the metrics used, this study shows that the bird and arthropod communities that occupy the sampled green roofs are similar to those in conventional urban gardens, and that both these structures are more diverse than grey areas.

In conclusion, this study not only contributes to a more comprehensive understanding of green roofs and the impact of their plant structure on urban faunistic communities, but also highlights their potential as a mean to expand green spaces within urban landscapes, highlighting their critical importance for biodiversity in urban environments.

Keywords: urban ecology, green roofs, birds, arthropods, biodiversity conservation

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List of Abbreviations, Acronyms and Symbols

Alameda – Alameda Dom Afonso Henriques

ANCV – Associação Nacional de Coberturas Verdes

ANOVA – Analysis of Variance

Ciências ULisboa – Faculdade de Ciências da Universidade de Lisboa

ETAR – Estação de Tratamento de Águas Residuais

FCT – Fundação para a Ciência e Tecnologia

GRAVITY – Green Roofs/WAlls BiodiVersITY. Evaluating the Contribution of Green Roofs/Walls for cities' Biodiversity with the support of Citizen Science

Gulbenkian – Fundação Calouste Gulbenkian

IndVal – Indicator Value(s)

IST – Instituto Superior Técnico

NBS – Nature-Based Solutions

NMDS – Non-metric Multidimensional Scaling

PFM – Parque Florestal de Monsanto

1. Introduction

It is estimated that, by 2050, 68% of the human population will live in urban areas (United Nations, 2018). The expansion of urban areas increases habitat fragmentation and destruction (Xiao *et al.*, 2020), due to the construction of infrastructures for housing, businesses and services, as well as road networks. The rhythm at which urbanization is expanding also leads to higher levels of pollution, resource depletion, rising temperatures, decline in biodiversity (Xing *et al.*, 2017), as well as community homogenization (McKinney, 2006). All these factors increase the need for the creation of solutions that contribute to make this urban growth more sustainable.

Nature-based solutions (NBS) are defined by the United Nations (2022) as "(…) actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits (…)." As such, these solutions have emerged as essential strategies for making cities more sustainable and enjoyable places to live (Teotónio *et al.*, 2021, Xing *et al.*, 2017). In urban areas, some examples of NBS mentioned by the European Commission (2020) are the construction of green corridors, sustainable urban drainage systems, pollinator sites and green roofs. The European Commission has also highlighted that, in the specific context of urban areas NBS, including green roofs, "can bring additional and more diverse nature into cities", although the impact of these infrastructures on urban fauna have not yet been well studied.

The term "green roof" is most commonly used when referring to the top of buildings that have been partially or completely covered by a layer of vegetation (as well as other layers, like an impermeable membrane and growth medium for the vegetation) (Castleton *et al.*, 2010), but the term can in fact refer to any built infrastructure on top of which vegetation has been installed, even if at ground level (an example are green areas that have been built on top of underground parking structures). Depending on soil depth and required maintenance, green roofs are generally classified into two categories – intensive and extensive (Rowe, 2011) (although sometimes another category is mentioned – semi-intensive), with intensive green roofs requiring deeper soil and more maintenance than extensive ones (ANCV, 2019). It has already been proven that green roofs bring benefits to the sustainability of urban areas, like temperature reduction, rain-water retention and improvement of air quality (Castleton *et al.*, 2010), along with economic benefits (Teotónio *et al.*, 2021), positive impact on human well-being through noise insulation (Connelly, 2015) and the creation of recreational spaces that are also aesthetically pleasing (Teotónio *et al.*, 2021, Xing *et al.*, 2017).

Williams *et al.* (2014) stated that it was premature to claim that green roofs had biodiversity benefits, and urged ecologists to work with the industry, to increase knowledge on the topic. Recently, Tiago *et al.* (2024) reported that, in the past decade and a half, there's been an increase of interest in the effects of green roofs and walls on biodiversity, but some knowledge gaps remain. For example, many studies focus on comparing animal communities in green roofs to those found on conventional roofs (Partridge & Clark, 2018; Washburn *et al.*, 2016) or surrounding areas with varied proportions of green and grey spaces (Eakin *et al.*, 2015), but others have no control areas (Fabián *et al.*, 2021) and no direct comparison with other types of green spaces. This leaves a knowledge gap regarding how green roofs perform relative to more established green spaces like urban gardens, which often have more diverse and complex vegetation structures.

Tiago *et al.* (2024) also found that most studies on this topic are focused on arthropods, and that most studies have been done in areas with Continental Temperate Climate. For example, no studies focusing on birds have been conducted in Mediterranean climates, and no studies have been conducted in Portugal. In Spain, Benedito Durà *et al.* (2023) compared flying arthropod communities from one green roof, one conventional roof and two ground-level gardens. Most of the studies found focus on arthropods and birds, but few analyse these two groups simultaneously (Tiago *et al.*, 2024). Furthermore, many studies either focus on a single group of arthropods, such as bees (Tonietto *et al.*, 2011), or only on few specific groups (Braaker *et al.*, 2014). However, Fábian *et al.* (2021) in Argentina identified all sampled arthropods to the species level, and Partridge & Clark (2018) in the US worked with both birds and arthropods, comparing green roofs with conventional roofs in their vicinity.

Birds are a well-known animal group, widely used in ecological studies. For this contributes the fact that most bird species are relatively easy to detect and observe, are widely distributed and are known to be good indicators of large-scale environmental changes, and thus quite useful to evaluate environmental quality/health (Mekonen, 2017). Specifically, in urban environments, some authors have shown that bird communities respond to the different aspects within the urban matrix and can therefore be used as "indicators of its ecological complexity". For example, in general, more developed urban areas tend to favour generalist species, and species richness decreases with increased urban disturbance, as opposed to urban green areas, that have higher species richness and evenness (Ortega-Álvarez & MacGregor-Fors, 2009). When it comes to green roofs, a study done in the Midwestern United States of America by Eakin *et al.* (2015) suggested that both extensive and intensive green roofs may provide additional resources for bird communities and increase habitat connectivity, including during breeding season.

Arthropods are another animal group that is often used as an environmental indicator, since they are relatively easy to sample, are very diverse (including in ecological functions), and respond relatively quickly to environmental changes (McIntyre, 2000). Previous studies have already shown that arthropod richness generally declines with higher levels of urbanization (Fenoglio, 2020) and that increased surface imperviousness contributes to a reduced diversity, impacting insect orders like Hymenoptera and Lepidoptera, which include key pollinators (Fenoglio, 2020; Lagucki *et al.*, 2017). In urban environments, green roofs seem to complement existing green areas and can be colonized by arthropod communities from nearby zones, especially larger green roofs and those installed in more vegetated urban landscapes (Fabián *et al.*, 2021). Moreover, it has also been shown that, when compared to conventional roofs, green roofs have increased arthropod abundance (Partridge & Clark, 2018).

Therefore, it seems that, in general, the vegetation structure of urban green spaces affects both birds and arthropods. For example, the use of native plant species and the heterogeneous structure of urban green habitats have been shown to help to promote biodiversity in urban green spaces (Threlfall *et al.*, 2017; Beninde *et al.*, 2015, Paker *et al*., 2014), and that even small green spaces can help promote biodiversity within cities (Liordos *et al.*, 2021), especially when in the proximity to other green areas (Chamberlain *et al.*, 2007) including green roofs (Braaker *et al.*, 2014). These factors, together with size, characteristics of the surrounding landscape (Partridge & Clark, 2022) and even maintenance (Deng & Jim, 2016), should be taken into account when installing green roofs.

In the specific case of Lisbon, previous studies on green roofs have primarily focused on the economic feasibility of their installation, emphasizing well-known benefits such as improved thermal regulation, sound insulation, and aesthetic value (Teotónio, 2016, Cruz *et al.*, 2017, Melo *et al.*, 2020). However, less attention has been given to their impact on biodiversity. Lisbon has many green spaces, scattered throughout the city, with varying sizes, plant communities and structure. The greatest is Parque Florestal de Monsanto (PFM) – a forest park with about 900 hectares, that is connected to many points of the city through green corridors (Câmara Municipal de Lisboa, 2023). Green roofs may offer new possibilities for the implementation of more vegetated areas within the urban matrix of Lisbon, contributing for these corridors, especially because it was estimated by Silva *et al.* (2017) that about 52% of the city's grey area had potential for green roof installation.

The main objective of this study is to understand the importance of green roofs for the communities of both birds and arthropods, in the city of Lisbon. The work is divided in three main objectives: (1) characterizing bird and arthropod communities that use green roofs, (2) analysing the effect of different types of green roof vegetation complexity on these communities, and (3) comparing birds and arthropods communities present on green roofs with those of urban gardens and grey areas.

This work was developed as a part of the GRAVITY (Green Roofs/WAlls BiodiVersITY. Evaluating the Contribution of Green Roofs/Walls for cities' Biodiversity with the support of Citizen Science) project (10.54499/2022.02093.PTDC), funded by Fundação para a Ciência e Tecnologia (FCT), promoted by Instituto Superior Técnico (IST), in collaboration with Faculdade de Ciências da Universidade de Lisboa (Ciências ULisboa).

2. Methods

2.1. Characterization of the Study Area

This study took place in Lisbon, the capital of Portugal, which is the most populated city of the country, with almost 550 000 inhabitants in 2021 (INE, 2021). According to the Köppen-Geiger updated climate classification (Kottek *et al.*, 2006, Peel *et al.*, 2007), Lisbon has the classification Csa, which translates to a warm temperate climate with dry, hot summers.

Sampling was done on several green roofs across different areas of the city of Lisbon. An identification of the currently existing green roofs within the city was first made by other elements of the GRAVITY project team, belonging to the Civil Engineering Department at IST, who listed a total of about 50 green roofs. Using these as a starting point, satellite images were analysed, and *in-situ* confirmation of the sites was done to access their suitability for this study. The criteria for the choice of sites included logistics (accessibility- with preference for public sites), sufficient area for bird and arthropod sampling and, for some of the green roofs, the existence of adequate control areas in their vicinity. The location and structure also influenced the selection process, since achieving the objectives of this study required covering a wide area within the city of Lisbon, including different types of green roofs. So, of the initial data set, 19 green roofs were chosen for sampling (Fig. 1).

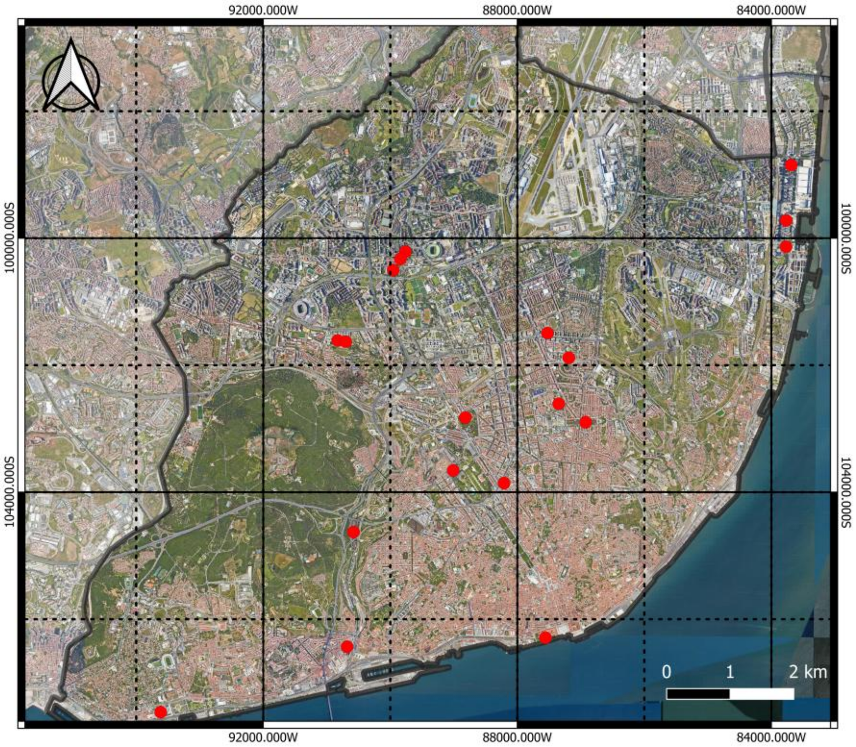


Fig. 1 – Map with the locations of the 19 sampled green roofs (red dots) within the city of Lisbon (Map created using the Free and Open Source QGIS).

The vast majority of the 19 sampled green roofs were constructed at ground level and accessible to the general public, with the exceptions of Fábrica de Água de Alcântara (henceforth, ETAR de Alcântara), and some of the green roofs at Fundação Calouste Gulbenkian (henceforth, Gulbenkian) that were located at the top of the buildings. Appendix A presents a detailed list of all the sampled sites included in this study.

2.2. Classification of Green Roofs

As defined by *Associação Nacional de Coberturas Verdes* (ANCV, 2019), and previously mentioned in the Introduction, depending on soil depth and required maintenance, green roofs can be classified in three types: extensive, semi-intensive and intensive. Extensive green roofs require low maintenance and have shallower soil, so they can only include herbaceous and/or succulent plants, while intensive green roofs require high maintenance and have a much deeper soil, meaning their structure allows for shrubbery and trees to be planted. Semi-intensive green roofs sit at a "mid-way point" of maintenance and soil depth and cannot have trees. For the purpose of this study, the Green Roofs classified as extensive and semi-intensive were merged into a single category, referred hereafter as Extensive. Intensive green roofs are put in their own category. Examples of Green Roofs in each of these categories sampled during this study can be seen in Fig. 2. As one of the objectives of this work was to compare different types of Green Roofs, to understand how the plant structure might affect the communities that colonize these spaces, it was important to sample green roofs of every category. However, most accessible green roofs in suitable condition for sampling (e.g. sufficient area), were Intensive, resulting in an unbalanced sample.

All sampled green roofs and their respective category are listed in Table 1. Specifically, in the case of the green roof of the Vodafone building, although it has some trees and high shrubbery, because of its very small area, it was decided that it was more adequate to included it in the Extensive category. For Gulbenkian, the site as a whole is included in both categories, since two out of the five sampling points were located in Extensive green roofs, and the other in Intensive sites.

Fig. 2 – Examples of Extensive (A) and Intensive (B) Green Roofs sampled during this study: A – ETAR de Alcântara; B – Jardim Ruy Jervis d'Athouguia. Credits: Patrícia Tiago.

Table 1 – List of the 19 sampled green roofs, their location (by parish) in Lisbon and its classification regarding their type: Extensive *versus* Intensive. Extensive refers to green roofs with shallower soil, less required maintenance and only grass and/ or shrubs planted, while Intensive refers to green roofs with deeper soil, higher maintenance requirements and possibility for trees to be planted as well.

GREEN ROOF	LOCATION	TYPE
ETAR Alcântara	Alcântara	Extensive
Rua Prof. Juvenal Esteves	Alcântara	Intensive
Avenida Estados Unidos da América	Alvalade	Intensive
Jardim Ruy Jervis d'Athouguia	Alvalade	Intensive
Jardim Irmã Lúcia	Areeiro	Intensive
Alameda D. Afonso Henriques	Areeiro/ Arroios	Extensive
Jardins do Palácio Sottomayor	Arroios	Intensive
Fundação Calouste Gulbenkian	Avenidas Novas	Extensive & Intensive
Jardim Amália Rodrigues	Avenidas Novas	Intensive
Centro Cultural de Belém	Belém	Intensive
Azinhaga das Galhardas	Lumiar	Intensive
Prof. Francisco Caldeira Cabral and Prof. António de Sousa Franco Gardens	Lumiar	Intensive
Rua Prof. Francisco Gentil	Lumiar	Intensive
Campus de Justiça	Parque das Nações	Intensive
Junta de Freguesia Parque das Nações	Parque das Nações	Intensive
Vodafone Parque das Nações	Parque das Nações	Extensive
Doca da Ribeira das Naus	Santa Maria Maior	Extensive
Rua João Chagas (1)	São Domingos de Benfica	Intensive
Rua João Chagas (2)	São Domingos de Benfica	Intensive

2.3. Definition of Controls

One of the objectives of this study was to compare biodiversity records in green roofs with other urban infrastructures so, for 11 of the selected green roofs, two types of control sites were selected: urban gardens and grey areas. The choice of control locations had to meet the following criteria: (i) the control areas had to be within a 250 m distance from their respective green roofs, (ii) urban gardens were considered vegetated areas that are not installed on building infrastructure (so are not classified as green roofs), and (iii) grey areas were zones with little to no vegetation (i.e., not necessarily devoid of vegetation but, when present, it was extremely sparse and/or existed in minimal quantities) (Fig. 3).

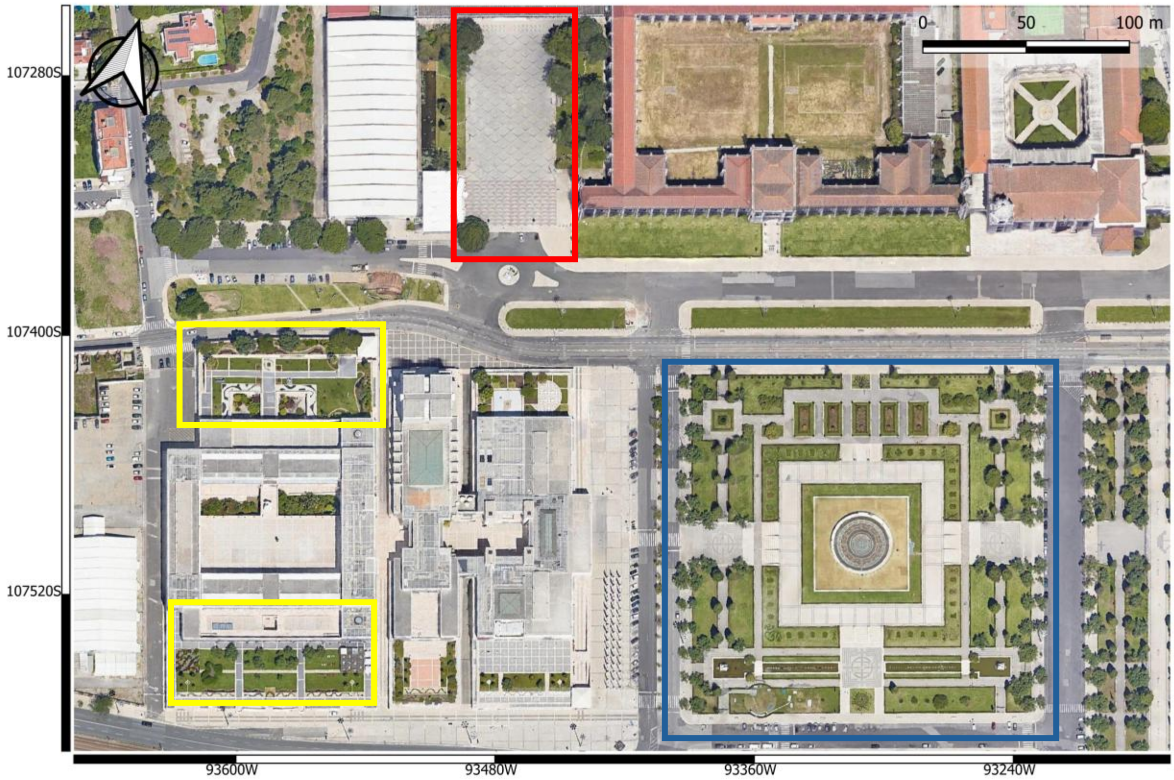


Fig. 3 – Map with an example of a set of green roof and respective controls, in Belém, Lisbon: a) Centro Cultural de Belém (green roofs, in yellow); b) Jardim da Praça do Império (urban garden, in blue), and c) Museu da Marinha (grey area, in red) (map created using the Free and Open Source QGIS).

Thus, for this part of the study, sampling took place in 11 Green Roofs, 11 Urban Gardens and 11 Grey Areas. All these sampled sites, with corresponding habitat type, location coordinates and number of both bird point counts and arthropod transects can be found in Appendix A.

2.4. Field Work

The first sampling season took place from the 4th of December 2023 to the 7th of February 2024 (winter), and the second sampling season between the 10th of April 2024 and the 21st of May 2024 (spring). No sampling sessions were held in days with adverse weather conditions, like rain and strong wind, as these conditions tend to affect the activity of both birds and arthropods, as well as the detection ability of the observer(s). Bird sampling usually started about two hours after sunrise, followed by arthropod sampling (sometimes with some waiting time between these to start arthropod sampling at a more adequate time).

Birds were sampled using 10-minute point counts and every bird seen or heard was recorded, distinguishing between those that were within or outside a radius of 30 m from the observer, and only those within the 30 m were considered for statistical purposes. This specific distance was chosen because it was the one that best adapted to the sampling sites covering most, or all, of the green roof area, and allowing for multiple point counts in bigger sites, without overlapping. In the cases of particularly small sampling areas (such as in the green roofs of Vodafone and the garden space in Largo do Corpo Santo), birds that were seen within the 30 m radius, but were not using the garden/green roof space, were not considered for statistical analysis.

The identification of birds was always made *in-situ* and, in most cases, to the species level. The exceptions were the genera *Larus* (Large White-headed Gulls), represented by *L. fuscus* (Lesser Black-backed Gull), and *L. michahellis* (Yellow-Legged Gull), which can be difficult to distinguish when they are juveniles, and flying at long distances; *Sturnus* (Starlings), more specifically during winter, when both *S. unicolor* (Spotless Starling), and *S. vulgaris* (Common Starling) are present and can be confounded through vocalization; and *Apus* (Swifts), with *A. apus* (Common Swift), and *A. pallidus* (Pallid Swift) not always being distinguishable flying at great heights. For statistical purposes, those species were treated at the genera level, even if the identification was made at a species level, with that information being left as an annotation, to be usable *a posteriori*, if needed.

The number of point counts done at each site was determined by the area to sample, and its characteristics in terms of vegetation. At first, these numbers were determined considering the area of each site using Google Maps (2019) images to assess green roof dimensions, considering that every point had a radius of 30 m, and points should not overlap.

For arthropod sampling, a 30 m transect of active search was surveyed at each site by two observers moving at a relatively constant pace. All arthropods observed within approximately one meter to each side of the transect were recorded. Using an entomological sweep net of 0.4 m diameter, every individual that could not be identified to the family level *in situ* was captured and put into a solution of 70% ethanol, to be identified in the laboratory at Ciências ULisboa. The number of transects done at each site was determined by the same factors that influenced the number of bird point counts. The dimensions of the sampled areas were a critical factor, as transects needed to be sufficiently spaced to prevent mutual influence and avoid repeated observations. The composition of the plant communities was the other major factor considered, as the objective was to cover the greatest variety of plant strata present within each site.

2.5. Laboratory Work

The laboratory work consisted in the observation and classification of all the collected arthropods to the lowest possible taxonomic level. This classification was done using a Leica S6E stereo microscope and appropriate identification keys for the various groups (Canadian Government Publishing, 1993; Choates, 1999; Marshall et al., 2017; Thyssen, 2009). Although the aim was to classify the individuals at least to the family level, in some cases, and for several different reasons – as difficulty in identification and specimen size –, the classification was done at a higher level (e.g. order Collembola, some minute parasitoid Hymenoptera, as well as very small spiders).

2.6. Statistical Analysis

All statistical analysis were done using the statistical software R (v4.2.2; R Core Team 2002), using the packages vegan (Oksanen *et al.*, 2022), iNEXT (Hsieh et al., 2024, Chao et al., 2014) and indicspecies

(De Cáceres & Legendre, 2009) for statistical analysis, and ggplot2 (Wickham, 2016) for data visualization.

For statistical analysis, birds seen or heard not using the sampled areas (green roof, urban garden or grey area), even if they were within the 30 m radius – e.g. birds seen only flying over the area – were not considered, since the goal was to characterize the communities using the habitats being sampled, and including those individuals could skew results. As for arthropods, any specimen not identified to the family level was also not considered for the data analysis in this study. All calculations and comparisons were made at the sampling point/transect level, i.e. when sites had more than one point or transect, the values are calculated per sampling unit, not by averaging values of all sampling units within that site.

Both birds and arthropods were analysed using the same metrics: species or family richness, abundance (number of individuals at a given sampling point), and the Shannon Diversity Index. This index that takes into account the proportion of each species within a community, usually varying between 1.5 and 3.5, with higher values represent more diverse communities with a more even distribution of individuals among species (Magurran, 1988).

Regarding sample mean comparison tests, data was first tested for normality using Shapiro-Wilk tests. Since the assumptions for normality were not met, the existence of statistically significant differences was tested through the use of non-parametric Wilcoxon and Kruskal-Wallis tests (for sets of two and three groups, respectively). Furthermore, when differences within the sets of three groups were found, post-hoc tests (Dunn tests) were performed to assess differences between groups.

When comparing bird communities in Green Roofs, Urban Gardens and Grey Areas, sampled-base rarefaction curves were used to compare richness between groups, as well as determine and compare the completeness of the samples and adequacy of the sample size. Extrapolation of the rarefaction curves was made to double the reference sample size, as recommended by Chao *et al.* (2014).

Finally, Non-metric Multi-Dimensional Scaling (NMDS) was done to further compare bird communities within the sampling sites, grouping them according to the type of green roof category (Intensive versus Extensive), and type of habitat (Green Roof, Urban Garden and Grey Area). For this analysis, the Bray-Curtis dissimilarity index was used to compare sampling points. This index is widely used in biology and ecology to compare community composition based on abundance data (Ricotta, & Pavoine, 2022), which is the case for this analysis, but it should be noted that this dissimilarity index does not use data that only contains zeros (i.e. points that have no individuals), meaning that this can lead to lower sample sizes. Along with this analysis, Indicator Values (IndVal) were calculated to measure the association between a species and a site group: this value hits a maximum (1) when all individuals of a species are found in only one of the groups of sites, or when that species occurs in all the sites within that group (Dufrêne, & Legendre, 1997). For the purposes of this study, bird species and arthropod families were considered as indicators when the indicator value was higher than 50% (IndVal > 0.5) and was statistically significant ($\alpha = 0.05$).

3. Results

3.1. Biodiversity in Green Roofs

A total of 19 green roofs were sampled, which corresponded to a total of 31 bird point counts and 43 arthropod active search transects in each season. Starting with birds, in both seasons, a total of 1899 individuals of 48 bird species were recorded (this includes 2 species within the genera *Larus*, *Sturnus* and *Apus*, which, although not always identified to the species level, had at least one individual of each species confirmed). Out of this total, 642 individuals of 38 species were registered using the green roofs (Appendix C). Regarding arthropods, 64 families, totalling 5150 individuals, were identified in the 19 sampled green roofs (Appendix D).

The maps below (Fig. 4) show the total richness data (number of bird species and arthropod families) in each sampled green roof, in both seasons. The green roof with the highest overall richness was Gulbenkian, with 19 bird species and 25 arthropod families registered (although the highest arthropod richness, 29 families, was registered in Jardim Irmã Lúcia), and the green roof with the lowest richness was Alameda Dom Afonso Henriques (henceforth, Alameda) with only a total of two bird species and one arthropod family observed (Fig. 4).

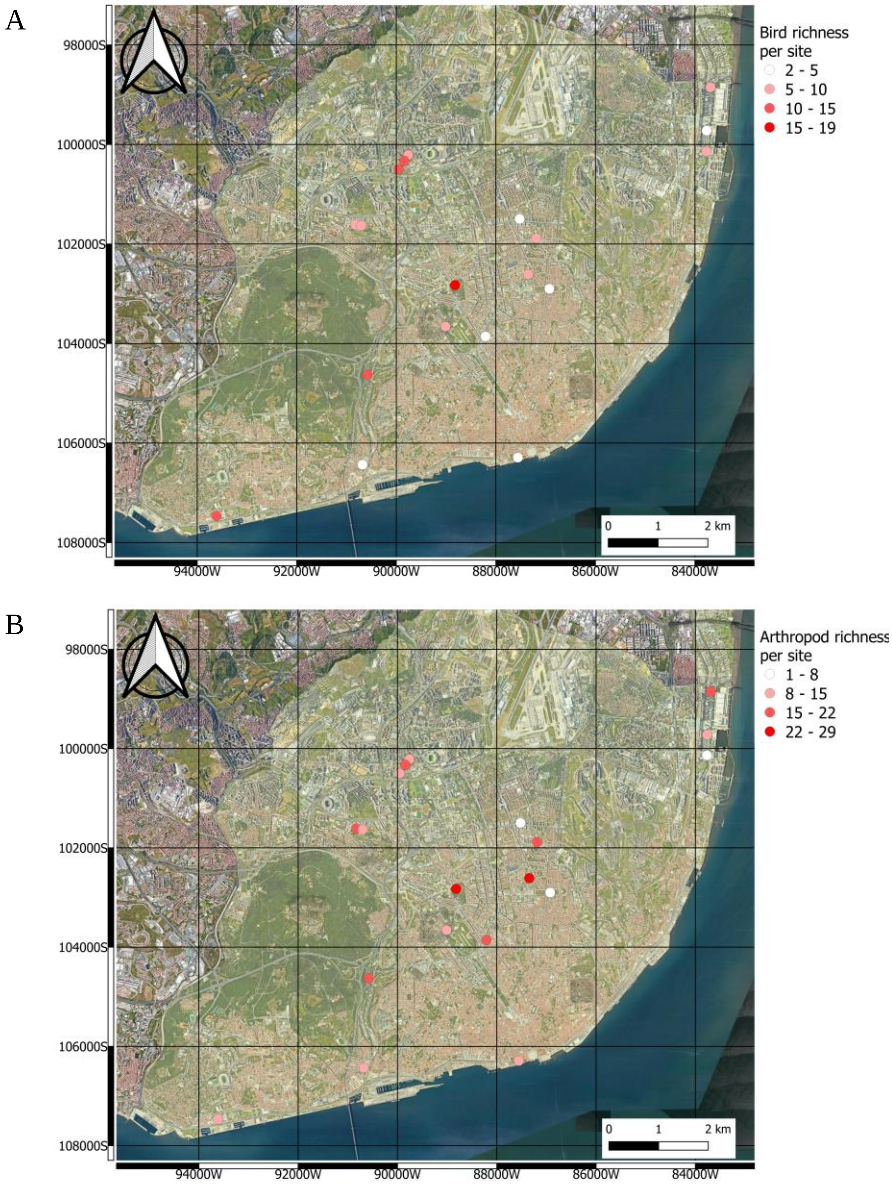


Fig. 4 – Map of the study area in Lisbon (Portugal). Dots represent all 19 sampled green roofs. The colour of the dots represents the bird species richness (A) and arthropod family richness (B), in both sampling seasons winter and spring (maps created using the Free and Open Source QGIS).

Four arthropod orders were not classified to the family level: Entomobryomorpha, Symphypleona (both orders of Collembola), Psocodea and Embioptera. Some Hymenoptera were only classified to the super-family level, and most Acari remained classified only to the sub-class, with Erythraeidae being the only confirmed family (represented by *Balaustium* sp.). Details about the observed bird species and arthropod families, and the sites where they were registered, can be found in Appendixes D and E.

It is worth noting that some bird species were only recorded in one of the seasons, mainly because they are migratory, either coming to Portugal for wintering, as *Phylloscopus collybita* (Common Chiffchaff) and *Sturnus vulgaris*, or breeding, as *Delichon urbicum* (Common House-Martin) and *Hirundo rustica* (Barn Swallow). Furthermore, five non-native species were registered using green roofs, with the most abundant of these being *Estrilda astrild* (Common Waxbill), with about 60 total individuals registered

(48 in winter and 12 in spring), all of them in ETAR de Alcântara. In fact, Gulbenkian and ETAR were the green roofs where more exotic species were recorded (two in each site). *Psittacula krameri* (Rose-ringed Parakeet) was the only exotic species found in more than one site (total of three) and all the other exotic species were detected using only one green roof.

The most common bird species was *Columba livia* var. *domestica* (Domestic Pigeon) with 137 individuals registered, followed by *Passer domestiscus* (House Sparrow) with 97 individuals, and *Turdus merula* (Common Blackbird) with 88 individuals. However, *T. merula* was the most spread species, since it was registered in all but one site. From the total of 19 sampled green roofs, *P. domesticus* was not found only at three sites, and *C. livia* was not found at six sites.

Regarding arthropods, 21 of the 64 recorded families were only found in one of the sampled sites. The most recorded family was Formicidae (recorded in 17 of the 19 sites), followed by Muscidae and Syrphidae (recorded in 15 and 12 sites, respectively).

3.2. Comparison Between Different Types of Green Roofs

Regarding the comparison between Extensive and Intensive green roofs, a total of 31 bird point counts were done, nine of them in Extensive green roofs, and 22 in Intensive ones. Furthermore, from the 43 arthropod transects, 11 and 32 were located in the Extensive and Intensive categories, respectively.

3.2.1. Birds

A total of 36 bird species were registered using the green roofs used for this comparison. A total of 26 species of birds were recorded using Intensive green roofs, both in winter and spring. In Extensive green roofs, 12 and 11 species were recorded, in winter and spring respectively. In winter, the most commonly registered species in Intensive green roofs was *Columba livia*, and in Extensive ones was *Estrilda astrild.* In spring, *C. livia* became the most observed species in Extensive green roofs, while *Passer domestiscus* was the most registered bird species in Intensive ones (Table 2).

Out of all registered bird species, five were found exclusively in Extensive Green Roofs, while 19 were found exclusively on Intensive ones.

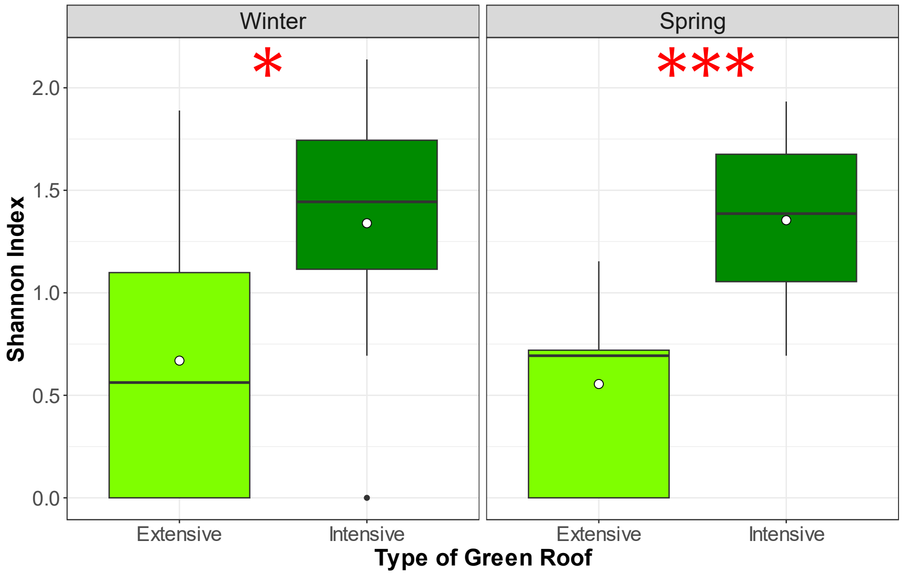
Table 2 - Average abundance (mean number of individuals/point count), of each recorded bird species, on the two types of studied green roofs (Extensive and Intensive) in winter and spring. Non-native species are denoted with an asterisk (*). The three most abundant species in each type of green roof and season are underlined.

	Winter		Spring	
SPECIES	**EXTENSIVE**	**INTENSIVE**	**EXTENSIVE**	**INTENSIVE**
***Acridotheres cristatellus* ***	--	0.18	--	--
***Alopochen aegyptica* ***	--	--	--	0.09
Anas platyrhynchos	--	0.14	--	1.18
***Cairina moschata* ***	0.11	--	--	--
Carduelis carduelis	--	0.05	--	0.05
Certhia brachydactyla	--	0.18	--	0.05
Chloris chloris	--	0.05	--	0.23
Cisticola juncidis	--	0.05	--	--
Columba livia	<u>1.22</u>	<u>2.00</u>	<u>5.78</u>	<u>1.36</u>
Columba palumbus	--	0.36	--	0.36
Corvus corone	--	0.05	--	--
Curruca melanocephala	0.33	0.14	0.22	0.45
Cyanistes caeruleus	--	0.41	--	0.23
Delichon urbicum	--	--	0.11	--
Erithacus rubecula	0.33	0.32	--	0.09
***Estrilda astrild* ***	<u>3.11</u>	--	<u>1.33</u>	--
Fringilla coelebs	--	0.05	--	--
Garrulus glandarius	--	--	0.11	--
Hirundo rustica	--	--	--	0.09
***Larus* sp.**	0.22	0.09	--	0.05
Linaria cannabina	--	--	--	0.05
Motacilla alba	0.33	0.18	--	0.36
Parus major	--	0.09	--	--
Passer domesticus	--	<u>1.64</u>	<u>0.56</u>	<u>2.55</u>
Periparus ater	--	0.05	--	0.09
Phoenicurus ochruros	<u>0.89</u>	0.50	0.44	0.68
Phylloscopus collybita	0.11	1.05	--	0.05
***Psittacula krameri* ***	--	0.14	--	0.18
Regulus ignicapilla	--	--	--	0.05
Serinus serinus	0.22	0.50	0.22	1.05
Spinus spinus	--	0.09	--	--
Streptopelia decaocto	--	--	--	0.05
***Sturnus* sp.**	--	0.14	0.33	0.23
Sylvia atricapilla	--	0.41	--	0.18
Troglodytes troglodytes	0.11	--	0.11	--
Turdus merula	0.22	<u>1.82</u>	0.33	<u>1.95</u>

Pictures representing some of the most abundant bird species are in Appendix F.

The comparison of the Shannon Index shows a significant difference between Extensive and Intensive green roofs, in both seasons (Fig. 5). The Shannon Index winter average values were 0.64 for Extensive and 1.34 for Intensive green roofs, and the spring average values were 0.55 for Extensive and 1.35 for Intensive green roofs (winter: Wilcoxon W = 150, p-value = 0.027; spring: W = 179, p-value <0.001).

Fig. 5 – Boxplots comparing the Shannon index of bird communities on the two types of studied green roofs (Extensive in light



green and Intensive in dark green) in winter and spring. Average values are represented by the white dots. Significance is represented as: * <0.05, ** <0.01, *** <0.001.

When it comes to species richness, the average value in Intensive green roofs was the same in both seasons, 5.05 individuals/point. In Extensive green roofs, the average species richness was of 2.89 individuals/point in winter and 2.22 in spring. The Wilcoxon tests comparing these samples yielded significant p-values for both seasons (W = 144.5, p-value = 0.048 in winter and W = 174.5, p-value = <0.001 in spring) (Fig. 6).

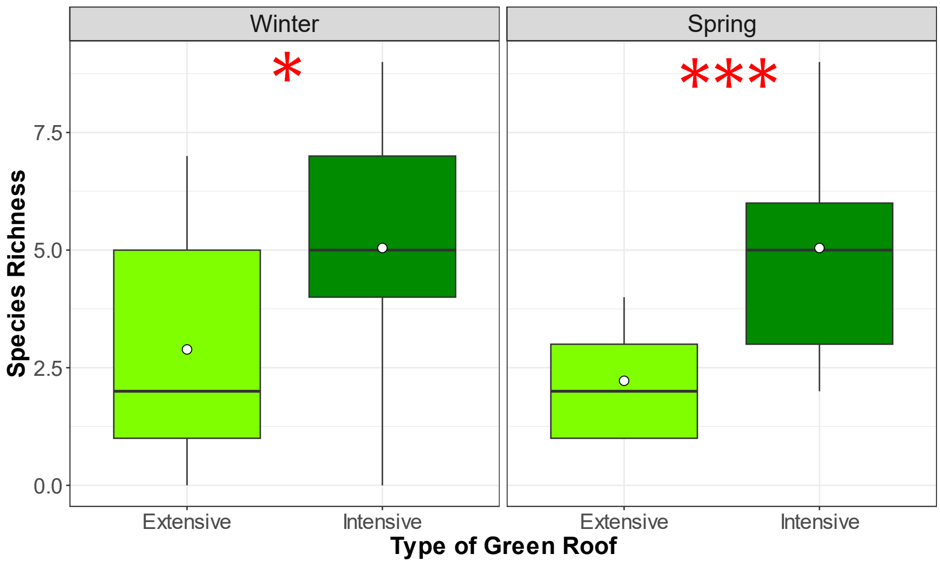


Fig. 6 – Boxplot comparing the bird species richness per point count in the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter and spring. Average values are represented by the white dots. Significance is represented as: * <0.05, ** <0.01, *** <0.001.

Regarding bird abundance, in winter the mean number of individuals/point was 9.44 in Extensive areas and 10.64 in Intensive green roofs. In spring these values were of 9.56 individuals/point and 11.68 individuals/point in Extensive and Intensive green roofs, respectively. The comparisons of this abundance values in green roofs with different complexities showed no significant differences for both seasons (W = 142, p-value = 0.064 for winter; and W = 141, p-value = 0.070 for spring) (Fig. 7).

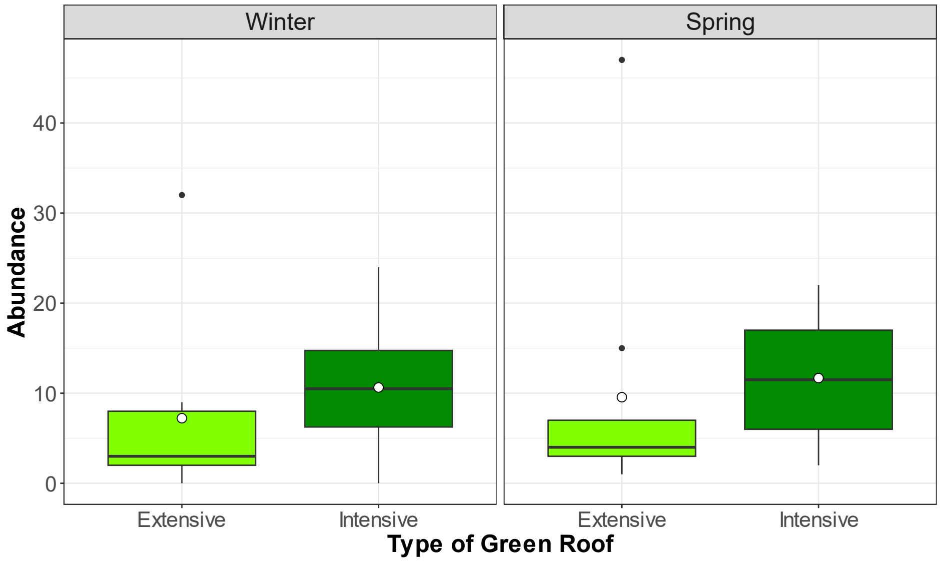


Fig. 7 –Boxplot comparing the number of individuals (birds) per point count, registered on the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter and spring. Average values are represented by the white dots.

When it comes to the NMDS analysis, although there is an overlap of the ellipses of both types of green roofs, the points corresponding to the Intensive green roofs are always closer to each other than those corresponding to the Extensive ones, in both seasons (Fig. 8).

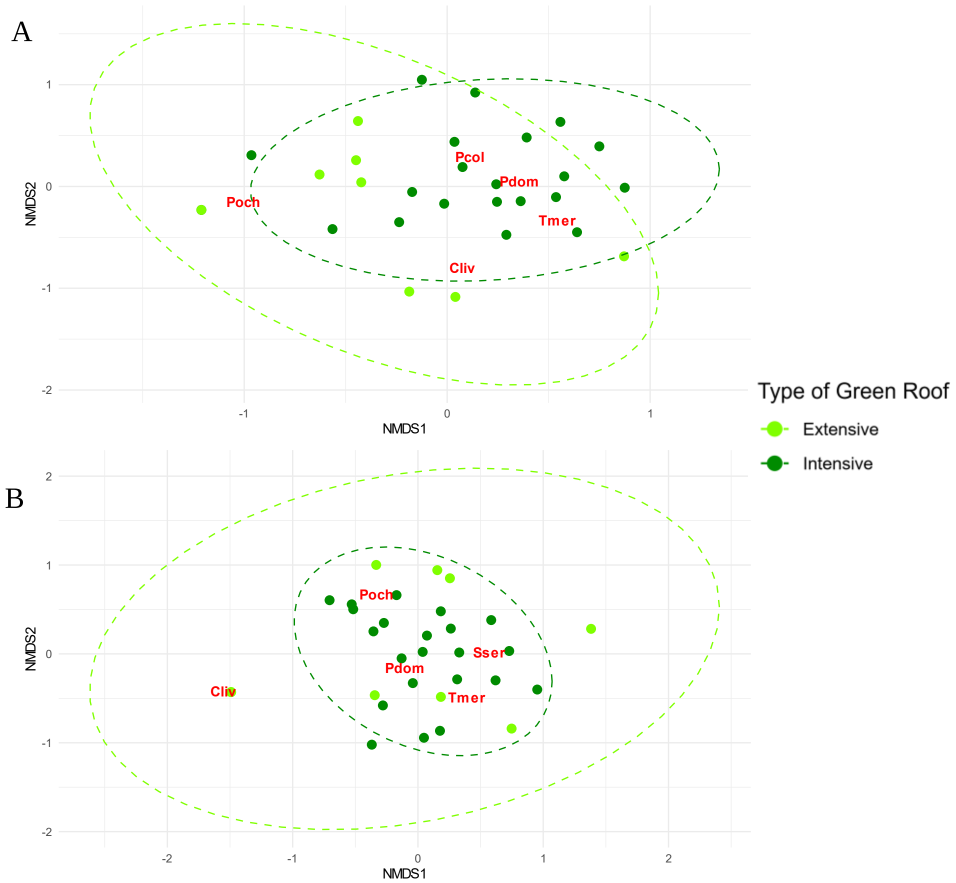


Fig. 8 – NMDS plots of bird communities on the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter (A) and spring (B). Abbreviations of species names (see Appendix B Table B.1) are shown in red and represent those occurring at a minimum of 10 sampling points.

In both Figs. 8A and 8B, *Columba livia* (Cliv) is located closer to points corresponding to the sites of Alameda and the highest set green roof at Gulbenkian. In fact, in both points and in both seasons, the only species recorded was *C. livia*. In spring, the species abbreviation is overlapped with both sites, as they have the same coordinates, making it somehow difficult to visualize in the NMDS plot (Fig. 8B). The same occurs in winter with *Phoenicurus ochruros* (Black Redstart) (Poch), as its closest point (in light green) corresponds to an overlap between a point at Campus de Justiça and another at ETAR, where *P. ochruros* was the only species recorded.

In both seasons, only Intensive green roofs had statistically significant relationships with species based on Indicator Values results. In winter, these species were *Turdus merula* (IndVal = 0.82, p-value = 0.018) and *Passer domesticus* (IndVal = 0.82, p-value = 0.006); in spring, *T. merula* (IndVal = 0.81, p-value = 0.018) and *Serinus serinus* (European Serin) (IndVal = 0.80, p-value = 0.046).

3.2.2. Arthropods

Regarding arthropod sampling, 11 transects were done in Extensive green roofs, and 32 on Intensive ones. A total of 8677 individuals were identified, with 96.15% being classified at least to the family level (total of 8343 specimens), in a total of 64 confirmed families, 60 of them being found in Intensive green roofs, while only 33 of these were found in Extensive green roofs.

More specifically, in winter, 17 families of arthropods were identified in Extensive green roofs, while 21 were identified in Intensive ones. In spring, these numbers increased to 29 and 56, respectively. The family Formicidae was the most abundant in both seasons in Extensive green roofs, while in Intensive green roofs, the most common family in winter was Chironomidae, and in spring was Aphididae (Table 3).

Of all registered families, only 4 were found exclusively in Extensive Green Roofs, 31 were found only in Intensive Green Roofs.

Table 3 – Average abundance, by sampling transect, of each arthropod family identified on both types of studied green roofs (Extensive and Intensive), in winter and spring. The three highest abundance values in each type of green roof and in each season are underlined.

	Winter		Spring	
FAMILY	**EXTENSIVE**	**INTENSIVE**	**EXTENSIVE**	**INTENSIVE**
Agromyzidae	--	--	1.64	0.13
Anthomyiidae	0.36	0.03	--	0.38
Aphididae	--	0.06	<u>3.09</u>	<u>58.28</u>
Apidae	0.36	0.69	0.09	<u>1.69</u>
Araneidae	0.09	0.06	--	--
Armadillidiidae	--	--	0.45	0.09
Braconidae	--	--	--	0.25
Calliphoridae	0.45	<u>0.72</u>	0.18	0.38
Carabidae	--	--	0.09	0.06
Cecidomyiidae	--	--	--	0.13
Ceratopogonidae	0.09	--	0.09	0.31
Chironomidae	<u>9.18</u>	<u>8.81</u>	0.64	1.28
Chloropidae	--	--	--	0.09
Chrysomelidae	--	0.50	1.55	0.31
Cicadellidae	--	--	--	0.06
Coccinellidae	0.09	--	0.45	0.13
Crabronidae	--	--	--	0.03
Curculionidae	--	--	0.09	--
Delphacidae	--	--	--	0.03
Dolichopodidae	--	--	--	0.16
Drosophilidae	1.09	0.06	0.09	0.09
Ephydridae	<u>2.64</u>	--	<u>1.82</u>	0.47
Erythraeidae	--	--	--	0.53
Fannidae	--	--	--	0.06
Formicidae	<u>9.64</u>	<u>4.84</u>	<u>102.36</u>	<u>21.59</u>
Heleomyzidae	--	--	--	0.34

	Winter		Spring	
FAMILY	**EXTENSIVE**	**INTENSIVE**	**EXTENSIVE**	**INTENSIVE**
Hybotidae	0.09	--	--	0.03
Ichneumonidae	--	--	--	0.16
Lauxaniidae	--	--	--	0.06
Libellulidae	--	--	--	0.09
Linyphiidae	--	--	--	0.13
Lonchopteridae	--	--	0.27	0.03
Megachilidae	--	--	--	0.03
Miridae	--	--	--	0.03
Monophlebidae	--	0.03	--	--
Muscidae	--	0.72	0.27	1.00
Nabidae	--	--	--	0.03
Noctuidae	--	--	0.09	--
Nymphalidae	0.27	0.16	0.45	0.31
Oedemeridae	--	--	--	0.03
Pentatomidae	--	--	--	0.63
Phlaeothripidae	--	--	--	0.03
Phoridae	--	--	0.27	0.16
Pieridae	0.18	0.03	0.73	0.19
Platystomatidae	--	--	--	0.03
Psychodidae	--	--	--	0.03
Pyrrhocoridae	--	--	--	0.16
Rhinophoridae	--	--	0.18	0.16
Salticidae	--	0.06	--	0.09
Sarcophagidae	--	0.09	0.09	0.16
Scarabaeidae	--	--	--	0.03
Scelionidae	--	--	--	0.03
Sciaridae	1.27	0.38	0.09	0.06
Sepsidae	--	--	--	0.09
Simuliidae	--	--	0.09	--
Sphaeroceridae	1.82	--	0.91	0.56
Staphylinidae	--	0.22	--	--
Syrphidae	0.64	0.28	1.27	0.66
Tachinidae	--	--	--	0.06
Tenebrionidae	--	--	0.18	0.06
Tephritidae	--	0.31	--	--
Thomisidae	--	--	0.18	--
Tipulidae	0.09	0.13	--	0.06
Vespidae	--	0.09	0.27	0.31

Pictures representing some of the most abundant arthropod families are in Appendix G.

When analysing arthropod communities, the Shannon Index had average values of 0.51 and 0.42 in winter, and 0.95 and 1.18 in spring, for Extensive and Intensive green roofs, respectively. Statistical analysis yielded non-significant differences between the green roof types in both seasons (Wilcoxon rank sum tests: W = 154, p-value = 0.539 in winter, and W = 208, p-value = 0.381) (Fig. 9).

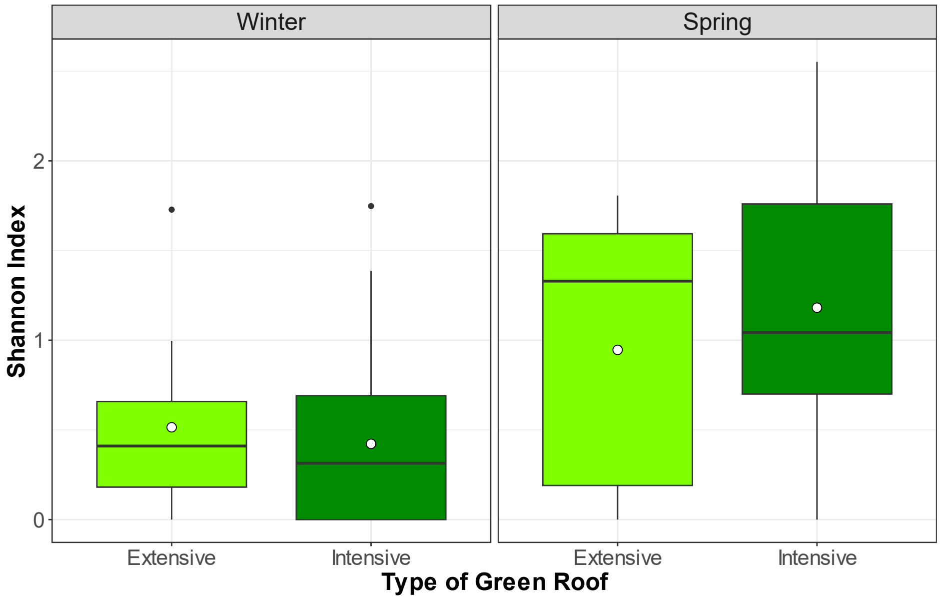


Fig. 9 – Boxplot comparing the Shannon index of arthropod communities on the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter and spring, per sampling transect. Average values are represented by the white dots.

Regarding family richness, the average values per sampling transect in winter were 2.91 for Extensive green roofs and 2.41 for Intensive ones. In spring, these values increased to 5.55 families per transect for Extensive structures and 7.41 for Intensive ones. No significant differences were observed between the sites in either season (winter: W = 156.5, p-value = 0.59; spring: W = 199, p-value = 0.53) (Fig. 10).

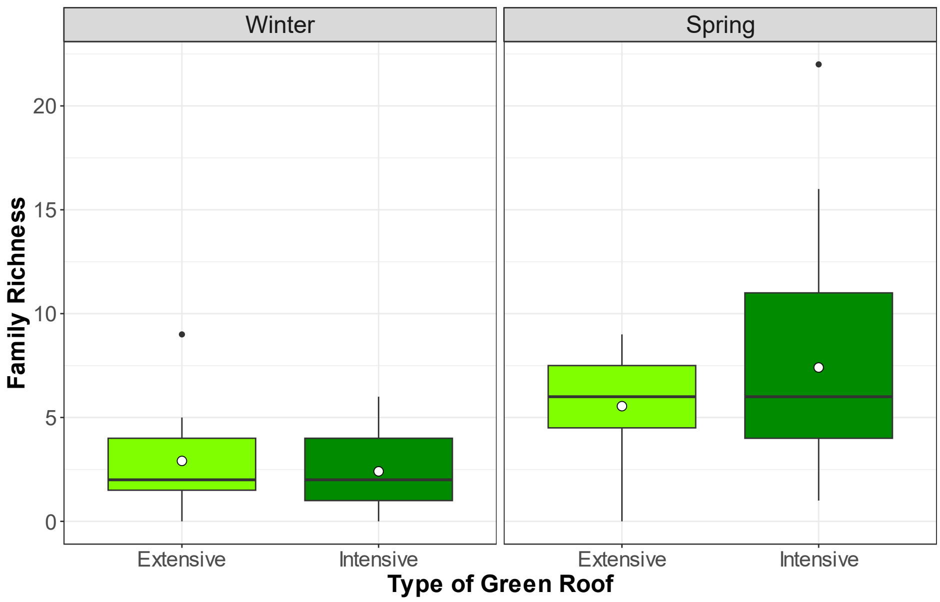


Fig. 10 – Boxplot comparing arthropod family richness per sampling transect in the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter and spring. Average values are represented by the white dots.

Regarding average abundance values, winter had 31.09 individuals/transect for Extensive green roofs and 19.84 individuals/transect for Intensive ones, while in spring these values were 119.64 and 96.0 for Extensive and Intensive green roofs, respectively. Again, Wilcoxon rank sum test (Mann-Whitney) yielded non-significant differences (W = 138.5, p-value = 0.302 for winter and W = 186, p-value = 0.791 for spring) (Fig. 11).

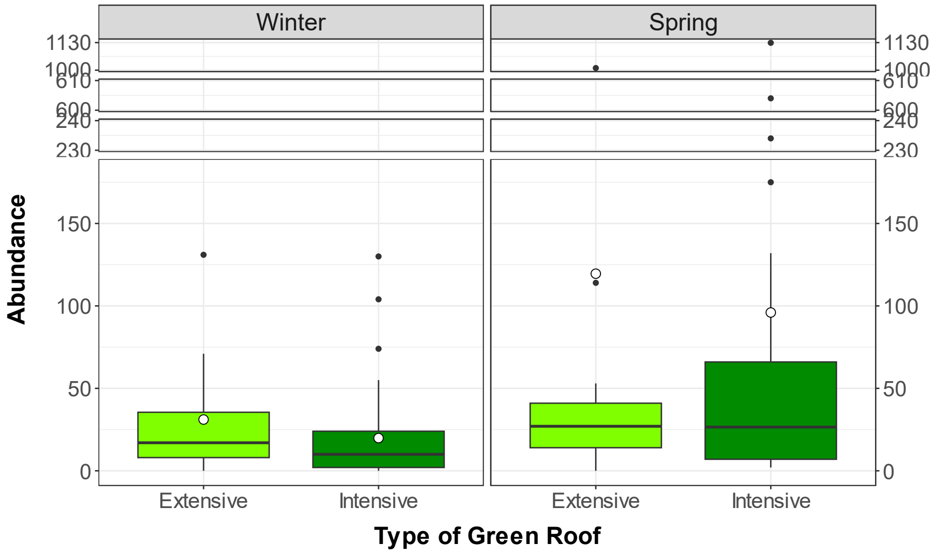


Fig. 11 – Boxplot comparing the number of arthropods per sampling transect, registered on the two types of studied green roofs (Extensive in light green and Intensive in dark green) in winter and spring. Average values are represented by the white dots.

However, as can be seen in the boxplots (Fig.11), in spring the average values are quite high, above the 3rd quartile and even closer to the outliers. This happens because of the high abundance of both aphids and ants in spring – the highest outlier in Extensive Green Roofs is represented by about 1000 ants at ETAR, and the three highest outliers are (from highest to lowest) represented by about 1000 aphids at Jardim Irmã Lúcia, about 500 aphids in Gulbenkian (specifically Jardim das Rosas), and about 100 aphids and 150 ants in a transect at Jardim Professor António de Sousa Franco.

3.3 Comparison Between Green Roofs, Urban Gardens and Grey Areas

3.3.1. Birds

For comparing green roofs with other urban structures that were used as controls, 11 sets of sites (Green Roofs + Urban Gardens + Grey Areas) were sampled, resulting in a total of 14 bird point counts done in Green Roofs, 12 in Urban Gardens and 12 in Grey Areas.

A total of 45 species were registered in the sampled Green Roofs, 50 in Urban Gardens and 23 in Grey Areas (Table 4). In winter, the three most abundant species in both Green Roofs and Urban Gardens were *Columba livia*, *Passer domesticus* and *Turdus merula*. In Grey Areas the most abundant species were *C. livia* and *Larus* sp., followed by *Motacilla alba* (White Wagtail), *P. domesticus*, *Phoenicurus* *ochruros* and *T. merula* which shared the same average abundance, making them the third most abundant species. In spring, *C. livia*, *P. domesticus* and *T. merula* were the most abundant species in the three studied habitats.

Three species were detected exclusively in Green Roofs – *Corvus corone* (Carrion Crow), *Linaria cannabina* (Common Linnet) and *Spinus spinus* (Eurasian Siskin), although only one individual of each species was detected throughout the duration of the study.

Table 4 – Average abundance (mean number of individuals/point count) of each recorded bird species, on the three types of studied habitats (Green Roofs, Urban Gardens and Grey Areas), in winter and spring. Non-native species are denoted with an asterisk (*). The three highest abundance values in each type of habitat and each season are underlined.

	Winter			Spring		
Species	**Green Roofs**	**Urban Gardens**	**Grey Areas**	**Green Roofs**	**Urban Gardens**	**Grey Areas**
Acridotheres cristatellus *	0.29	0.08	--	--	0.75	--
Anas platyrhynchos	0.21	0.25	--	0.71	0.17	--
Anthus pratensis	--	0.17	--	--	--	--
Cairina moschata *	--	0.42	--	--	0.50	--
Carduelis carduelis	0.07	0.17	0.08	0.07	0.08	--
Certhia brachydactyla	0.14	0.17	--	0.07	0.17	--
Chloris chloris	--	--	--	0.14	0.50	--
Cisticola juncidis	0.07	--	--	--	0.08	--
Columba livia	1.36	2.25	1.08	4.36	4.17	1.08
Columba palumbus	0.07	0.25	--	0.29	0.58	--
Corvus corone	0.07	--	--	--	--	--
Curruca melanocephala	0.21	0.33	--	0.43	0.08	--
Cyanistes caeruleus	0.21	0.50	--	0.14	0.08	--
Delichon urbicum	--	--	--	0.07	0.17	--
Erithacus rubecula	0.21	0.67	--	--	0.08	--
Estrilda astrild *	--	0.75	--	--	--	--
Fringilla coelebs	--	0.08	--	--	--	--
Hirundo rustica	--	--	--	0.07	0.17	--
Larus sp.	0.29	--	1.00	0.07	--	--
Linaria cannabina	--	--	--	0.07	--	--
Motacilla alba	0.29	0.75	0.33	0.43	0.92	--
Parus major	0.07	0.25	--	--	--	--
Passer domesticus	1.14	2.17	0.33	2.14	1.83	0.33
Periparus ater	0.07	0.08	--	--	--	--
Phoenicurus ochruros	0.50	0.08	0.33	0.64	0.25	--
Phylloscopus collybita	0.50	0.58	0.17	--	--	--
Psittacula krameria *	--	0.08	--	--	--	--
Ptyonoprogne rupestris	--	--	--	--	0.08	--
Regullus ignicapilla	--	--	--	--	0.08	--
Serinus serinus	0.21	0.17	--	0.93	0.67	--
Spinus spinus	0.07	--	--			
Streptopelia decaocto	--	0.17	--	--	0.50	--
Sturnus sp.	0.21	0.50	--	0.36	1.00	0.17
Sylvia atricapilla	0.36	0.17	--	--	0.33	--
Thectocercus acuticaudatus *	--	0.08	--	--	--	--
Turdus merula	1.00	2.25	0.33	1.79	3.50	0.42

The winter average values of the Shannon Index in bird communities were of 1.10, 1.34 and 0.44 for Green Roofs, Urban Gardens and Grey Areas. In spring, these values were 1.19, 1.34 and 0.18, respectively (Fig. 12).

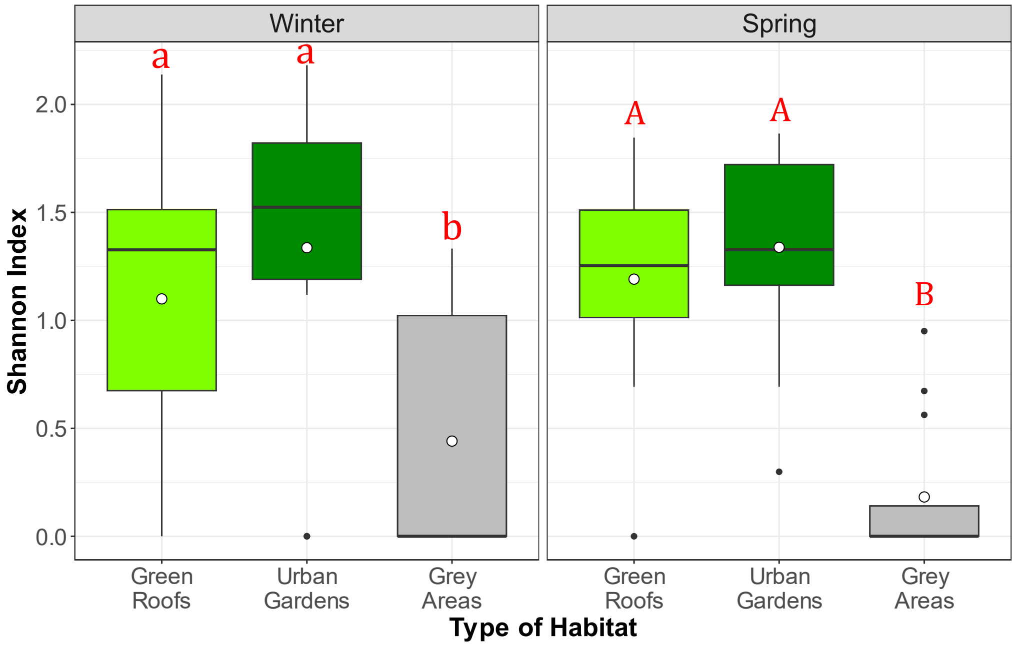


Fig. 12 – Boxplots comparing the Shannon index of bird communities on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,b,A,B) above the individual boxplots.

The statistical comparison of the Shannon Index values revealed significant differences between habitat types in both seasons (winter – Kruskal-Wallis, H = 10.623, p-value = 0.005; spring – H = 21.004, p-value ≤ 0.001). The Dunn test showed significant differences only between Grey Areas and the other two habitats, in both seasons (Table 5).

Table 5 – P-values resulting from the Dunn test, comparing Shannon Index values of the bird communities in the three habitat types, in both sampling seasons. Significant values are highlighted in bold.

	Winter		Spring	
	Grey Areas	Green Roofs	Grey Areas	Green Roofs
Green Roofs	**0.021**	--	**2.64e-04**	--
Urban Gardens	**0.002**	0.331	**2.01e-05**	0.437

Regarding bird species richness, average values in winter were 3.93 species/point for Green Roofs, 5.58 for Urban Gardens and 1.58 for Grey Areas. In spring these values changed to 4.36 species/point for Green Roofs, 5.42 for Urban Gardens and 1.0 for Grey areas (Fig.13).

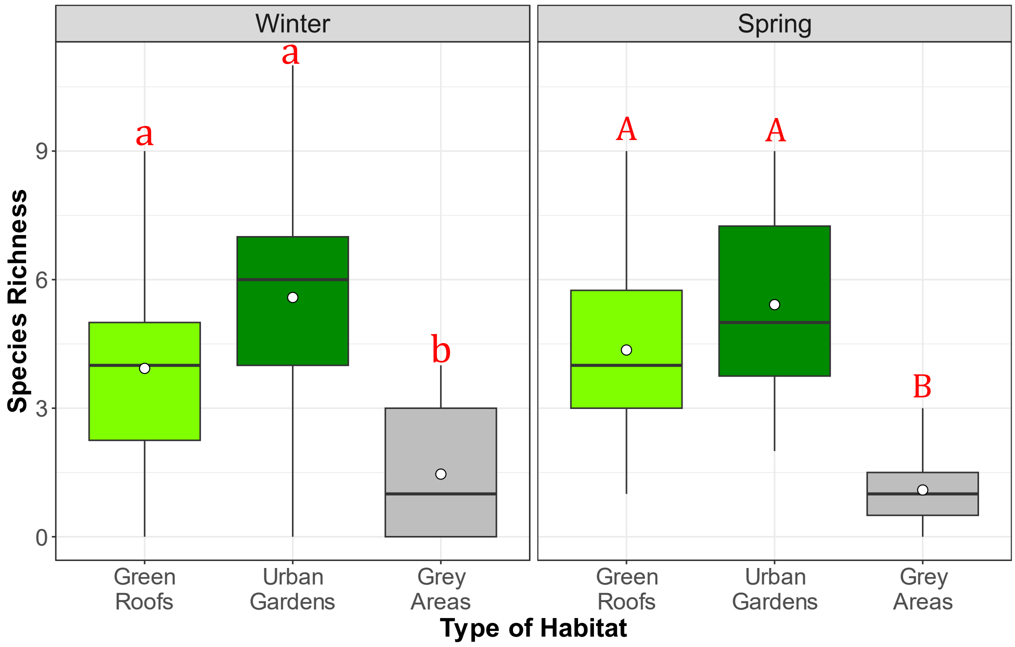


Fig. 13 – Boxplots comparing bird species richness, per point count, on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,b,A,B) above the individual boxplots.

When comparing species richness, Kruskal-Wallis tests showed significant differences between the studied sites in both seasons ($H = 11.008$, p-value = 0.004 in winter, and $H = 21.343$, p-value < 0.001 in spring). The Dunn test showed significant differences only between Grey Areas and the other two habitats, in both seasons (Table 6).

Table 6 – P-values resulting from the Dunn test, comparing bird species richness in the three habitat types, in both sampling seasons. Significant values are highlighted in bold.

	Winter		Spring	
	Grey Areas	Green Roofs	Grey Areas	Green Roofs
Green Roofs	**0.028**	--	**2.75e-04**	--
Urban Gardens	**0.001**	0.424	**1.55e-05**	0.3965

The average bird abundance in winter was 7.64 individuals/point in Green Roofs, 13.33 in Urban Gardens and 3.67 in Grey Areas. In spring, these numbers changed to 12.79, 16.83 and 2.0, respectively (Fig. 14).

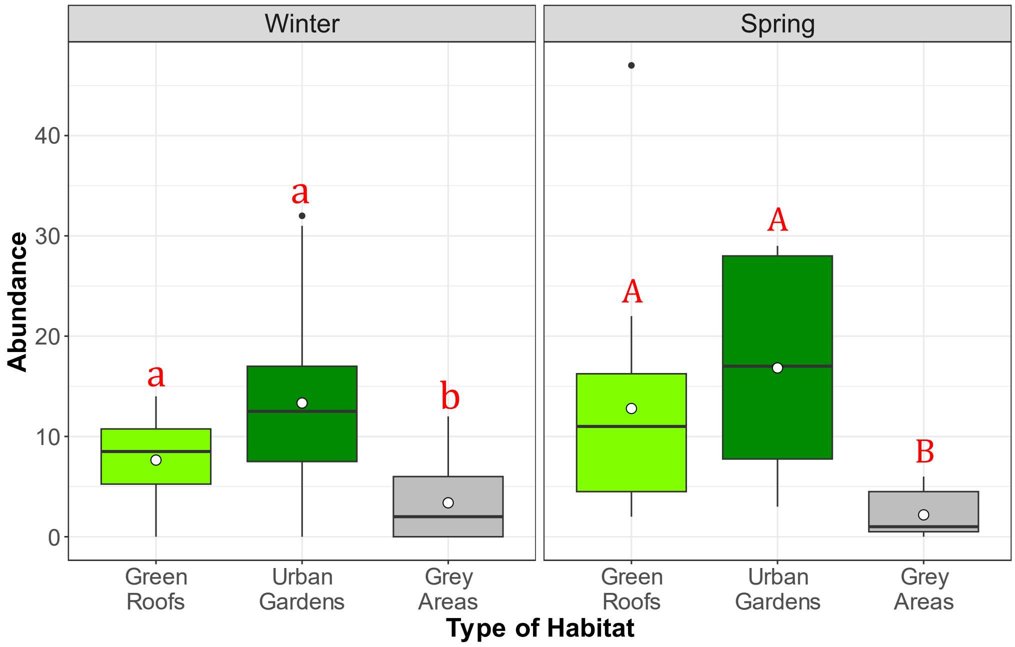


Fig. 14 – Boxplots comparing the bird abundance on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,b,A,B) above the individual boxplots.

Again, the statistical comparison between these three areas revealed significant differences (Kruskal-Wallis $H = 9.968$, p-value = 0.007 in winter and $H = 17.497$, p-value < 0.001 in spring). The Dunn test showed significant differences only between Grey Areas and the other two habitats, in both seasons (Table 7).

Table 7 – P-values resulting from the Dunn test, comparing average bird abundance in the three habitat types, in both sampling seasons. Significant values are highlighted in bold.

	Winter		Spring	
	Grey Areas	Green Roofs	Grey Areas	Green Roofs
Green Roofs	**0.048**	--	**0.001**	--
Urban Gardens	**0.001**	0.203	**7.21e-05**	0.352

Sampled-based rarefaction curves were done to compare sample completeness and community richness. As the sample size was 14 for Green Roofs, 12 for Urban Gardens and 12 for Grey Areas, the endpoint for calculation of extrapolation was set at 28 and 24, respectively (Fig. 15). Results show that, in both seasons, Grey Areas have a much lower species richness, and the curve also quickly hit a plateau, showing sample size adequacy. This, however, is not the case for both Green Roofs and Urban Gardens, that show no tendency to hit a plateau, even with extrapolation. Furthermore, in winter (Fig. 15A), there is a great overlap between the curves of Green Roofs and Urban Gardens. This tendency continues in spring, although with smaller overlapping (Fig. 15B).

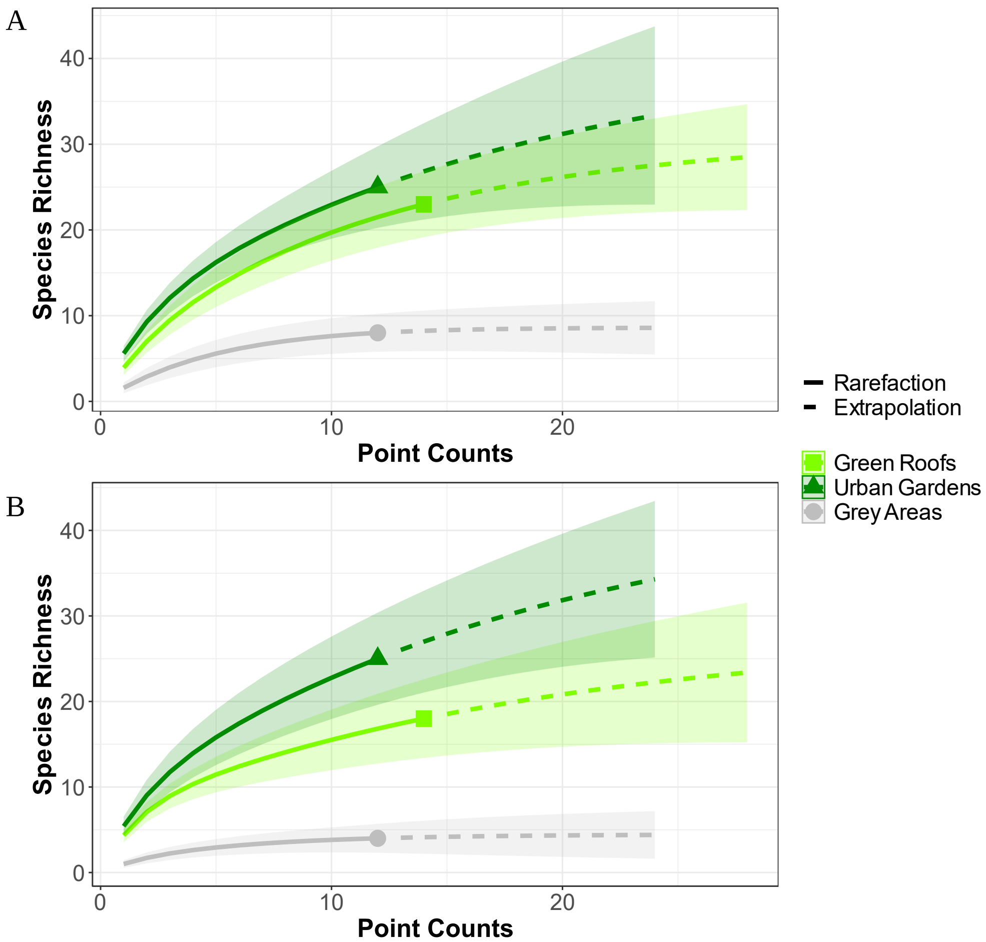


Fig. 15 – Sample-based rarefaction curves for birds in three types of habitats, Green Roofs, Urban Gardens and Grey Areas, in winter (A) and spring (B). Dashed line indicates the part of the curve that presents extrapolation data (endpoint set at 28 for Green Roofs, 24 for both Grey Areas and Urban Gardens) and the shaded areas represent error intervals (95% CI).

In winter, the NMDS analysis shows a big overlap between the three ellipses, while in spring there is a greater overlap between the ellipses corresponding to Green Roofs and Urban Gardens, and a smaller overlap between these and the Grey Areas (Fig. 16).

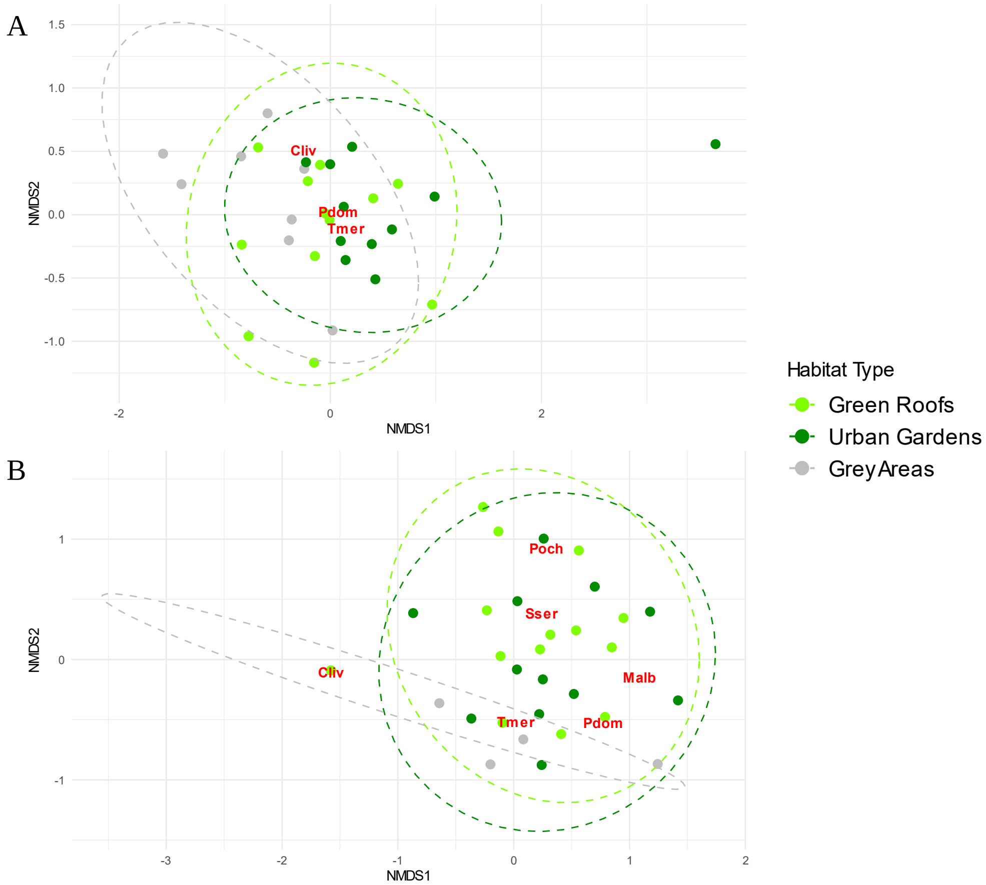


Fig. 16 – NMDS analysis of the bird communities in three types of habitat, Green Roofs, Grey Areas and Urban Gardens, in winter (A) and spring (B). Species included in the plots (abbreviations in red) are those that appear in at least 10 sites.

In winter (Fig. 16A), the green dot that is located further on the right, outside of the ellipses, corresponds to Jardim da Fonte Luminosa, the Urban Garden that served as control for Alameda. The location of this site in the plot is justified by the fact that only one individual of one species, *Streptopelia decaocto* (Eurasian Collared Dove) was registered during the visit to this Urban Garden. In fact, *S. decaocto* was only registered in two sites in winter.

In spring (Fig. 16B), although not directly visible in the NMDS plot, there is an overlap of five sites placed below the abbreviation of *Columba livia* (Cliv): four Grey Areas and one Green Roof. The overlap in site coordinates occurs because *C. livia* was the only species recorded at these sites during spring, with counts ranging from 1 to 47 individuals. Furthermore, *Phoenicurus ochruros* can be seen closest to an Urban Garden site where the species represented 1/3 of all individuals recorded, and *Passer domesticus* is closest to a Green Roof site where it represented 2/3 of all observations.

Results of the calculation of indicator values showed that, in winter, the *Larus* genus was heavily associated with Grey Areas (IndVal = 0.64, p-value = 0.022), while *Turdus merula* was associated with both Green Roofs and Urban Gardens (IndVal = 0.81, p-value = 0.028). In spring, *Sylvia atricapilla* (Eurasian Blackcap) only had a significant association with Urban Gardens (IndVal = 0.58, p-value = 0.018), and both *Turdus merula* and *Serinus serinus* were associated with both Green Roofs and Urban Gardens (indicator values 0.83 and 0.71, p-values 0.030 and 0.031, respectively).

3.3.2. Arthropods

Arthropod sampling included data from a total of 62 sampling transects, with 23 of them being done in Green Roofs, 19 in Urban Gardens and 20 in Grey Areas.

A total of 75 families were identified: 64 in Green Roofs, 49 in Urban Gardens, and 22 in Grey Areas (Table 8). In winter, the family Chironomidae (Diptera – mosquitoes) was consistently among the most abundant, except in Green Roofs. In spring, Formicidae (ants) was generally the most abundant family, except in Grey Areas, where Erythraeidae (Acari – mites) dominated. Additionally, Aphididade (aphids) was among the most abundant families in Urban Gardens and Grey Areas. On Green Roofs, family Ephydridae stood out as one of the most abundant in both seasons.

Among all the identified families, 20 were found in green spaces (either Green Roofs or Urban Gardens), with seven being exclusive to Green Roofs, 14 exclusive to Urban Gardens, and three exclusive to Grey Areas. Additionally, 13 families were present across all habitat types. Seventeen families were represented by a single individual, with only two of these – Julidae (millipedes) and Tenebrionidae (Coleoptera – darkling beetles) – found in Grey Areas. Notably, the locations where these families were identified are relatively close to surrounding vegetated areas.

Table 8 – Average abundance, by transect, of each identified arthropod family, on the three types of studied habitats (Green Roofs, Urban Gardens and Grey Areas), in winter and spring. The three highest abundance values in each type of habitat and each season are underlined.

	Winter			**Spring**		
Families	**Green Roofs**	**Urban Gardens**	**Grey Areas**	**Green Roofs**	**Urban Gardens**	**Grey Areas**
Agromyzidae	--	--	--	0.91	0.26	--
Anthomyiidae	0.04	0.05	--	0.26	0.42	--
Aphididae	0.04	--	--	0.78	20.95	1.10
Apidae	0.39	0.05	0.10	1.52	0.74	0.05
Araneidae	--	--	--	--	0.05	--
Armadillidiidae	--	--	0.05	0.17	0.42	--
Braconidae	--	--	--	0.09	0.11	0.05
Calliphoridae	0.26	0.47	0.10	0.22	2.37	--
Carabidae	--	--	--	0.04	--	--
Cecidomyiidae	--	--	--	0.17	--	0.05
Ceraphronidae	--	--	--	--	0.05	--
Ceratopogonidae	--	0.05	--	0.22	0.32	0.10
Chironomidae	5.26	4.11	1.05	0.87	4.74	0.10
Chloropidae	--	0.32	--	0.04	0.68	--
Chrysomelidae	0.70	--	--	0.30	0.16	--
Cicadellidae	--	0.05	--	0.09	--	0.05
Coccinellidae	--	--	--	0.13	0.42	--
Crambidae	--	--	--	--	0.05	--
Culicidae	--	0.05	--	--	--	--
Curculionidae	--	--	--	0.04	--	--
Delphacidae	--	--	--	0.04	0.05	--
Dolichopodidae	--	--	--	0.04	0.11	--

	Winter			Spring		
Families	**Green Roofs**	**Urban Gardens**	**Grey Areas**	**Green Roofs**	**Urban Gardens**	**Grey Areas**
Drosophilidae	0.09	0.26	--	0.17	--	--
Ephydridae	1.13	--	--	1.22	0.42	--
Erythraeidae	--	--	--	0.48	--	25.00
Fannidae	--	--	--	--	0.26	--
Formicidae	0.17	6.26	0.55	14.04	69.21	13.95
Gnaphosidae	--	--	--	--	0.16	--
Halictidae	--	--	--	--	0.11	--
Heleomyzidae	--	--	--	0.04	0.21	--
Hybotidae	--	--	--	0.04	--	--
Ichneumonidae	--	0.05	--	0.09	0.21	0.05
Julidae	--	--	--	--	--	0.05
Lauxaniidae	--	--	--	0.04	--	--
Libellulidae	--	--	--	0.09	0.05	--
Linyphiidae	--	--	--	--	0.16	0.10
Lonchopteridae	--	--	--	0.13	0.05	--
Lygaeidae	--	0.05	--	--	--	--
Melyridae	--	--	--	--	0.05	--
Miridae	--	--	--	--	0.16	--
Monophlebidae	0.04	--	--	--	--	--
Muscidae	0.87	0.11	0.50	0.70	0.53	--
Nymphalidae	0.13	--	--	0.22	0.42	0.05
Oedemeridae	--	--	--	0.04	--	--
Phoridae	--	0.05	--	0.26	0.11	--
Pieridae	0.04	0.05	0.05	0.13	0.37	0.05
Platystomatidae	--	--	--	0.04	0.11	--
Polleniidae	--	0.21	--	--	--	--
Psychodidae	--	--	--	0.04	--	--
Rhiniidae	--	0.05	--	--	--	--
Rhinophoridae	--	--	--	0.04	--	0.10
Salticidae	--	0.05	--	--	0.11	--
Sarcophagidae	0.13	--	--	0.13	0.58	--
Sciaridae	0.52	--	--	--	0.05	--
Scraptiidae	--	--	--	--	--	0.10
Sepsidae	--	--	0.05	--	0.11	--
Sphaeroceridae	--	--	--	0.96	0.11	--
Staphylinidae	0.30	--	--	--	0.05	--
Stratiomyidae	--	--	--	--	0.05	--
Syrphidae	0.17	0.11	0.30	0.70	1.26	0.05
Tenebrionidae	--	--	--	--	--	0.05
Tephritidae	0.43	--	0.50	--	--	--
Tipulidae	0.09	0.16	--	--	0.11	--
Vespidae	0.13	0.05	--	0.39	0.37	--

In winter, average values of the Shannon Index of the arthropod communities were 0.33 in Green Roofs, 0.48 in Urban Gardens and 0.22 in Grey Areas. In spring, these values were 1.08, 1.15 and 0.20, respectively (Fig. 17).

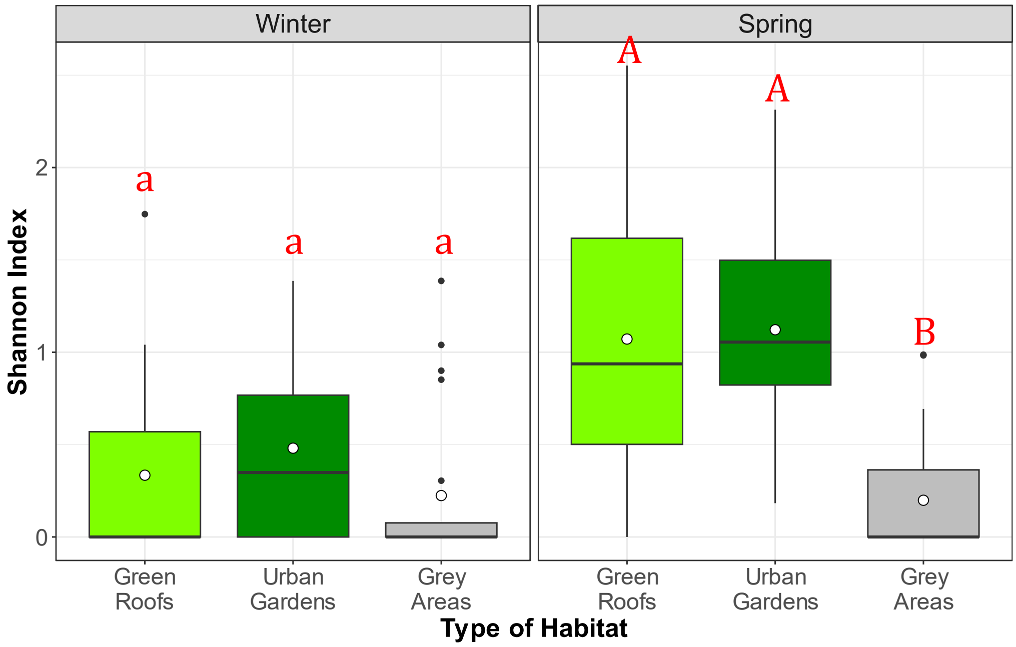


Fig. 17 – Boxplots comparing the Shannon index of the arthropod communities on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,A,B) above the individual boxplots.

When performing Kruskal-Wallis test, statistically significant differences were only found in spring (winter: H = 3.696, p-value = 0.158; spring: H = 25.229, p-value < 0.001). In this season, the Dunn test showed significant differences between Grey Areas and the other two habitats (Table 9).

Table 9 – P-values resulting from the Dunn test, comparing Shannon Index values of arthropod communities in the three habitat types, in spring. Significant values are highlighted in bold.

	Grey Areas	Green Roofs
Green Roofs	**4.06e-05**	--
Urban Gardens	**4.54e-06**	0.490

Average family richness in winter was 1.82 in Green Roofs, 2.11 in Urban Gardens and 1.00 in Grey Areas. In spring, it was 5.70, 7.79 and 1.75, respectively (Fig. 18).

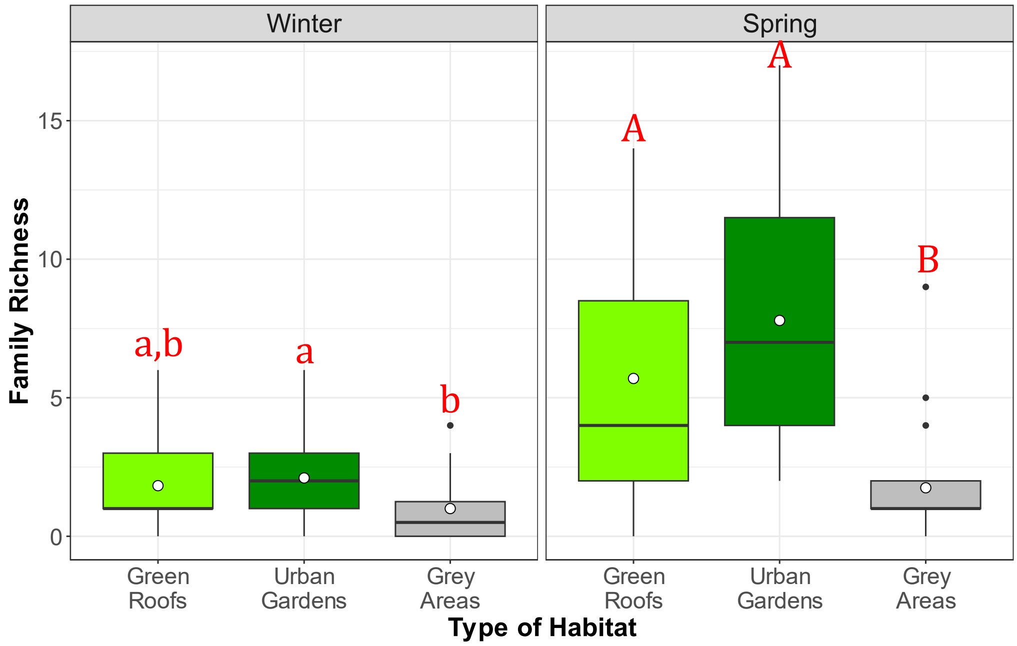


Fig. 18 – Boxplots comparing the arthropod family richness on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,b,A,B) above the individual boxplots.

In winter, Kruskal-Wallis test yielded a p-value of 0.051 (H = 5.927), and as it was very close to 0.05, a Dunn test was performed. In spring, this p-value was 3.81e-06 (H = 24.956). The Dunn test showed significant differences only between Grey Areas and Urban Gardens in winter and between Grey Areas and the other two habitats in spring (Table 10).

Table 10 – P-values resulting from the Dunn test, comparing arthropod family richness values in the three habitat types, in both sampling seasons. Significant values are highlighted in bold.

	Winter		Spring	
	Grey Areas	Green Roofs	Grey Areas	Green Roofs
Green Roofs	0.066	--	**3.68e-04**	--
Urban Gardens	**0.021**	0.569	**1.37e-06**	0.139

Average values of abundance in winter were 10.96 in green roofs, 12.63 in urban gardens and 3.25 in grey areas. In spring, these values rose to 25.96, 107.26 and 41.05, respectively (Fig. 19).

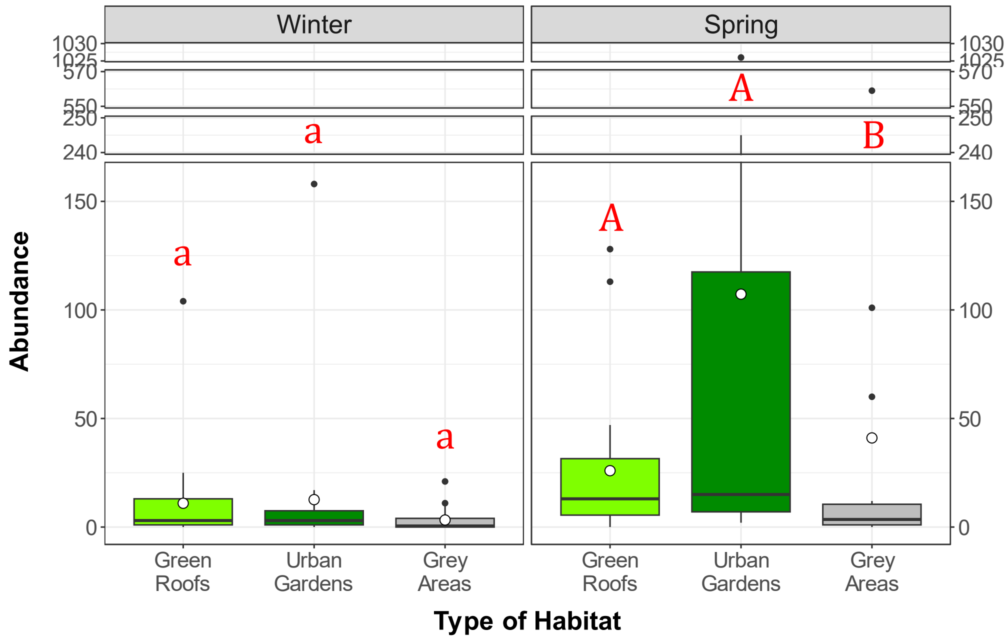


Fig. 19 – Boxplots comparing the arthropod abundance on the three types of studied habitats, Green Roofs, Urban Gardens and Grey Areas, in winter and spring. Statistically significant differences between habitats (p-value < 0.05) in each season are denoted by different letters (a,A,B) above the individual boxplots.

Kruskal-Wallis test for winter yielded non-significant differences. In spring, however, the p-value of the Kruskal test was 0.016 (H = 8.326). In this season, the Dunn test showed significant differences between Grey Areas and the other two habitats (Table 11).

Table 11 – P-values resulting from the Dunn test, comparing arthropod abundance in the three habitat types, in spring. Significant values are highlighted in bold.

	Grey Areas	Green Roofs
Green Roofs	**0.0499**	--
Urban Gardens	**0.005**	0.326

Once again, sampled-based rarefaction curves were done to compare sample completeness and community richness, now for arthropod data. As the sample size was 23 for Green Roofs and 19 for Urban Gardens and 20 for Grey Areas, the endpoint for calculation of extrapolation was set at 46, 38 and 40, respectively (Fig. 20). The results indicate that Grey Areas have significantly lower arthropod richness, in both seasons, but while there appears to be a tendency for reaching a plateau in winter, this does not occur in spring. In the case of Green Roofs and Urban Gardens, they have similar tendencies – in winter, overlapping considerably (with Urban Gardens not showing a plateau tendency). In spring, although the overlap is less than in winter, they are still very similar and are both very close to hitting a plateau.

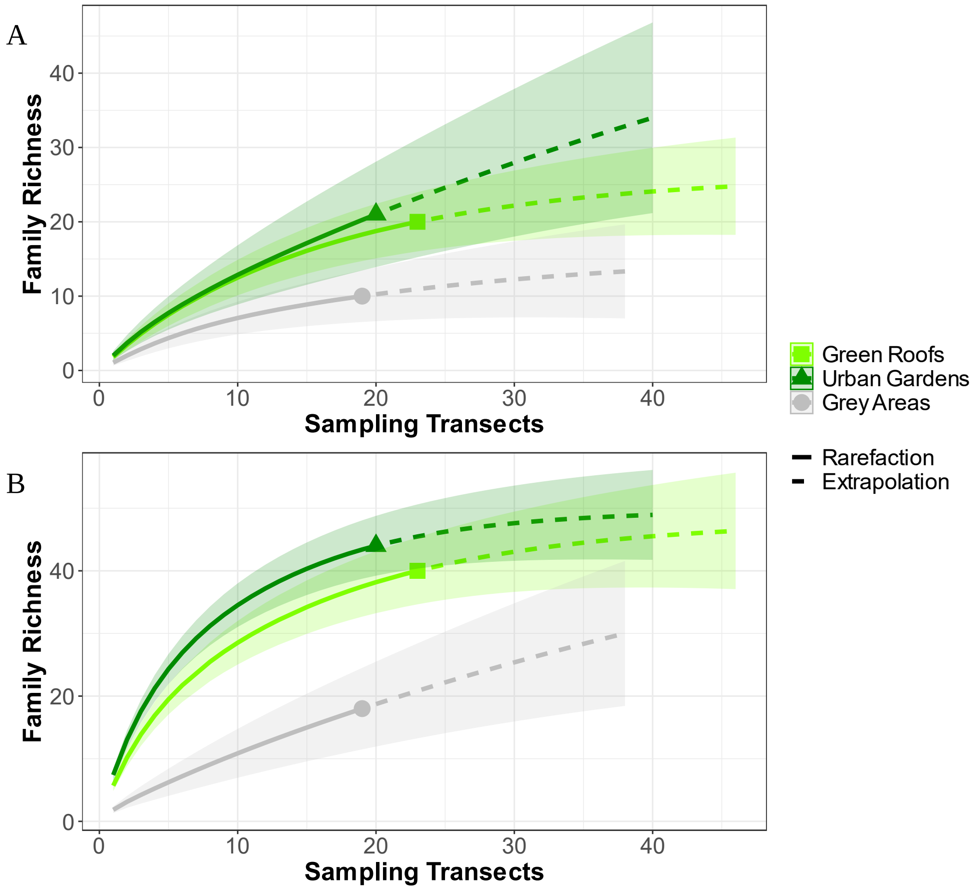


Fig. 20 – Sample-based rarefaction curves of arthropod family richness in three types of habitat: Green Roofs, Grey Areas and Urban Gardens, in winter (A) and spring (B). Dashed line indicates the part of the curve that presents extrapolation data (endpoint set at 46 for Green Roofs,40 for Urban Gardens and 38 for Grey Areas) and the shaded areas represent error intervals (95% CI).

4. Discussion

It is known that urbanization will continue to rise in the next decades, and it has significant negative effects on urban faunistic communities, including birds (Seress & Liker, 2015) and arthropods (Fenoglio *et al.*, 2020). There is also a general consensus that green roofs help urban biodiversity, but the quantification of their value is still being currently assessed, as research on this topic grows (Tiago *et al.* 2024). This study has looked to green roofs as a potential contribution to adapt cities to the effects of urbanization, adding more habitable areas for the urban faunistic communities, in opposition to impervious surfaces devoid of vegetation, where most species will not thrive.

4.1. Biodiversity in Green Roofs

With a total of 38 bird species and 64 arthropod families registered using Green Roofs, these results seem in line with previous studies. For example, in New York City, Patridge & Clark (2018) recorded 41 species of birds in two different green roofs. They also collected data on arthropods, but since the records were made only up to the order or class level, comparing the results becomes more difficult. In Valencia, Benedito-Durà *et al.* (2023) recorded 37 arthropod families, a lower number than observed in this study. This difference is expected, given that their research focused on a single green roof and was conducted only during the warmest periods of the year. In contrast, the present study encompasses 19 green roofs and also includes data from the winter season. Nonetheless, the number of families recorded by Benedito-Durà *et al*. is relatively close to the maximum value recorded on a single Green Roof in this study (29 families in Jardim Irmã Lúcia).

The green roofs with maximum and minimum total diversity were, respectively, Gulbenkian and Alameda. These results were to be expected, as these green roofs have very different characteristics. Gulbenkian is a large green area, very diverse in plant composition and structure, having open areas of grass along with shrubs and trees, which contributes, for example, to a greater bird diversity (Paker *et al.*, 2014). Moreover, it is also well connected to other green spaces of the city through the Central Green Corridor (Câmara Municipal de Lisboa, 2023). This connectivity, paired with the previous mentioned characteristics, has been shown to influence arthropod communities (Braaker *et al.*, 2014). On the other hand, Alameda is mainly composed of grass, and the area is very popular for sports activities, leading to a lot more disturbance in that area. These factors may justify its low use even by common city bird species as *Turdus merula* (Fernández-Juricic & Tellería, 2000), that was only detected in trees surrounding the area of the green roof (personal observation).

Regarding the exotic species, as expected *Psittacula krameri* was the most widespread, since this species has been presented in Portugal since the 1970's and has become well established in urban habitats (Luna *et al.*, 2016).

The most common arthropod families observed in this study show some similarities to those reported in Valencia by Benedito-Durà (2023) and Nova Scotia by MacIvor & Lundholm (2010), despite slight differences attributable to variations in sampling methods and taxonomic resolution. In both of their studies, ants (Formicidae) were among the most common families. Similarly, in the present study, the other most common families were Muscidae and Syrphidae (two families of flies) and although Benedito-Durà and MacIvor & Lundholm only analysed Dipterans at the order level, the prominence of these two families within the Diptera order suggests a degree of consistency across findings. Additionally, this study corroborates Benedito-Durà's observation of aphid prevalence, as Aphididae ranked as the fourth most widespread family and had the second-highest abundance on green roofs. In Benedito-Durà's research, the most abundant taxon was *Aphis* sp., a member of the Aphididae family, which was also identified in this study, represented by *Aphis nerii*.

4.2. Comparison Between Different Types of Green Roofs

Regarding birds, most analysed metrics showed clear differences between the types of green roofs sampled, with Intensive green roofs constantly having higher bird diversity values. This is to be expected, as Intensive green roofs have deeper soil/planting medium, allowing for more complex vegetation structure, with trees and shrubs, that can provide more nesting grounds and food resources (Fernandez-Canero & Gonzalez-Redondo, 2010), thus influencing the bird communities that use those roofs (Eakin *et al.,* 2015). Paker *et al.* (2014) also found that urban green spaces which are more heterogeneous (with a balance between trees, shrub cover and open grass areas) tend to have increased bird richness.

Columba livia and *Passer domesticus* were two of the most abundant species in every type of green roof and in the two sampling seasons. These two species are quite common in urban environments and are well adapted to their habitats (Svensson *et al.*, 2017), even using human-made structures for nesting (Indykiewicz, 1991; Sacchi *et al.*, 2002). Another commonly observed species on Intensive Green Roofs is *Turdus merula*, which has successfully adapted to urban environments and has also been documented using anthropogenic structures for nesting (Wang et al., 2015). On Extensive Green Roofs, the other most common species observed in both seasons was the exotic *Estrilda astrild*. Despite being observed only at ETAR de Alcântara (an Extensive Green Roof), up to 45 individuals of this species were registered using its green roofs during winter. *E. astrild* typically forages on low vegetation and constructs its nests on or near the ground, making it more vulnerable to nest predation. (Ribeiro *et al.*, 2020). In its native range, this species suffers from mice predation on nests. However, the ETAR green roofs may offer a safer nesting environment, as their height reduces predation risk, and mouse traps help keep predators away.

The results of the comparison of Shannon Index, species richness and abundance indicate that, while Intensive Green Roofs seem to have higher richness values, this is not reflected in differences in abundance, meaning that, for approximately the same number of individuals using the Green Roof, there are less species. In general, it can be said that Extensive Green Roofs are less diverse and show lower evenness, which is corroborated by Paker *et al.* (2014), that found bird diversity in Urban Gardens to be higher when the plant structure is a mix between shrubbery, trees and open space (lawn), as is the case with the Intensive Green Roofs sampled for this study.

The NMDS analysis shows that the communities of Extensive and Intensive Green Roofs are not particularly different. However, in spring, Intensive Green Roofs seem to be more similar than Extensive ones, that show greater distance between points in the plot. The NMDS sites more greatly associated with *Columba livia* in both seasons are two Extensive Green Roofs that are only composed by grass. Weber *et al.*, (1994) showed that *C. livia* prefers open areas in urban environments, which would explain this association. Moreover, for the much higher abundance of *C. livia* at Alameda can also contribute the presence of people feeding the birds in the area (personal observation).

When looking at the results of the Indicator Values, the lack of species associated with Extensive Green Roofs may derive from the lower sample size in this type of Green Roof, making it harder to have statistically significant associations. It is also possible that, as the structure is much more simple than that of Intensive Green Roofs, Extensive ones are occupied mostly by generalist species, not allowing for species with other habitat requirements/ preferences to be specifically associated with them. The species connected to Intensive Green Roofs were *Turdus merula* in both seasons, *Passer domesticus* in winter and *Serinus serinus* in spring. Both *T. merula* and *P. domesticus* have been registered nesting in green roofs (Fernandez-Canero & Gonzalez-Redondo, 2010). Furthermore, these three species may nest either on bushes or trees (Svensson *et al.,* 2017), which are more common (bushes) or only present (trees) in Intensive Green Roofs, that also offer more food resources.

Regarding arthropods, all metrics and analysis do not show differences between communities of Extensive and Intensive Green Roofs. This is particularly evident in winter, which is somehow expected since, in this period of the year, insects (the most abundant group of arthropods) are least abundant, because of lower temperatures and resource scarcity, and many species enter a stage of diapause in their development (Numata & Shintani, 2023).

Total green roof areas and proximity to other green spaces, may also be contributing to these results, as mentioned by Fabián *et al.* (2021) – Green Roofs with larger areas, as well as those surrounded by higher green cover, seem to have greater richness of arthropods. Another important factor may be the plant community composition on green roofs, as increasing the proportion of native vegetation has been shown to enhance the abundance and diversity of several taxa (Threlfall *et al.*, 2017). Additionally, combining extensive and semi-intensive green roofs into a single category (Extensive) may introduce a confounding factor. This grouping includes areas with only grass alongside others with shrubbery, which typically have higher plant species richness, a factor shown to increase richness and abundance of certain arthropod groups (Fabián *et al.*, 2021).

Although no studies were found to help explain the high abundance of the family Chironomidae in winter, Lencioni & Moubayed-Breil (2021) have described a community of urban chironomids in Italy, which included species that are very well adapted to lower temperatures and may reproduce during winter, and this is corroborated by Karima (2021) when describing ecology within this family of mosquitoes. The higher abundance of ants in Extensive Green Roofs may be explained by Clarke *et al.* (2008), who found that, in urban parks, forested areas showed decreased ant abundance when compared to areas composed by herbaceous vegetation. Furthermore, Korányi *et al.* (2020) found high abundances of aphids in urbanized areas, specifically on trees, which are only present in Intensive Green Roofs.

Wang *et al.* (2022) reviewed the relationship between green roofs and urban biodiversity, noting that greater soil depth can boost ant abundance, as well as both bee abundance and richness. In this study, ants were more abundant on Extensive Green Roofs year-round, but as Wang *et al.* pointed out, soil depth is closely tied to vegetation type, making it difficult to determine the individual effects of each factor. In contrast, two bee families (Apidae and Megachilidae) were found on Intensive Green Roofs, while only one (Apidae) was observed on Extensive ones, and bee abundance was consistently higher on Intensive Green Roofs in both seasons, corroborating Wang *et al.*'s findings.

Even though the analysed metrics were not statistically significant, differences in the overall values of richness should be highlighted. From the 64 arthropod families found in Green Roofs, only 33 were present in Extensive Green Roofs, while 60 were detected in Intensive Green Roofs. Moreover, 31 out of 64, were exclusively found in Intensive Green Roofs, corroborating past studies' results that correlate higher vegetation complexity/richness to more diverse arthropod communities (Wang *et al.*, 2022).

4.3. Comparison Between Green Roofs, Urban Gardens and Grey Areas

Looking at bird communities, the results achieved here are supported by literature, as past studies have shown that green roofs contribute to bird habitats in cities (Eakin *et al.*, 2015). Green areas tend to have greater evenness, richness and abundance (Órtega-Álvarez & MacGregor-Fors, 2009), in contrast to grey areas (including conventional roofs) (Liordos *et al.*, 2021; Partridge & Clark, 2018).

The results for the most abundant species were aligned with expectations: *C. livia*, *P. domesticus* and *T. merula*, all species well adapted to urban environments (De Laet, & Summers-Smith, 2007; Przybylska *et al.*, 2012; Wang *et al.*, 2015), were the most abundant in green spaces. In contrary, *C. livia* and *Larus* sp. were the most abundant in Grey Areas, consistent with the described use of grey areas in cities, such as city squares (Pais de Faria *et al.*, 2021, Sacchi *et al.*, 2002). The species occupying the third position in this habitat, specifically in winter, *Motacilla alba*, *P. domesticus*, *P. ochruros*, and *T. merula* are also known for using man-made structures and adapting well to the urban environment (Pegu *et al.*, 2024; Schwarzová & Exnerova, 2004; Wang *et al.*, 2015). For example, *M. alba* tends to forage in areas with asphalt (Svensson *et al.*, 2017).

All the biodiversity metrics analysed, Shannon index, species richness and abundance, indicate clear similarities between Green Roofs and Urban Gardens, and a separation from Grey Areas. This is a positive result, that highlight the potential value of Green Roofs for biodiversity and is corroborated by some former studies. For example, Wang *et al.* (2022), reported that some works indicate that regarding bird richness, some Green Roofs have no differences with adjacent ground-level habitats, but other showed lower values. However, when compared to conventional roofs (or, in this case, Grey Areas), Green Roofs also showed higher bird richness and abundance. Unfortunately, few studies have used Shannon index for comparison of bird communities, but given the results achieved here, they are in line with the rest of the conclusions.

The rarefaction curves support this trend, as Grey Areas quickly reach a plateau, indicating that the sample size was in this case sufficient possible due to the lower species richness. Both Green Roofs and Urban Gardens lack a clear tendency to reach a plateau, suggesting that the sample size should ideally be larger than the one used here. Additionally, the overlap in the error intervals, especially in winter, indicates minimal differences between these communities in this season. In spring, although overlap exists, it is less pronounced, suggesting that while the communities remain similar, Urban Gardens may exhibit slightly greater diversity.

Corroborating the previous results, the NMDS analysis shows some overlap of all the habitat types, but much more evident between Green Roofs and Urban Gardens than with Grey Areas, that tend to be more dispersed, suggesting these are more variable. The overlap of 6 sites in spring – 5 Grey Areas and 1 Green Roof – and the coordinates corresponding to *Columba livia* shows that the species tends to be associated with higher levels of urbanization (Sacchi *et al.*, 2002; Weber *et al.*, 1994), but also that the green roof of Alameda shows a lot of similarities to those grey sites, despite being a vegetated area. As noted earlier, this is likely due to the area's high level of disturbance, with many people using this green roof for sports activities and dog walking (a factor known to correlate with reduced bird diversity) (Paker *et al.*, 2014). These activities generate noise and may also contribute to the degradation of the existing vegetation.

Looking again at the Indicator Values results, *Turdus merula* shows a strong association with both types of green spaces (Green Roofs and Urban Gardens), as did *Serinus serinus* in spring. Both species showed average abundances over 0.5 in each habitat, likely due to their adaptability to urban environments, while still using green spaces for nesting and feeding, where resources are more abundant (Ortega-Álvarez & MacGregor-Fors, 2009). As for *Sylvia atricapilla*, it is possible that the stronger association with Urban Gardens may be associated with the vegetation structure of the sites where it was registered, as this species nests in bushes (Svensson *et al.*, 2017), and every garden where it was registered had shrubbery. Specifically for urban settings, Douini *et al.* (2023) reported *S. atricapilla* nesting in green gardens, in trees. As such, it was expected to find this species nesting in the city, but the reason for the association only with Urban Gardens remains unclear. As mentioned above, one explanation for this result may lie in the plant structure of the sampled sites and their specificities, and it is thus possible that the sampled Green Roofs did not meet the requirements for the existence of *S. atricapilla*. The association of *Larus* sp. with Grey Areas, can be partially explained the opportunist behaviour of gulls in urban environments foraging on human food, including waste (Pais de Faria *et al.* 2021), which seems to be more abundant in Grey Areas than in the city's green spaces (personal observation). Additionally, their resting places and forage sites frequently include city squares, which usually resemble Grey Areas more closely than the other habitats. Human-gull interactions appear to increase during winter (Pais de Faria *et al.* 2021).

Regarding arthropod results, the family Formicidae is frequently the most abundant family in almost every type of habitat in both seasons (with the exception of Green Roofs in winter). Although no particular reason was found for this, Benedito Durà *et al.* (2023) also found ants to not be among the most abundant taxa in the Green Roofs sampled in their work. The high abundance of Erythraeidae, represented by *Balaustium* sp., in Grey Areas in spring is corroborated by Hedges *et al.* (2013), who reported that their high heat tolerance and requirement of a dry habitat makes dry sunny sites (like exposed areas of asphalt or concrete) ideal for them.

Analysis of the arthropod communities in different habitats showed similar patterns to that of the birds, especially in spring. During winter, no clear patterns were observed, likely due to the low arthropod diversity and abundance characteristic of this season. In contrast, analysis of the diversity metrics in spring showed no differences between Green Roofs and Urban Gardens, while highlighting differences between these spaces and Grey Areas. These results are, again, supported by literature, since Partridge & Clark (2018) and Benedito Durà *et al.* (2023) found that Green Roofs can host a higher richness and abundance of arthropods than conventional roofs, and MacIvor & Lundholm (2010) found no difference between the communities of Green Roofs and in ground-level sites.

Rarefaction curves consistently showed the tendency described above with Grey Areas always having significant lower richness, despite extrapolation in spring predicting the potential for much higher richness. The relation between Green Roofs and Urban Gardens remains closely aligned, with their curves appearing very similar in both seasons. In winter, the degree of overlap suggests similar communities, but extrapolation indicates that the sample size is slightly more adequate for Green Roofs than Urban Gardens, as the former seems closer to reaching a plateau. In spring, there is less overlap between the curves, but the extrapolation error intervals show a high overlap, and both curves seem very close to a plateau, suggesting that the sample size was reasonably adequate in this season. Past studies support these findings. Fenoglio *et al.* (2020) showed that, in general, higher levels of urbanization have negative effects on arthropod communities. Similarly, Braaker *et al.* (2014) highlighted green roofs as valuable habitat for arthropods, advising that improving both the conditions of Green Roofs and their connectivity to other green spaces, could enable, at least high-mobility groups, to use Green Roofs as stepping stones within the cities. Furthermore, Lagucki *et al.* (2017) showed that an increase in impervious surfaces leads to shifts in flying arthropod communities, but noted that these hypotheses required further testing, as different groups may be influenced by distinct mechanisms. This could explain the lack of difference in abundance between Green Roofs and Grey Areas, and including functional traits in future analyses may be needed to find more specific insights.

5. Final Considerations and Constraints

This is the first study to analyse faunistic communities of Green Roofs in Portugal, and the first to examine bird communities in such sites within a Mediterranean climate. The results of this study contributed to a more comprehensive understanding of the potential of Green Roofs to benefit urban communities of both birds and arthropods. It has been shown that, effectively, Green Roofs "behave" similarly to conventional Urban Gardens and add habitable area to the urban matrix, in contrast to Grey Areas, which are poorly vegetated and impervious. Furthermore, it has been shown that, at least for birds, Intensive Green Roofs show more potential for increased diversity within cities. In future studies, it would be interesting to analyse the impact of characteristics of Green Roofs not used here, such as their area and plant communities, i.e., the species that compose them and whether they are native to the study area.

In this work, Extensive and Semi-Intensive Green Roofs were grouped into a single category and statistically treated as one group. However, this approach should be interpreted with some reservations, as these types of Green Roofs, and consequently their faunistic communities, can be quite different. For instance, soil depth can range from a minimum of 8 cm in Extensive Green Roofs to 25 cm in Semi-Intensive ones. The decision to combine these categories was driven by logistic constraints in the sampling, as only a small proportion of the total sampled Green Roofs fell into these categories, with the great majority of them being Intensive Green Roofs. Conducting fieldwork in an urban centre, and specifically in public parks, presents unique challenges. The chosen method for arthropod sampling used in this study was the best compromise between collecting a large amount of data in a short period of time and minimizing damage to the infrastructures. Moreover, given the public nature of these areas, the use of alternative traps (as pan traps and pitfalls) could be difficult to manage. The methods used may somehow have contributed to incomplete arthropod sampling, once they primarily targeted species visible to the naked eye, as well as either flying or visible in vegetation. Although this does not compromise the comparisons made between the studied sites, it may lead to a discrepancy between the recorded biodiversity and its actual value, excluding, for example, ground-dwelling groups.

Green Roofs are well-known for their numerous benefits to urban living, and this study reinforces their significant role in supporting urban biodiversity. These findings highlight the importance of prioritizing Green Roof implementation wherever possible, with a focus on using native plant species and designing plant strata that maximize benefits for a wide range of animal groups.

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Appendix

Appendix A

Table A.1 – Sampled sites – location, type of site (Green roof, Urban Garden and Grey Area), coordinates (in decimal degrees), and number of bird point counts and arthropod transects done at each site.

LOCATION	TYPE OF SITE	COORDINATES	Point Counts	Transects
Av. E.U.A.	Green Roof	38.749722, -9.139943	1	2
Av. E.U.A.	Urban Garden	38.749559, -9.138187	1	2
Av. E.U.A.	Grey Area	38.748733, -9.138259	1	2
Jardim Ruy Jervis d'Athouguia	Green Roof	38.746232, -9.136139	1	2
Rua Pedro Ivo	Urban Garden	38.746293, -9.137475	1	2
Largo Machado de Assis	Grey Area	38.747241, -9.139479	1	2
Jardim Amália Rodrigues	Green Roof	38.730211, -9.156724	1	2
Jardim Amália Rodrigues	Urban Garden	38.731221, -9.154363	2	2
Palácio de Justiça	Grey Area	38.731677, -9.156862	2	2
Jardins do Palácio Sottomayor	Green Roof	38.728365, -9.147491	1	2
Parque Eduardo VII	Urban Garden	38.728601, -9.150775	1	1
Largo de Andaluz	Grey Area	38.727717, -9.147839	1	1
Rua João Chagas (1)	Green Roof	38.748180, -9.176465	1	2
Rua João Chagas (2)	Green Roof	38.748282, -9.177898	1	2
Rua Cidade de Rabat	Urban Garden	38.747929, -9.179033	1	2
Rua Abílio Mendes	Grey Area	38.748628, -9.179436	1	2
Alameda D. Afonso Henriques	Green Roof	38.737103, -9.132837	1	2
Jardim da Fonte Luminosa	Urban Garden	38.737346, -9.129733	1	2
Entrada Instituto Superior Técnico	Grey Area	38.736890, -9.137023	1	2
Campus de Justiça	Green Roof	38.773257, -9.096279	3	3
Av. Boa Esperança	Urban Garden	38.775171, -9.093774	1	2
ESEL Parking Área	Grey Area	38.777209, -9.098516	1	3
Centro Cultural de Belém	Green Roof	38.695217, -9.209164	2	4
Praça do Império	Urban Garden	38.695575, -9.206368	1	2
Entrada Museu da Marinha	Grey Area	38.697419, -9.208631	1	3
Junta de Freguesia Parque das Nações	Green Roof	38.762247, -9.096887	1	1
Jardim Cabeço das Rolas	Urban Garden	38.760648, -9.097311	1	2
Rua Pedro e Inês	Grey Area	38.760693, -9.094361	1	1
Doca da Ribeira das Naus	Green Roof	38.706473, -9.139452	1	2
Largo do Corpo Santo	Urban Garden	38.706317, -9.142224	1	1
Praça do Município	Grey Area	38.707974, -9.139240	1	1
Metro Telheiras – Prof. Francisco Caldeira Cabral and Prof. António de Sousa Franco Gardens	Green Roof	38.760006, -9.166115 38.760224, -9.167316	2	3
Rua Prof. Francisco Gentil	Green Roof	38.761051, -9.166000	1	1
Azinhaga das Galhardas	Green Roof	38.758514, -9.168031	1	1
Jardim da Av. Ventura Terra	Urban Garden	38.758684, -9.166408	1	1

Escola Alemã de Lisboa – parking area	Grey Area	38.759149, -9.163569	1	1
Rua Prof. Juvenal Esteves	Green Roof	38.704869, -9.175426	2	2
Vodafone Parque das Nações	Green Roof	38.766036, -9.096876	1	1
Jardim Irmã Lúcia	Green Roof	38.739599, -9.137631	1	2
ETAR Alcântara	Green Roof	38.720947, -9.174674	4	4
Fundação Calouste Gulbenkian	Green Roof	38.737589, -9.154880	5	5

Appendix B

Table B.1 – List of all bird species recorded during the two sampling periods (winter and spring) in the 19 studied green roofs. Scientific names, common names in Portuguese and English, and abbreviation of the scientific names, used later on in this work in the NMDS analysis. Non-native species are denoted with an asterisk (*).

SCIENTIFIC NAME	PORTUGUESE COMMON NAME	ENGLISH COMMON NAMES	Abbrev
***Acridotheres cristatellus* ***	Mainá-de-crista	Crested Myna	Acri
***Alisterus scapularis* ***	Periquito-rei-australiano	Australian King Parrot	Asca
***Alopochen aegyptica* ***	Ganso-do-Egipto	Egyptian Goose	Aaeg
Anas platyrhynchos	Pato-real	Mallard	Apla
Anthus pratensis	Petinha-dos-prados	Meadow Pipit	Apra
Apus	Andorinhões	Typical Swifts	Apus
Apus apus	Andorinhão-preto	Common Swift	Aapu
Apus pallidus	Andorinhão-real	Pallid Swift	Apal
Buteo buteo	Águia-d'asa-redonda	Common Buzzard	Bbut
***Cairina moschata* ***	Pato-mudo	Muscovy Duck	Cmos
Carduelis carduelis	Pintassilgo	European Goldfinch	Ccar
Cecropis daurica	Andorinha-dáurica	Red-rumped Swallow	Cdau
Certhia brachydactyla	Trepadeira-comum	Short-toed Treecreeper	Cbra
Cettia cetti	Rouxinol-bravo	Cetti's Warbler	Ccet
Chloris chloris	Verdilhão	European Greenfinch	Cchl
Chroicocephalus ridibundus	Guincho-comum	Black-headed Gull	Crid
Cisticola juncidis	Fuinha-dos-juncos	Zitting Cisticola	Cjun
***Columba livia* (var. *domestica*)**	Pombo-doméstico	Domestic Pigeon	Cliv
Columba palumbus	Pombo-torcaz	Common Wood Pigeon	Cpal
Corvus corone	Gralha-preta	Carrion Crow	Ccor
Curruca melanocephala	Toutinegra-dos-valados	Sardinian Warbler	Cmel
Cyanistes caeruleus	Chapim-azul	Eurasian Blue Tit	Ccae
Delichon urbicum	Andorinha-dos-beirais	Common House-Martin	Durb
Emberiza cia	Cia	Rock Bunting	Ecia
Erithacus rubecula	Pisco-de-peito-ruivo	European Robin	Erub
***Estrilda astrild* ***	Bico-de-lacre	Common Waxbill	East
Fringilla coelebs	Tentilhão-comum	Common Chaffinch	Fcoe
Gallinula chloropus	Galinha-de-água	Common Moorhen	Gchl
Garrulus glandarius	Gaio	Eurasian Jay	Ggla
Hirundo rustica	Andorinha-das-chaminés	Barn Swallow	Hrus
Larus sp.	Gaivotas	Large White-headed Gulls	Larus
Larus fuscus	Gaivota-d'asa-escura	Lesser Black-backed Gull	Lfus
Larus michahellis	Gaivota-de-patas-amarelas	Yellow-legged Gull	Lmic
Linaria cannabina	Pintarroxo	Common Linnet	Lcan
Motacilla alba	Alvéola-branca	White Wagtail	Malb
Parus major	Chapim-real	Great Tit	Pmaj
Passer domesticus	Pardal-doméstico	House Sparrow	Pdom
Periparus ater	Chapim-carvoeiro	Coal Tit	Pate
Phalacrocorax carbo	Corvo-marinho	Great Cormorant	Pcar
Phoenicurus ochruros	Rabirruivo-preto	Black Redstart	Poch
Phylloscopus collybita	Felosinha	Common Chiffchaff	Pcol

SCIENTIFIC NAME	PORTUGUESE COMMON NAME	ENGLISH COMMON NAME	Abbrev
Psittacula krameri *	Periquito-rabijunco	Rose-ringed Parakeet	Pkra
Ptyonoprogne rupestris	Andorinha-das-rochas	Eurosian Crag Martin	Prup
Regulus ignicapilla	Estrelinha-real	Common Firecrest	Rign
Serinus serinus	Milheirinha	European Serin	Sser
Spinus spinus	Lugre	Eurasian Siskin	Sspi
Streptopelia decaocto	Rola-turca	Eurasian Collared Dove	Sdec
Sturnus	Estorninhos	Starlings	Sturnus
Sturnus unicolor	Estorninho-preto	Spotless Starling	Suni
Sturnus vulgaris	Estorninho-malhado	Common Starling	Svul
Sylvia atricapilla	Toutinegra-de-barrete	Eurasian Blackcap	Satr
Thectocercus acuticaudatus *	Periquitão	Blue-crowned Parakeet	Tacu
Troglodytes troglodytes	Carriça	Eurasian Wren	Ttro
Turdus philomelos	Tordo-pinto	Song Thrush	Tphi
Turdus merula	Melro	Common Blackbird	Tmer

Appendix C

Table C.1 – List of all identified arthropod families, and their respective orders and classes, recorded during the two sampling periods (winter and spring) in the 19 studied green roofs.

CLASS	ORDER	FAMILY
ARACHNIDA	Araneae	Araneidae
		Gnaphosidae
		Linyphiidae
		Salticidae
		Thomisidae
	Trombidiformes	Erythraeidae
DIPLOPODA	Julida	Julidae
INSECTA	Coleoptera	Carabidae
		Chrysomelidae
		Coccinellidae
		Curculionidae
		Melyridae
		Oedemeridae
		Scarabaeidae
		Scraptiidae
		Staphylinidae
		Tenebrionidae
	Diptera	Agromyzidae
		Anthomyiidae
		Apidae
		Calliphoridae
		Cecidomyiidae
		Ceratopogonidae
		Chironomidae
		Chloropidae
		Culicidae
		Dolichopodidae
		Drosophilidae
		Ephydridae
		Fannidae
		Heleomyzidae
		Hybotidae
		Lauxaniidae
		Lonchopteridae
		Muscidae
		Phoridae
		Platystomatidae
		Polleniidae
		Psychodidae
		Rhiniidae
		Rhinophoridae
		Sarcophagidae

CLASS	ORDER	FAMILY
INSECTA	Diptera	Sciaridae
		Sepsidae
		Simuliidae
		Sphaeroceridae
		Stratiomyidae
		Syrphidae
		Tachinidae
		Tephritidae
		Tipulidae
	Hemiptera	Aphididae
		Cicadellidae
		Delphacidae
		Lygaeidae
		Miridae
		Monophlebidae
		Nabidae
		Pentatomidae
		Pyrrhocoridae
	Hymenoptera	Apidae
		Braconidae
		Ceraphronidae
		Crabronidae
		Formicidae
		Halictidae
		Ichneumonidae
		Megachilidae
		Scelionidae
		Vespidae
	Lepidoptera	Crambidae
		Noctuidae
		Nymphalidae
		Pieridae
	Odonata	Libellulidae
	Thysanoptera	Phlaeothripidae
MALACOSTRACA	Isopoda	Armadillidiidae

Appendix D

Table D.1 – List of all identified bird species, and the green roofs where they were recorded (marked with a X), during the two sampling periods (winter and spring). Non-native species are denoted with an asterisk (*).

Bird Species	Alameda	Av EUA	Azinh. das Galhardas	Campus de Justiça	CCB	ETAR	Francisco Gentil	Gulbenkian	Jardim Irmã Lúcia	Jar. Amália Rodrigues	João Chagas (1)	João Chagas (2)	Junta de Freguesia	Jar. Ruy Jervis	Juvenal Esteves	Metro Telheiras	Ribeira das Naus	Palácio Sottomayor	Vodafone
***Acridotheres cristatellus* ***	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--
***Alopochen aegyptica* ***	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Anas platyrhynchos	--	--	--	--	X	--	--	X	--	--	X	X	--	--	--	--	--	--	--
***Cairina moschata* ***	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Carduelis carduelis	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	X	--
Certhia brachydactyla	--	--	X	--	--	--	--	X	--	X	--	--	--	X	--	--	--	--	--
Chloris chloris	--	--	X	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Cisticola juncidis	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Columba livia	X	X	--	--	X	X	X	X	X	--	--	X	X	X	X	X	X	--	--
Columba palumbus	--	--	--	--	--	--	--	X	X	X	--	--	--	X	--	--	--	--	--
Corvus corone	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Curruca melanocephala	--	--	X	X	X	X	X	X	--	--	--	--	X	--	--	X	--	--	--
Cyanistes caeruleus	--	--	X	--	X	--	--	X	--	X	--	--	--	X	--	X	--	--	--
Delichon urbicum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--
Erithacus rubecula	--	--	--	X	--	X	X	X	X	X	X	--	--	--	--	X	--	--	--
***Estrilda astrild* ***	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Fringilla coelebs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--
Garrulus glandarius	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Hirundo rustica	--	--	--	--	--	--	--	X	--	X	--	--	--	--	--	--	--	--	--
***Larus* sp.**	X	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Bird Species	Alameda	Av. EUA	Azinh. das Galhardas	Campus de Justiça	CCB	ETAR	Francisco Gentil	Gulbenkian	Jardim Irmã Lúcia	Jar. Amália Rodrigues	João Chagas (1)	João Chagas (2)	Junta de Freguesia	Jar. Ruy Jervis	Juvenal Esteves	Metro Telheiras	Ribeira das Naus	Palácio Sottomayor	Vodafone
Linaria cannabina	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Motacilla alba	--	X	--	X	X	X	X	X	--	X	X	--	X	X	--	--	--	--	--
Parus major	--	--	--	--	--	--	--	X	--	--	--	--	--	X	--	--	--	--	--
Passer domesticus	--	X	X	X	X	--	X	X	X	--	X	X	X	X	X	X	X	X	X
Periparus ater	--	--	--	--	X	--	--	--	X	--	--	--	--	--	--	--	--	--	--
Phoenicurus ochruros	--	--	X	X	X	X	X	--	--	--	X	X	--	X	X	X	--	X	--
Phylloscopus collybita	--	--	X	X	--	--	X	X	--	--	--	X	--	--	X	X	--	--	--
Psittacula krameria *	--	--	--	--	--	--	--	X	X	--	--	--	--	--	--	X	--	--	--
Regullus ignicapilla	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--
Serinus serinus	--	--	X	X	X	X	X	X	X	X	--	--	--	X	--	X	--	X	--
Spinus spinus	--	--	--	--	--	--	--	X	--	--	--	X	--	--	--	--	--	--	--
Streptopelia decaocto	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--
***Sturnus* sp.**	--	--	X	--	X	X	--	--	--	X	--	--	--	--	--	--	--	--	--
Sylvia atricapilla	--	--	X	--	X	--	X	X	X	--	--	--	X	--	--	X	--	--	--
Troglodytes troglodytes	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Turdus merula	--	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Appendix E

Table E.1 – List of all identified arthropod families, and the green roofs where they were recorded (marked with a X), during the two sampling periods (winter and spring).

Arthropod Family	Alameda	Av. EUA	Azinh. das Galhardas	Campus de Justiça	CCB	ETAR	Francisco Gentil	Gulbenkian	Jardim Irmã Lúcia	Jar. Amália Rodrigues	João Chagas (1)	João Chagas (2)	Junta de Freguesia	Jar. Ruy Jervis	Juvenal Esteves	Metro Telheiras	Ribeira das Naus	Palácio Sottomayor	Vodafone
Agromyzidae	--	--	--	X	--	--	--	--	--	X	--	--	--	--	--	--	X	--	--
Anthomyiidae	--	X	X	--	--	--	--	X	--	X	--	--	--	X	X	--	X	X	X
Aphididae	--	--	X	X	--	X	X	X	X	X	X	--	--	X	X	X	--	X	X
Apidae	--	--	X	X	X	X	X	X	X	X	--	--	--	X	X	--	--	X	--
Araneidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	X
Armadillidiidae	--	--	--	X	--	X	--	--	--	X	--	--	--	--	--	--	X	--	--
Braconidae	--	--	--	X	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Calliphoridae	--	--	--	X	--	X	X	X	--	X	X	X	--	X	X	X	X	X	X
Carabidae	--	--	--	--	X	X	--	--	--	--	X	--	--	--	--	--	--	--	--
Cecidomyiidae	--	--	--	--	--	--	--	--	X	--	--	--	--	X	--	--	--	X	--
Ceratopogonidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	X	--	X	X	X
Chironomidae	--	--	X	X	X	X	X	X	X	X	X	X	X	X	X	--	--	X	X
Chloropidae	--	--	--	X	--	--	--	X	--	X	--	--	--	--	--	--	--	--	--
Chrysomelidae	--	X	--	--	--	X	--	--	--	--	--	X	--	--	X	X	--	--	--
Cicadellidae	--	--	--	X	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--
Coccinellidae	--	--	--	--	--	X	--	--	--	--	--	--	X	--	X	--	--	X	X
Crabronidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Curculionidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--
Delphacidae	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Dolichopodidae	--	--	--	--	--	--	--	--	--	X	--	--	X	--	--	--	--	--	--

Arthropod Family	Alameda	Av. EUA	Azinh. das Galhardas	Campus de Justiça	CCB	ETAR	Francisco Gentil	Gulbenkian	Jardim Irmã Lúcia	Jar. Amália Rodrigues	João Chagas (1)	João Chagas (2)	Junta de Freguesia	Jar. Ruy Jervis	Juvenal Esteves	Metro Telheiras	Ribeira das Naus	Palácio Sottomayor	Vodafone
Drosophilidae	--	--	X	--	--	--	--	--	X	--	--	--	--	X	--	--	X	--	X
Ephydridae	--	--	--	X	--	--	--	X	X	X	--	X	--	X	--	X	X	--	X
Erythraeidae	--	--	--	--	--	--	X	--	--	--	--	X	X	--	--	--	--	--	--
Fannidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Formicidae	--	X	X	X	X	X	X	X	X	X	X	X	--	X	X	X	X	X	X
Heleomyzidae	--	--	--	--	--	--	--	--	--	X	--	--	--	X	--	--	--	--	--
Hybotidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	X
Ichneumonidae	--	--	--	--	--	--	--	X	X	--	X	--	--	--	--	X	--	X	--
Lauxaniidae	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	X	--	--	--
Libellulidae	--	--	--	--	--	--	--	--	--	X	--	X	--	--	--	--	--	--	--
Linyphiidae	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Lonchopteridae	--	--	--	--	--	--	--	X	--	--	--	X	--	--	--	--	X	--	--
Megachilidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Miridae	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Monophlebidae	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--
Muscidae	--	X	X	X	X	--	X	X	X	X	X	X	--	X	X	X	X	X	--
Nabidae	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Noctuidae	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Nymphalidae	--	--	X	--	X	X	--	X	X	X	X	X	--	X	X	--	--	--	--
Oedemeridae	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--
Pentatomidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Phlaeothripidae	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--
Phoridae	--	--	X	X	--	--	--	X	--	X	--	--	--	X	--	--	X	--	--
Pieridae	--	--	X	X	--	X	--	--	--	X	--	--	--	--	X	--	--	X	--

Arthropod Family	Alameda	Av. EUA	Azinh. das Galhardas	Campus de Justiça	CCB	ETAR	Francisco Gentil	Gulbenkian	Jardim Irmã Lúcia	Jar. Amália Rodrigues	João Chagas (1)	João Chagas (2)	Junta de Freguesia	Jar. Ruy Jervis	Juvenal Esteves	Metro Telheiras	Ribeira das Naus	Palácio Sottomayor	Vodafone
Platystomatidae	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Psychodidae	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pyrrhocoridae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--
Rhinophoridae	--	--	--	--	--	X	--	--	X	X	--	--	--	--	--	X	--	--	X
Salticidae	--	--	--	--	--	--	X	--	--	--	X	--	--	--	X	--	--	--	--
Sarcophagidae	X	--	--	--	--	--	--	--	X	--	--	X	--	X	X	X	--	--	--
Scarabaeidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	--
Scelionidae	--	--	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--
Sciaridae	--	--	--	--	X	--	--	X	--	--	--	--	--	--	X	--	--	--	X
Sepsidae	--	--	--	--	--	--	--	X	--	X	--	--	--	--	--	--	--	--	--
Simuliidae	--	--	--	--	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--
Sphaeroceridae	--	--	--	X	--	X	--	X	--	X	--	X	--	X	--	--	X	--	--
Staphylinidae	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Syrphidae	--	X	X	X	--	X	--	X	X	X	X	X	--	--	X	--	X	X	--
Tachinidae	--	--	--	--	--	--	--	X	--	--	--	--	--	--	X	--	--	--	--
Tenebrionidae	--	--	--	--	--	X	X	X	--	--	--	--	--	--	--	--	--	--	--
Tephritidae	--	--	--	--	--	--	--	--	--	--	--	--	--	X	--	--	--	--	--
Thomisidae	--	--	--	--	--	X	--	X	--	--	--	--	--	--	--	--	--	--	--
Tipulidae	--	--	--	--	--	X	--	X	X	X	X	--	--	--	X	--	--	X	--
Vespidae	--	X	X	X	--	X	--	--	--	--	--	X	X	X	X	--	--	X	--

Appendix F

Fig F.1 – Pictures of the three most abundant bird species recorded on Green Roofs. A – *Columba livia;* B – *Passer domesticus;* C – *Turdus merula.*

Appendix G

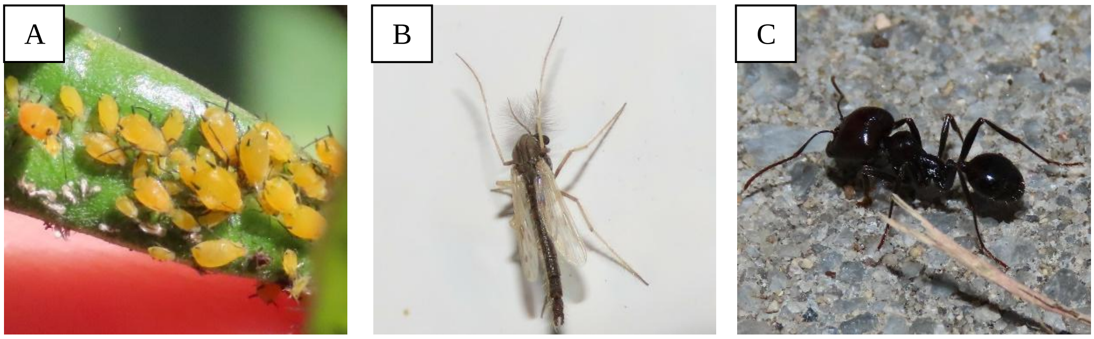

Fig. M. 1 – Pictures of three of the most abundant arthropod families recorded on Green Roofs. A – Aphididae; B – Chironomidae; C – Formicidae.

Appendix H

Other Outputs

Oral Presentations in Scientific Meetings

- Tiago, P., Leal, A., Falcão, A.P., Sousa, V., **Rei, M.**, Padinha, V., Pernes, J., Oliveira, D., Silva, C.M. (2024) "Evaluating the Contribution of Green Roofs/Walls for cities' Biodiversity with the support of Citizen Science". NBS Summit, 23r^{d} of May, Porto, Portugal.

- **Rei, M.,** Tiago, P., Leal, A.I. (2024) "Contributo das Coberturas Verdes para a Biodiversidade de Lisboa". Final Workshop of the GRAVITY project, 20th of September 2024, Instituto Superior Técnico, Lisboa, Portugal.

Fig. F.1 – First slide of the PowerPoint oral presentation at the Final Workshop of the GRAVITY project.

- **Rei, M.,** Leal, A. I., Tiago, P., Silva, C.M. (2024) "Contributo das Coberturas Verdes para a Biodiversidade de Lisboa". Conferência Luso-Brasileira de Materiais de Construção Sustentáveis, 7th November 2024, Instituto Superior Técnico, Lisboa, Portugal – available at https://www.clbmcs-construcao-2024.com/comunicacoes-1/atas, ISBN 978-989-95625-9-2

Fig. F.2 – First slide of the PowerPoint presentation given at Conferência Luso-Brasileira de Materiais de Construção Sustentáveis.

- Silva, C.M., Tiago, P., Leal, A., Sousa, V., Falcão, A.P., Proença, V., Pernes, J., **Rei, M.**, Padinha, V., Oliveira, D.V. (2024) "Contribution to Biodiversity of Existing Green Roofs in Lisbon". Final Workshop for EVIDENCE and GREENER workshops, 8th November 2024, Instituto Superior Técnico, Lisboa, Portugal - Book of Abstracts available at https://gigroup.tecnico.ulisboa.pt/PHP/events.php?ProjectId=EVIDENCE&info=Events

- **Rei, M.,** Leal, A.I., Tiago, P., (2024) "Contribution of Green Roofs to the Biodiversity of Lisbon". 10th Frontiers in E3 – CE3C Annual Meeting, 12-13 of December 2024, Lisboa, Portugal.

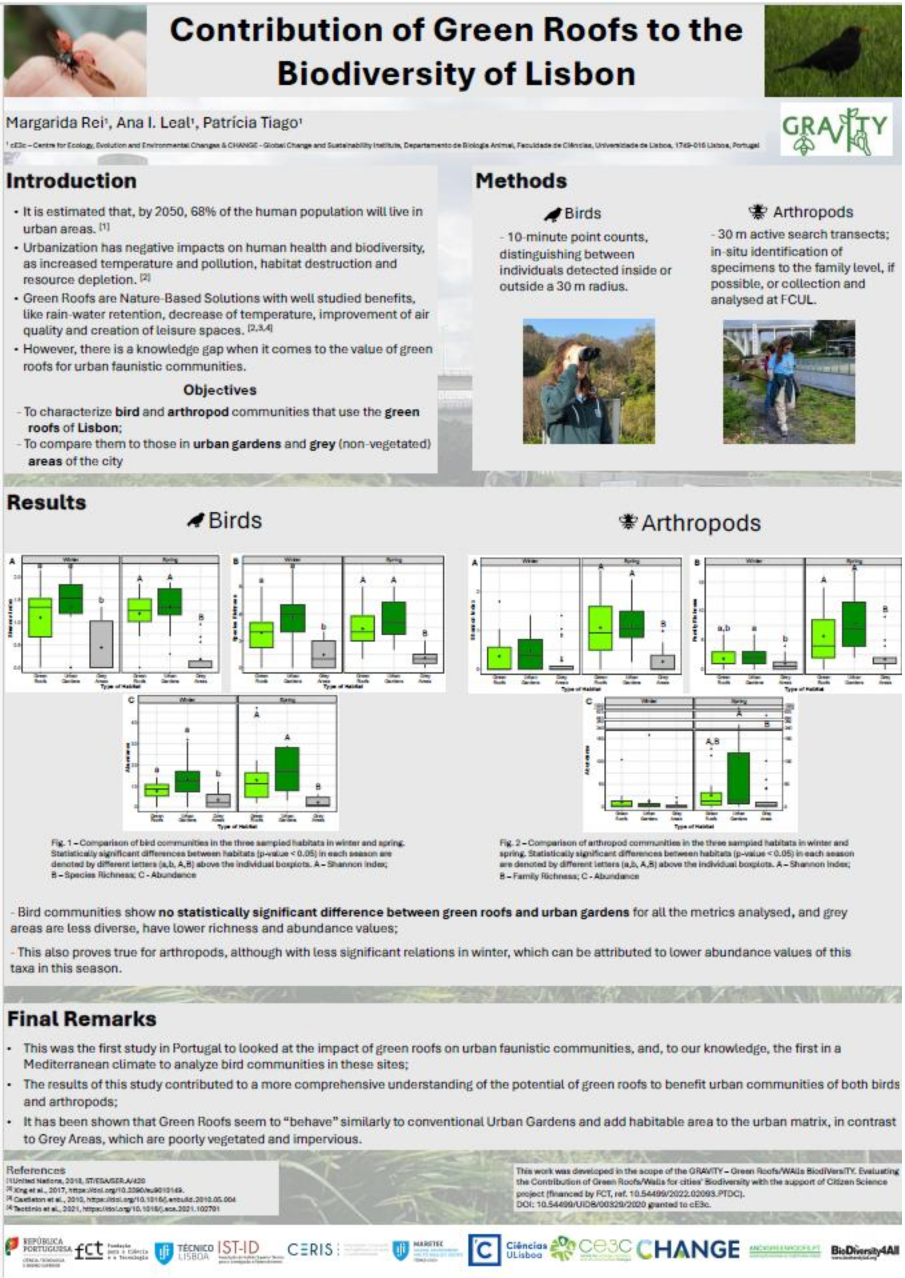

Fig. F.3 – Poster presented given at 10th Frontiers in E3 – CE3C Annual Meeting.

Management of Websites for the GRAVITY Project

- https://www.projectgravity-ist.com/
- https://gigroup.tecnico.ulisboa.pt/PHP/about.php?ProjectId=GRAVITY

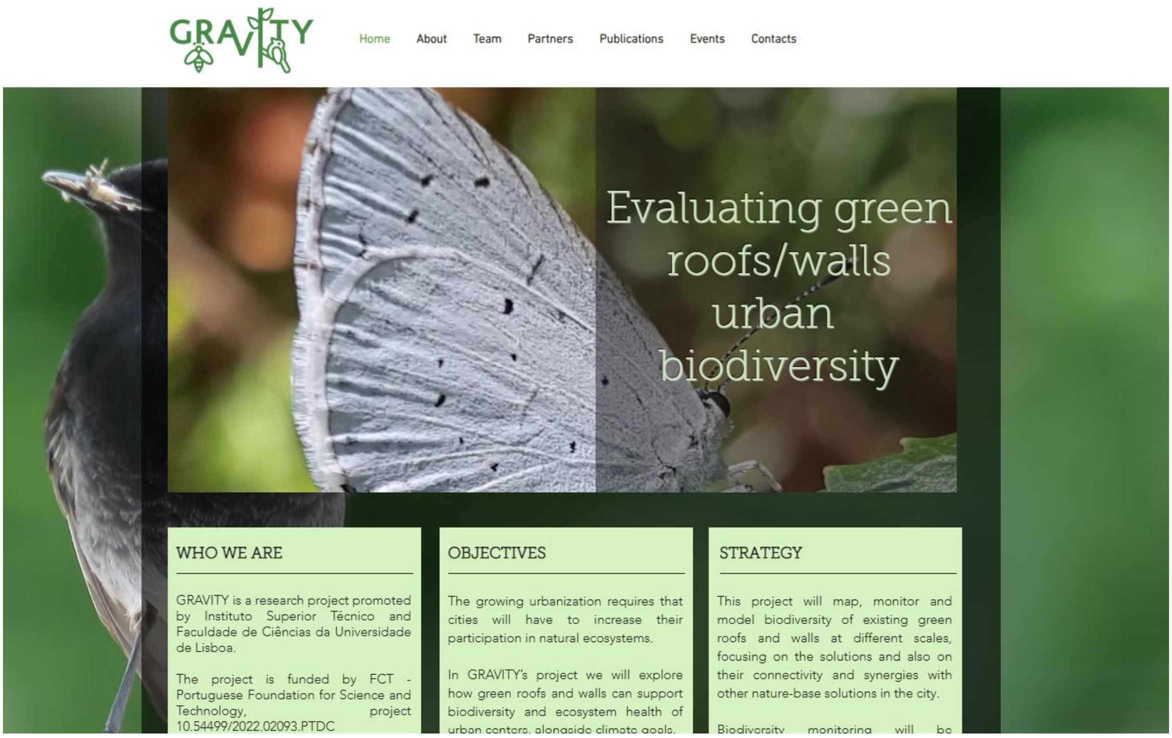

Fig. F.4 – Website of the GRAVITY project, available at https://www.projectgravity-ist.com/.

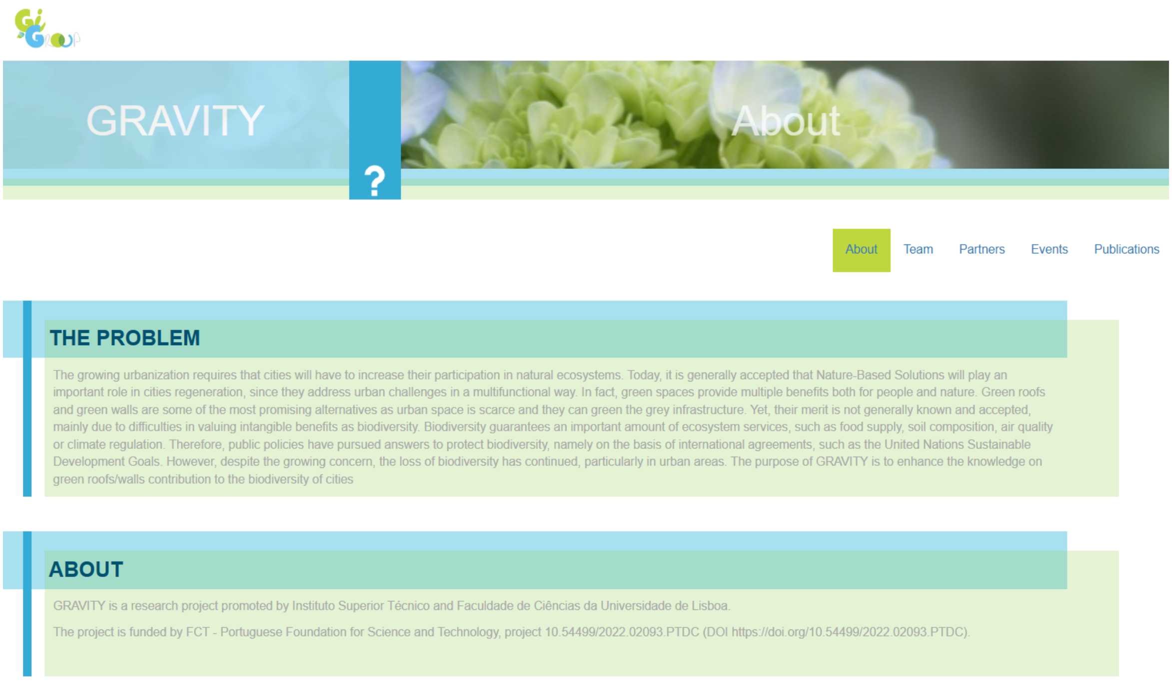

Fig. F.5 – Section of the GRAVITY project, within the GIGroup website, available at https://gigroup.tecnico.ulisboa.pt/PHP/about.php?ProjectId=GRAVITY.